Effect of Rate of Strain on the Strength of Compacted Soil

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This paper reports the results of a laboratory investigation of the effects of rate of strain on the strength of remolded soil. Two soils were selected for purposes of this study: (a) a clay derived from limestone and pedologically classified as Frederick, and (b) a glacial silty clay, pedologically classified as Crosby, "B" horizon. These soils were selected primarily on the basis of their difference in plasticity.

Rate of strain was considered the most important variable and it was studied from 0.55 in./min. to 1,780 in./min. The factors of moisture content and dry density were also of prime importance. Consequently, three compactive efforts were used and specimens were molded and tested on both sides of the optimum moisture content of each compactive effort.

The unconfined compressive strength test was used as the strength criterion and the effect of the aforementioned variables upon the ultimate strength and modulus of deformation of the samples, as determined by this test, are reported.

● THE FACT that the compressive strength is a function of the time required to reach the failure load has long been recognized. However, this area of soil mechanics has not been extensively explored and much work remains to be done, in order that the effects of this phenomenon can be properly evaluated. The specific areas where this information would be of the greatest benefit are as follows:

1. Stability of slopes subjected to earthquakes and other forms of transient loading.
2. Transmission of forces from explosions through soils.
3. Design of highway pavements.
4. Design of airfield pavements.

STABILITY OF SLOPES

In areas where there is a possibility of earthquakes, it is of the utmost importance to investigate the stability of slopes, both natural and man-made, under transient conditions. Such an investigation is especially necessary when failure of the slope in question would be disastrous. Earthquake shocks induced in the earth represent transient loading conditions and critical slopes should be designed and analyzed on this basis.

TRANSMISSION OF FORCES FROM EXPLOSIONS

The transmission of forces from explosions through soil, due to the short time of loading, is another example of where structures subject to such forces should be designed and analyzed on the basis of transient loading tests. Such a rigorous study would be valid only for critical military installations.

DESIGN OF HIGHWAY PAVEMENTS

It is generally recognized that the stress-strain characteristics of pavements are a function of the rate of strain. This can be readily seen by observing the condition of pavements at critical sections along a given route.

From such studies, it has been found that road intersections, uphill grades and other sections where traffic is required to move slowly, or to stop, show distress much more rapidly than their counterparts; that is, open road, free of stops, and downhill grades. This is believed to be caused, in part, by the difference in speed of travel over the aforementioned sections. As a result, there is much need of a comprehensive study on the effect of rate of strain on the behavior of soils.

DESIGN OF AIRFIELD PAVEMENTS

Because of the high speed at which airplanes travel over runways, the latter are subjected to transient loading conditions which are vastly different from the relatively static conditions to which the aprons, taxiways, and ends of runways are subjected. Hence, it is desirable to evaluate the stress-strain characteristics of the paving materials under both transient and static loading. Such a procedure would lead to the most economical as well as the best design.

PURPOSE AND SCOPE

The previous discussion points out that the effect of rate of strain on the strength of soil is important. Consequently, the primary purpose of the research reported herein was to investigate the strength properties of a clay and silty clay under conditions of transient loading. Specifically the aim was to ascertain the relationship between rate of strain and unconfined compressive strength at various moisture contents and densities. Also, it was hoped to relate the aforementioned variables to the modulus of deformation.

Rate of strain was considered the most important variable, and it was studied from 0.55 in./min to 1,780 in./min. Soil texture was a second variable and two fine-grained soils of significantly different characteristics were chosen—a silty clay and a clay. All soils are native to Indiana.

The factors of moisture content and dry density were also of prime importance. Three compactive efforts were used and specimens were molded and tested on both sides of the optimum moisture content (O.M.C.), of each compactive effort.

DEFINITIONS

It is assumed that the reader is familiar with terms pertaining to conventional strength tests on soils. However, before proceeding further he should familiarize himself with the following terms:

1. A Slow Transient Compression Test is one in which the rate of strain lies within the range of 0.45 in./min to 0.6 in./min.
2. A Medium Transient Compression Test is one in which the rate of strain lies between 11.0 in./min and 15.5 in./min.
3. A Fast Transient Compression Test is one in which the rate of strain is greater than 250 in./min.
4. Time of Loading is defined as the difference in time between the start of a loading test and the time at which the maximum compressive stress is reached.
5. Compressive Stress is the axial load per unit of cross-sectional area of a test specimen. In computing the compressive stress, a correction was applied to the area assuming that no volume change took place; that is, change in area assumed proportional to the change in height.
6. Modulus of Deformation is a secant modulus defined as the slope of a line from the origin through the point on the stress vs strain curve at which the stress is one-half of the compressive strength. Or, if the initial part of the stress vs strain curve is straight, it is the slope of this portion of the curve.
7. Rate of Strain is defined as the deformation at failure divided by the time required to reach failure.
8. Strength Ratio, S_u, is defined as the ratio of the strength, for a given rate of strain, to that for a slow transient test at the same moisture content and for the same compactive effort.

9. Modulus of Deformation Ratio, M_D, is defined as the ratio of the modulus of deformation for a given rate of strain to that for a slow transient test at the same moisture content and for the same compactive effort.

10. Strength, in this report will always apply to the axial load required to produce failure in an unconfined compression test.

It should be noted that the above definitions may be at variance with those by other investigators, but were adopted for this study because they give the best representation of the data.

REVIEW OF LITERATURE

The effect of time of loading on the strength and modulus of elasticity of metal and concrete has been extensively investigated. Also, a considerable amount of work has been done on rock and wood, but little on soil.

The standard methods of measuring the time effect, in previous investigations, was either by the time of loading, the rate of loading, or the rate of strain. In general, the method utilized was determined by the characteristics of the testing machines; that is, with the equipment available which of the aforementioned methods of measurement can be used most accurately and efficiently. Nevertheless, whenever the time-stress-strain relationships are known, any one of the above ways of measuring the time effect may be converted to either of the other two.

SOIL

In connection with the design of the Panama Canal, several triaxial compression tests were made to determine the effect of time of loading on the compressive strength of Gatun black muck (14). In one test, with a time of loading of approximately 90 sec, the compressive strength was about 40 percent greater than in four other tests, in which failure was obtained in about 1 hr.

A series of triaxial compression tests, on remolded-consolidated Boston blue clay, was reported by Taylor. The rate of strain ranged between 1 and 0.0005 percent per min and the compressive strength for the fastest test was approximately 20 percent greater than that for the slowest test (1).

Casagrande and Shannon (1) found that the modulus of deformation of clays for fast transient tests was approximately twice as great (for both unconfined and consolidated quick tests) as that for slow tests. Also, the modulus of deformation of Manchester sand increased slightly with decreasing time of loading; that is, the average value for static tests is about 300 kg per sq cm and for fast transient tests about 400 kg per sq cm.

Furthermore, for all tests on clays the transient compressive strength was greater than the static compressive strength. The fast transient compressive strength, taken at a time of loading of 0.02 seconds, ranges between 1.4 and 2.6 times greater than the 10-minute static compressive strength. The above holds true regardless of whether the clay is undisturbed or remolded.

Tests on the Manchester sand indicate that the transient compressive strength of sand in a fast transient compression test was only about 15 percent greater than the static compressive strength.

Investigations by Seed and Lundgren (15), on the effect of transient loading on the strength of saturated sands supports the above. It was found that the strength of dense specimens in rapid transient tests was 15 to 20 percent greater than the strengths of similar specimens in static or slow transient tests.

Whitman (23), also, found that the strength of both undisturbed and disturbed soil specimens was significantly increased by transient loading. This work was done over a wide range of cohesive soils and three sands—the latter ranging from uniform Ottawa sand to well-graded sands.

On the basis of the data collected Whitman concluded that the effect of rate of strain on cohesive soils should be evaluated from triaxial tests with confining pressures adequate to prevent splitting or shear plane development prior to the occurence of the peak load. Considering dry sand and moist sand, it was found that increasing the rate of strain did not produce a significant change in the strength of the material. However, the converse was true for saturated sand and Whitman attributed this to differences in pore water pressures in the slow and rapid tests.

DESCRIPTION OF MATERIALS

Two soils were selected for purposes of this study: (a) a red-colored clay derived from limestone, and (b) a brown glacial silty clay, pedologically classified as Crosby, "B" horizon; both soils are native to Indiana. These soils were selected primarily on the basis of their difference in plasticity (Table 1).

TABLE 1

SUMMARY OF ATTERBERG LIMTS

				Classification	
Soil	LL	PL	PI	HRB	Unified
Silty Clay	35.4	19.5	15.9	A-6	CL
Clay	72.0	28.1	48.9	A-7-6	CH

Both soils were aid dried, pulverized, and passed through a No. 40 U.S. standard sieve. It is recognized that a soil containing clay is irreversibly altered by drying, particularly if the drying is allowed to reach the shrinkage limit. Thus, the laboratory behavior of these soils is peculiar to their processed condition and may differ significantly from the in situ behavior.

PROCEDURE

Moisture-Density Relationships

The only relationships studied were those for kneading type compaction with three compactive efforts being used. There is no recognized standard procedure for the equipment used, for the Harvard Miniature Compaction apparatus; however, the compaction procedure recommended (22) was followed.

It was hoped to obtain densities which approximated the Standard AASHO and Modified AASHO compaction tests as well as a density intermediate between the two. The moisture vs density curves are shown in Figures 2 and 3. Also as a comparison between the dynamic and the kneading compaction characteristics of these soils Table 2 is presented. The data presented in Table 2 on kneading compaction represents the average values obtained from the three moisture density curves in Figures 2 and 3.

The Harvard Compaction Apparatus produces specimens 2.816 in. long and $1\frac{5}{16}$ in. in diameter. The volume of the compaction cylinder is $\frac{1}{454}$th of a cu ft which means that the weight of a compacted specimen in grams is numerically equal to its unit weight

TABLE 2

COMPARISON OF KNEADING AND DYNAMIC COMPACTION (16)

Soil	Compactive Effort	Max (pcf)	O.M.C. (%)
Silty-Clay	Standard AASHO	107.5	19.2
	Kneading Compactor (3 layers at 25 blows)	109.5	16.3
	Modified AASHO	119.3	13.7
	Kneading Compactor (10 layers at 50 blows)	117.0	13.8
Clay	Standard AASHO	91.7	27.8
	Kneading Compactor (3 layers at 25 blows)	94.8	26.0
	Modified AASHO	106.7	19.5
	Kneading Compactor (10 layers at 50 blows)	102.5	22.7

in pounds per cubic foot (pcf). The samples so obtained were used to establish the moisture density curves as well as for strength tests.

The compactive efforts used were 10 layers at 50 blows per layer, which approximates the Modified AASHO, and three layers at 25 blows per layer which gives dry densities comparable to the Standard AASHO test. The third compactive effort varied depending on the soil being tested. The latter was necessary in order to obtain significant differences in the dry densities obtained from the three compactive efforts. For the Crosby "B" soil the intermediate compactive effort was ten layers at 25 blows per layer while that for the Frederick Limestone soil was ten layers at ten blows per layer.

Unconfined Compression Tests

The unconfined compressive strength tests were run on either a hydraulic loading apparatus or the impact loading apparatus depending upon the rate of strain desired. The dynamic loading apparatus consists of a 10-lb weight dropped 39 in. upon a piston which applied the load to the specimen. In order to prevent damage to the loading frame and measuring instruments, and to slow down the rate of loading, a spring was inserted atop the loading piston. Another advantage was that the elasticity of the spring caused the weight to bounce, whereupon it was caught before it could again come in contact with the piston.

Collection of Data and Instrumentation

Low voltage differential transformers were employed to measure the load as well as the deformation during the compression process. In this type gage the output voltage of the secondary coils which are excited by a primary coil is proportional to the displacement of a magnetic core within these coils.

A schematic diagram of the load and deformation apparatus is shown in Figure 1. It can be seen that as the proving ring deforms, the position of the core moves relative to the coils. Also, as the arm of the strain gage deflects, the core contained therein moves relative to its primary and secondary coils. These movements produce changes in the output voltage, of these two instruments, which can be measured. A Model 655 Audio Oscillator operating on a frequency of 2, 000 cps was used to energize the transformers.

To record the changes in stress and strain during the progress of the test a Dumont Cathode-Ray Oscilloscope was used. In this study, the deflection of the oscilloscope trace was made proportional to the output of the differential transformers.

RESULTS

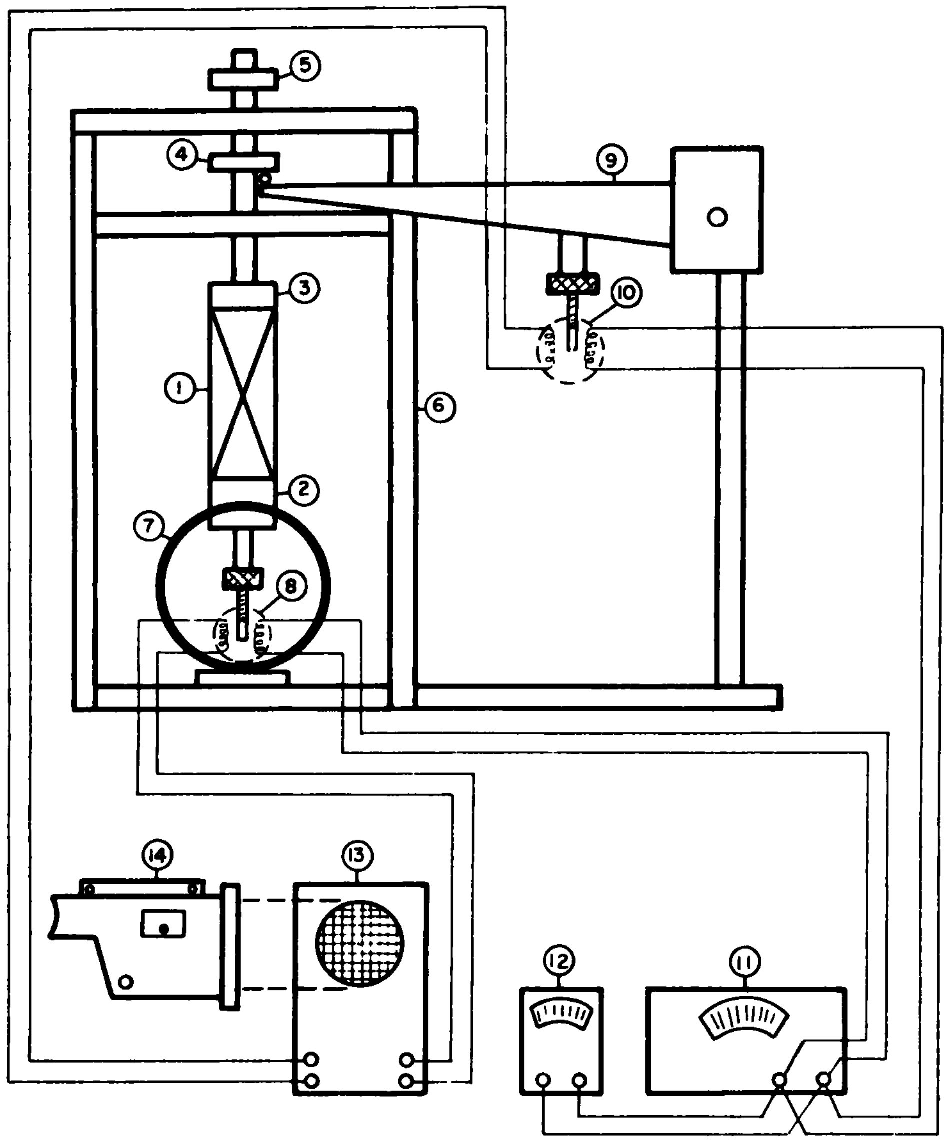
Strength

In both the clay and the silty clay, the strength vs moisture content curves all exhibited a "peaked" shape, as indicated in Figures 2 and 3. Theoretically the strength should continue to rise as the moisture content decreased. However, there was a tendency for a reduction in this "peaked" condition as the rate of strain increased.

There are two possible reasons for the aforementioned: (a) the condition is the result of the inherent characteristics of the test; that is, at low moisture contents the specimens fail by crumbling rather than shear, due to a lack of lateral confinement, or (b) the condition is a result of the molding process; that is, kneading type compaction imparts this characteristic to the soil.

At the lower moisture contents tested, 9-10 percent for the silty clay and 14-15 percent for the clay, the specimens were brittle and would crumble around the edges if not handled carefully. There is great possibility that this tendency existed at higher moisture contents but was just more difficult to detect.

In all cases the maximum strength, as indicated from these tests, occurred at a moisture content less than optimum (Figs. 2 and 3). Exactly how much seemed to depend upon the rate of strain and the compactive effort; that is, as the compactive effort decreased there was a tendency for the difference between O. M. C. and the moisture content at which maximum strength occurred to increase. The maximum difference



1 SOIL SPECIMEN
2 LOADING HEAD FOR PROVING RING
3 LOADING HEAD FOR SPECIMEN
4 STRAIN DATUM
5 STRAIN - STOP
6 FRAME
7 LOAD GAGE
8 DIFFERENTIAL TRANSFORMER
9 STRAIN GAGE
10 DIFFERENTIAL TRANSFORMER
11 AUDIO OSCILLATOR
12 VOLTMETER
13 OSCILLOSCOPE
14 OSCILLOSCOPE RECORD CAMERA

Figure 1. Schematic diagram of test set-up.

between the latter two was approximately 4 percent in the silty clay and 5 percent in the clay.

Once the moisture content at which the optimum strength was obtained was passed, the change in strength for a given change in moisture content increased significantly (Figs. 2 and 3). It appears that the greater the rate of strain the steeper this portion of the curve becomes.

The foregoing is true for both the silty clay and clay. However, in the clay, the rate of increase of strength for a given increase in moisture content on the dry side of optimum strength was equal and in some instances greater than the rate of decrease which occurred on the wet side. Whether or not this is significant depends on the validity of the tests conducted on the dry side; that is, whether or not the specimens were failing principally by crumbling or by shear.

Silty Clay

It was found that, for a given compactive effort and moisture content, increasing the rate of strain produced a measurable increase in the strength of the soils (Figs. 4 and 6). In the case of the silty clay, for the lowest compactive effort, an increase of over 100 percent in the unconfined compressive strength was obtained by increasing the

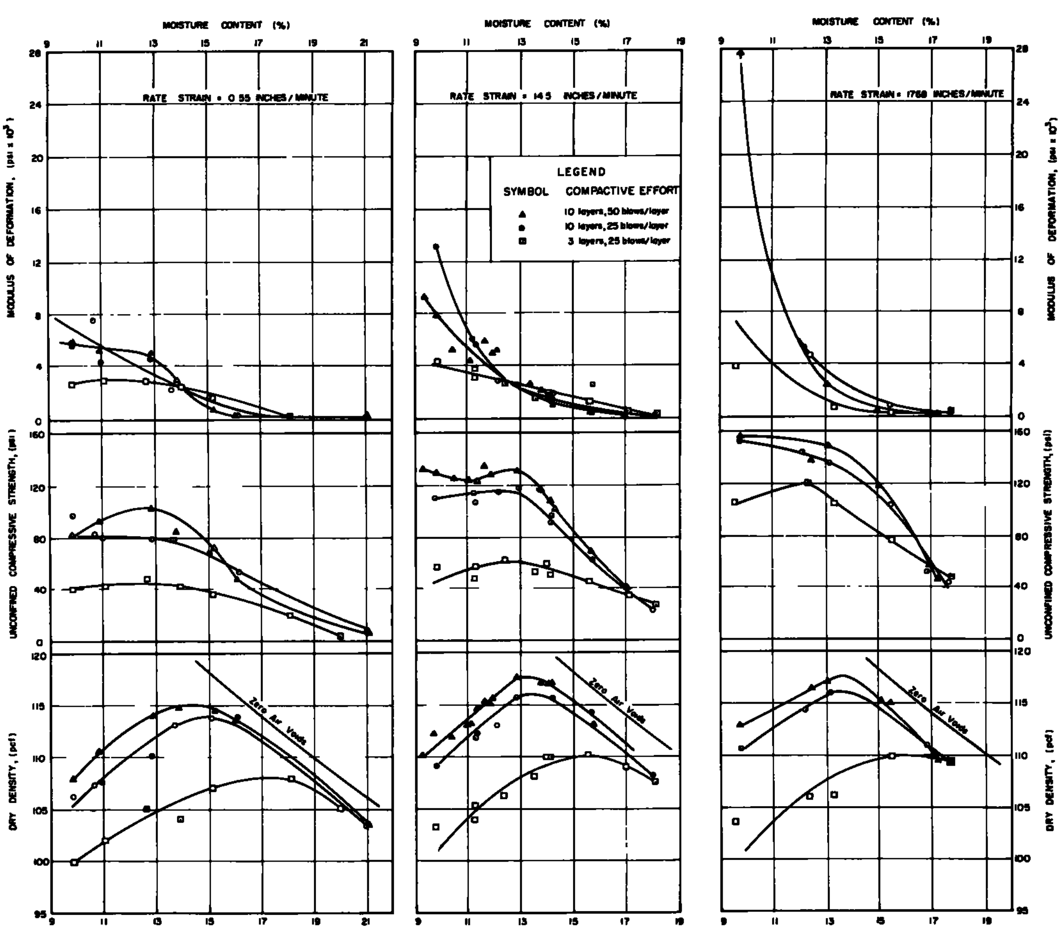


Figure 2. Moisture content vs dry density, unconfined compressive strength, and modulus of deformation—silty clay.

rate of strain from 0.55 in./min to 1,768 in./min, regardless of the moisture content of the sample (Table 3). For the highest compactive effort the increase in strength for the same change in rate of strain ranged between 52 and 87 percent while for the intermediate compactive effort the range was from 20 to 89 percent.

As regards the change in strength of the medium transient test with respect to the slow transient test, for a given density and compactive effort, the increase in strength was much less (Table 3). Considering the lowest compactive effort the increase in strength ranged from 12 to 32 percent, for the intermediate compactive effort the change ranged from -17 to 40 percent, and for the highest compactive effort the change in strength was from +10 to +51 percent.

There appears, on the basis of the data collected, to be a general trend toward a decrease in the effect of rate of strain as the moisture content increases, for a given

TABLE 3

SUMMARY OF RESULTS OF STRENGTH TESTS—SILTY CLAY

Rate Strain	Compactive Effort: 3 Layers/25 Blows		10 Layers/25 Blows		10 Layers/50 Blows	
	Moisture Content = 10%					
	Strength (psi)	S_u Ratio	Strength (psi)	S_u Ratio	Strength (psi)	S_u Ratio
0.55 in./min.	43	1.00	81	1.00	85	1.00
14.5 in./min.	48	1.12	110	1.36	128	1.51
1768 in./min.	109	2.54	153	1.89	159	1.87
	Moisture Content = 12%					
	Strength (psi)	S_u Ratio	Strength (psi)	S_u Ratio	Strength (psi)	S_u Ratio
0.55 in./min.	46	1.00	83	1.00	103	1.00
14.5 in./min.	61	1.33	116	1.40	130	1.26
1768 in./min.	119	2.59	146	1.76	156	1.52
	Moisture Content = 14%					
	Strength (psi)	S_u Ratio	Strength (psi)	S_u Ratio	Strength (psi)	S_u Ratio
0.55 in./min.	43	1.00	77	1.00	91	1.00
14.5 in./min.	57	1.32	96	1.25	110	1.21
1768 in./min.	95	2.21	127	1.65	140	1.54
	Moisture Content = 16%					
	Strength (psi)	S_u Ratio	Strength (psi)	S_u Ratio	Strength (psi)	S_u Ratio
0.55 in./min.	34	1.00	57	1.00	51	1.00
14.5 in./min.	43	1.26	56	0.98	62	1.22
1768 in./min.	71	2.09	88	1.54	93	1.82
	Moisture Content = 17%					
	Strength (psi)	S_u Ratio	Strength (psi)	S_u Ratio	Strength (psi)	S_u Ratio
0.55 in./min.	28	1.00	46	1.00	38	1.00
14.5 in./min.	35	1.25	38	0.83	42	1.10
1768 in./min.	57	2.04	55	1.20	58	1.53

compactive effort (Fig. 4 and Table 3). This, in all probability, is due to the greater effect of pore water pressures which would tend to decrease the strength of the sample. This could also be the reason why the strength ratio values tend to decrease as the compactive effort increases.

From the foregoing discussion, it can be seen that the effect of rate of strain is more significant in increasing the strength of material at low densities. In comparing the fast and slow transient tests, over 100 percent increase in strength was obtained for the lowest compactive effort. Considering the same range for the other two compactive efforts the maximum increase was 89 percent, and for the majority of cases it was much less.

Furthermore, as the compactive effort increased the effect of an increase in moisture, on the strength, increased for a given compactive effort (Fig. 4). As aforemen-

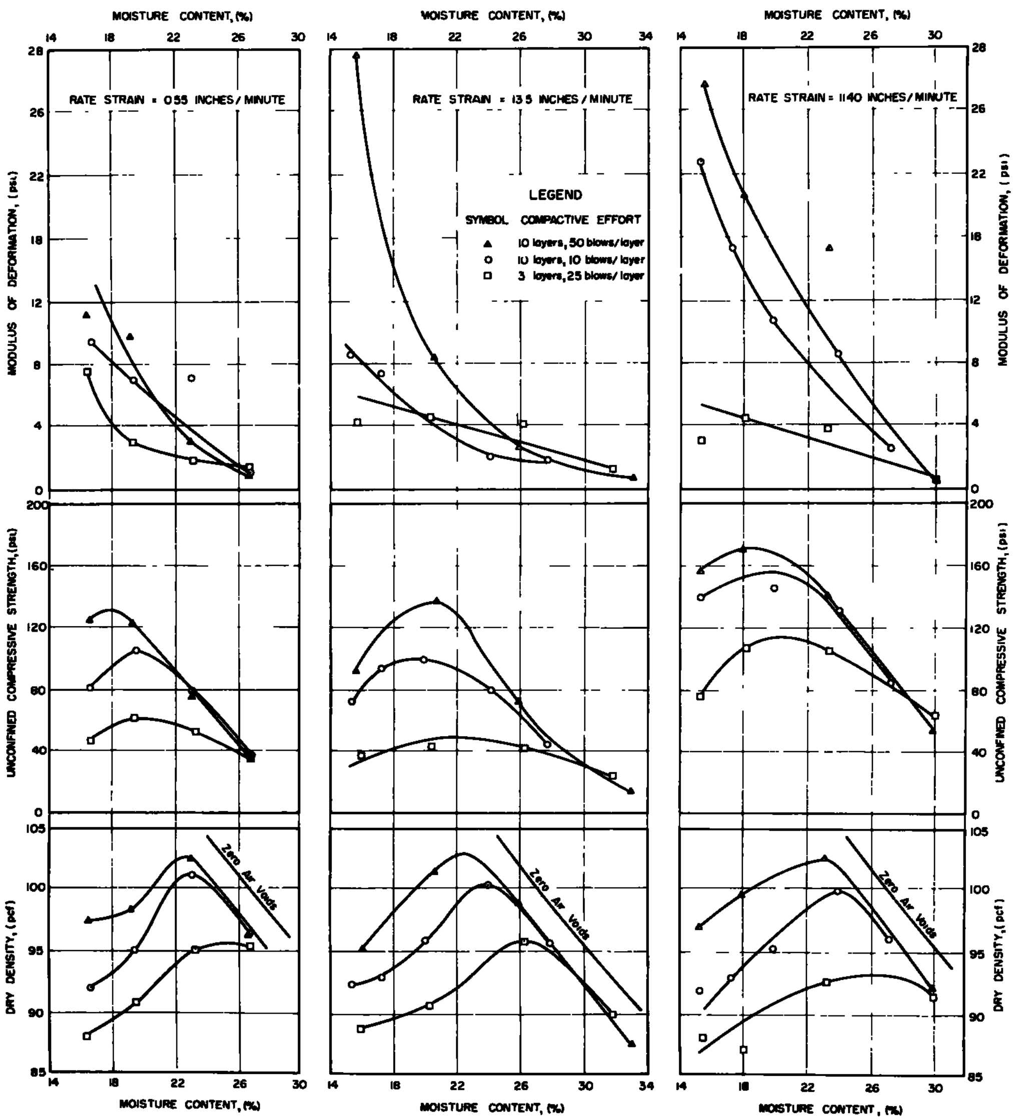


Figure 3. Moisture content vs dry density, unconfined compressive strength, and modulus of deformation—clay.

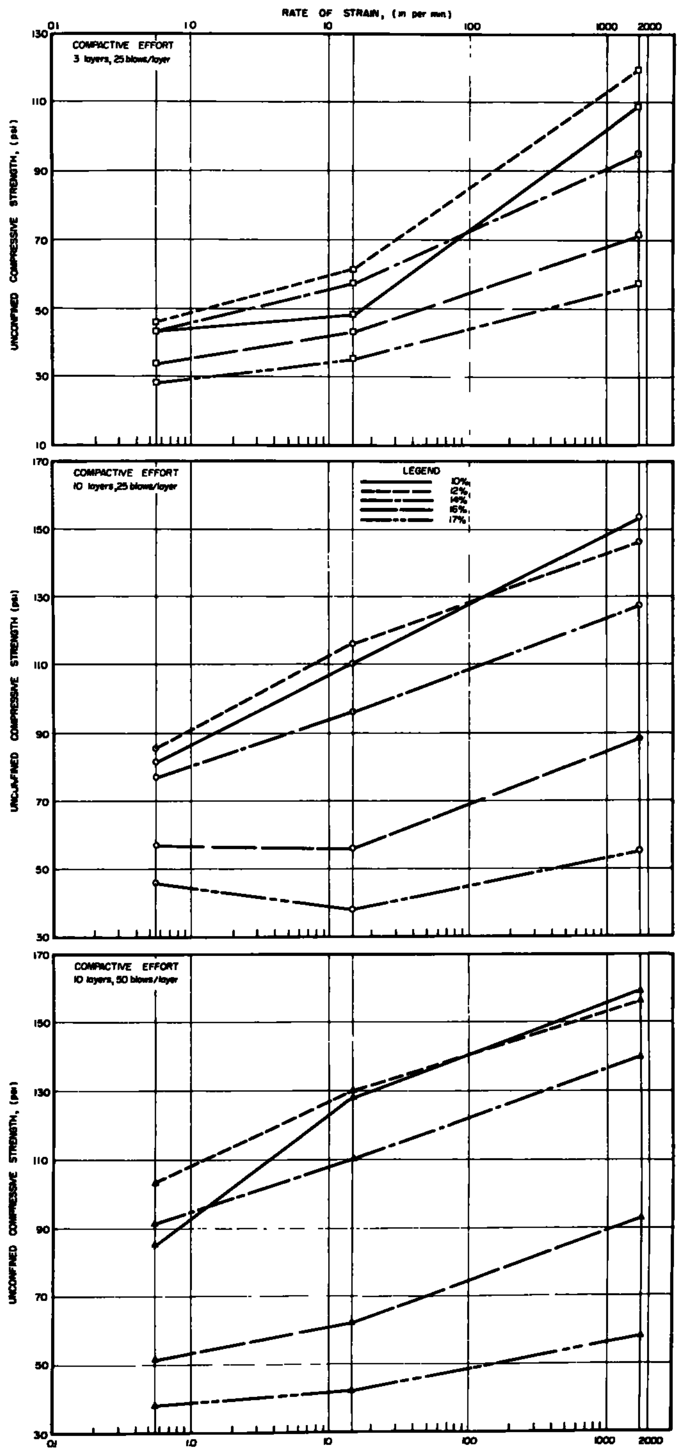


Figure 4. Rate of strain vs unconfined compressive strength—silty clay.

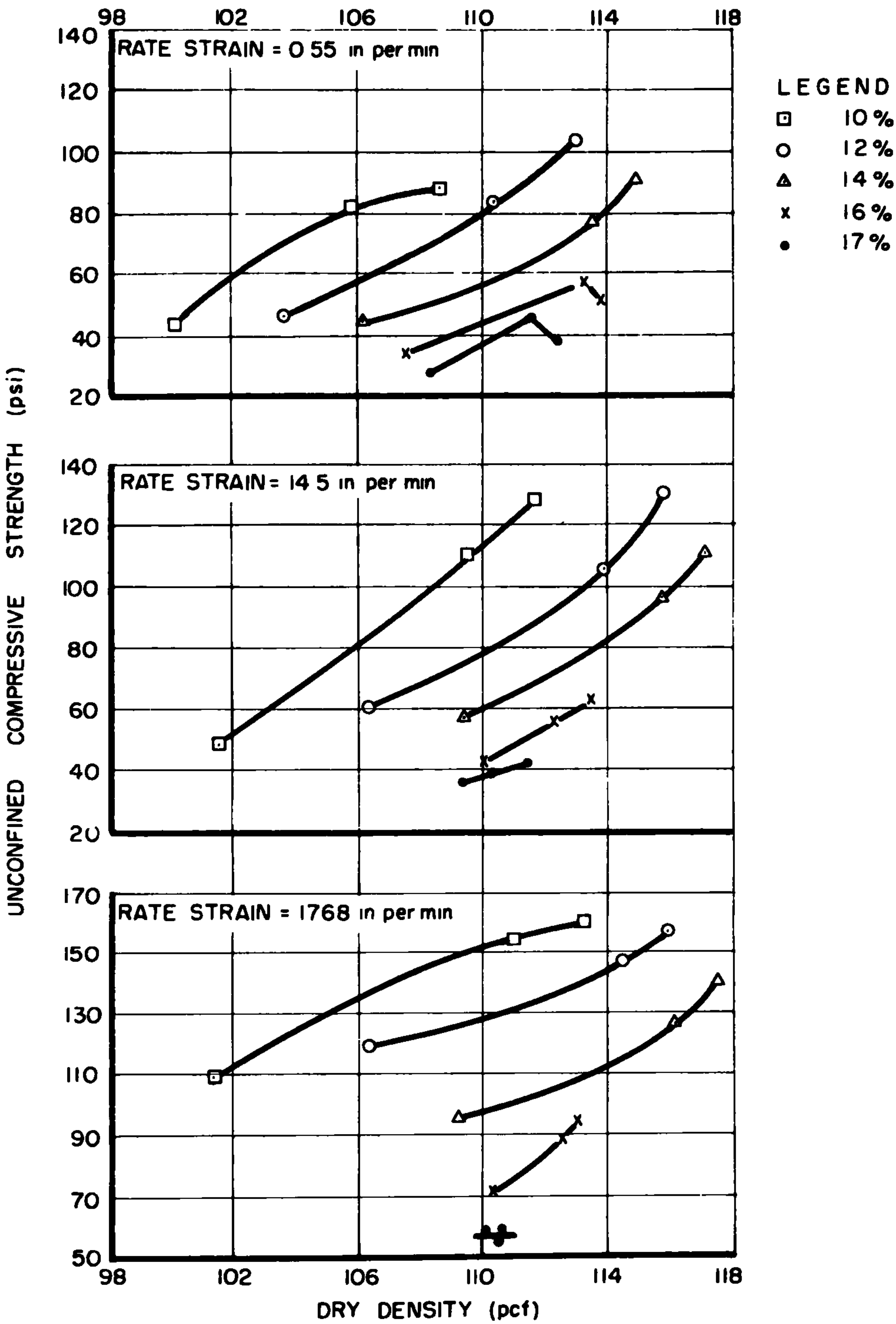


Figure 5. Dry density vs unconfined compressive strength—silty clay.

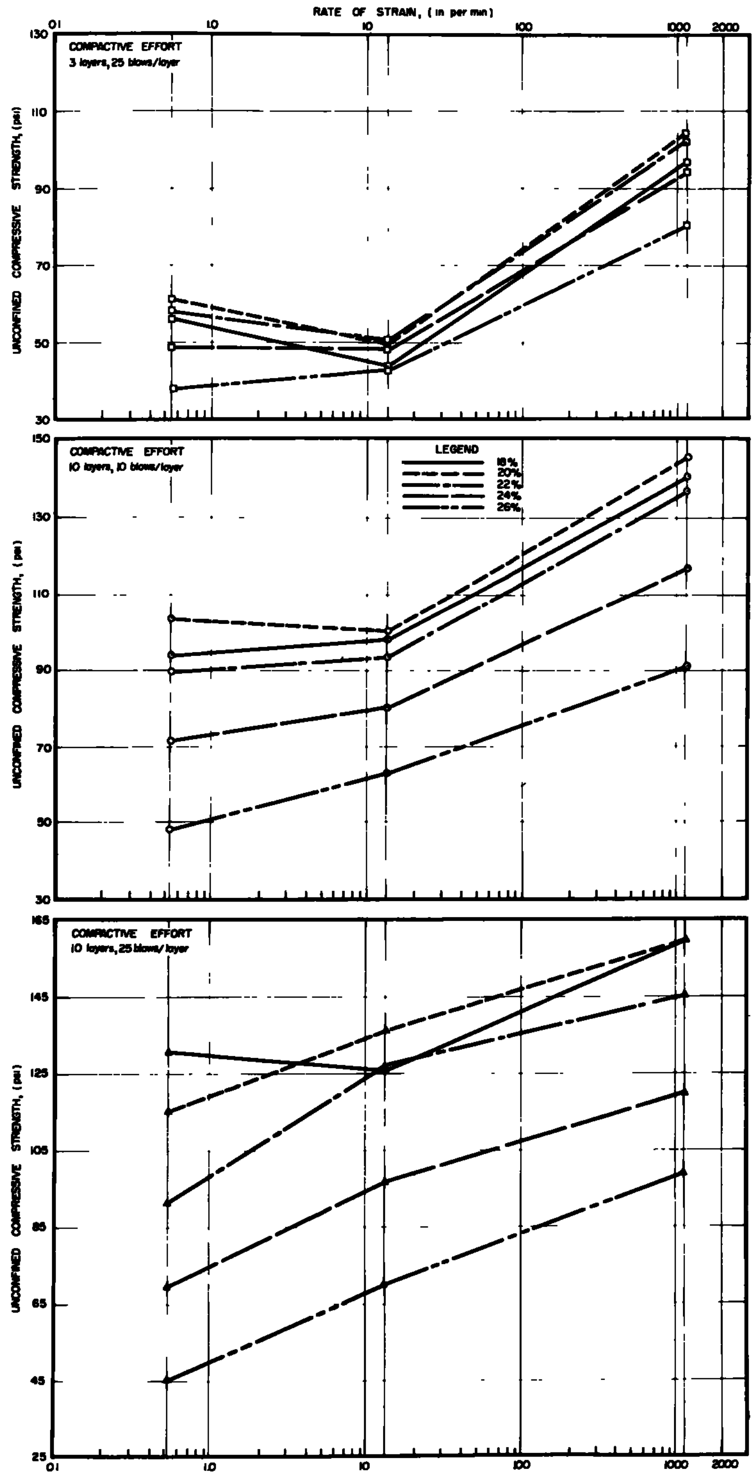


Figure 6. Rate of strain vs unconfined compressive strength—clay.

tioned, this is due to an increase in pore pressure brought about by a reduction in void ratio due to increased compaction.

From Figure 5, which is a plot of unconfined compressive strength vs dry density, at constant moisture content, it can be qualitatively stated that the effect of increased density decreases as rate of strain increases. For example, it can be noted that the slopes of the curves for rate of strain equal to 1,768 in. per min are less than those for either 0.55 or 14.5 in. per min. Also, moisture content did not effect the slopes appreciably.

Clay

For the clay, it was also found that for a given compactive effort and moisture content, increasing the rate of strain produced a measurable increase in the strength of

TABLE 4

SUMMARY OF RESULTS OF STRENGTH TESTS—CLAY

Rate Strain	Compactive Effort: 3 Layers/25 Blows		10 Layers/25 Blows		10 Layers/50 Blows	
	Moisture Content = 18%					
	Strength (psi)	S_u Ratio	Strength (psi)	S_u Ratio	Strength (psi)	S_u Ratio
0.55 in./min.	56	1.00	94	1.00	131	1.00
13.5 in./min.	44	0.79	98	1.04	126	0.96
1140 in./min.	97	1.73	142	1.51	160	1.22
	Moisture Content = 20%					
	Strength (psi)	S_u Ratio	Strength (psi)	S_u Ratio	Strength (psi)	S_u Ratio
0.55 in./min.	61	1.00	103	1.00	115	1.00
13.5 in./min.	49	0.80	100	0.97	136	1.18
1140 in./min.	104	1.71	146	1.42	160	1.39
	Moisture Content = 22%					
	Strength (psi)	S_u Ratio	Strength (psi)	S_u Ratio	Strength (psi)	S_u Ratio
0.55 in./min.	58	1.00	89	1.00	93	1.00
13.5 in./min.	50	0.86	93	1.04	128	1.36
1140 in./min.	102	1.76	137	1.54	146	1.57
	Moisture Content = 24%					
	Strength (psi)	S_u Ratio	Strength (psi)	S_u Ratio	Strength (psi)	S_u Ratio
0.55 in./min.	49	1.00	71	1.00	69	1.00
13.5 in./min.	48	0.98	80	1.13	98	1.42
1140 in./min.	92	1.88	117	1.65	120	1.74
	Moisture Content = 26%					
	Strength (psi)	S_u Ratio	Strength (psi)	S_u Ratio	Strength (psi)	S_u Ratio
0.55 in./min.	38	1.00	48	1.00	45	1.00
13.5 in./min.	43	1.13	63	1.31	70	1.56
1140 in./min.	80	2.11	91	1.90	95	2.11

the soil (Fig. 6). As with the silty clay, the strength ratio, for all moisture contents, was greatest for the lowest compactive effort (Table 4). Also, from Figure 6 it can be seen that moisture content has less effect on the strength, at a given rate of strain, the lower the compactive effort; that is, as the compactive effort is increased the effect of moisture content increases.

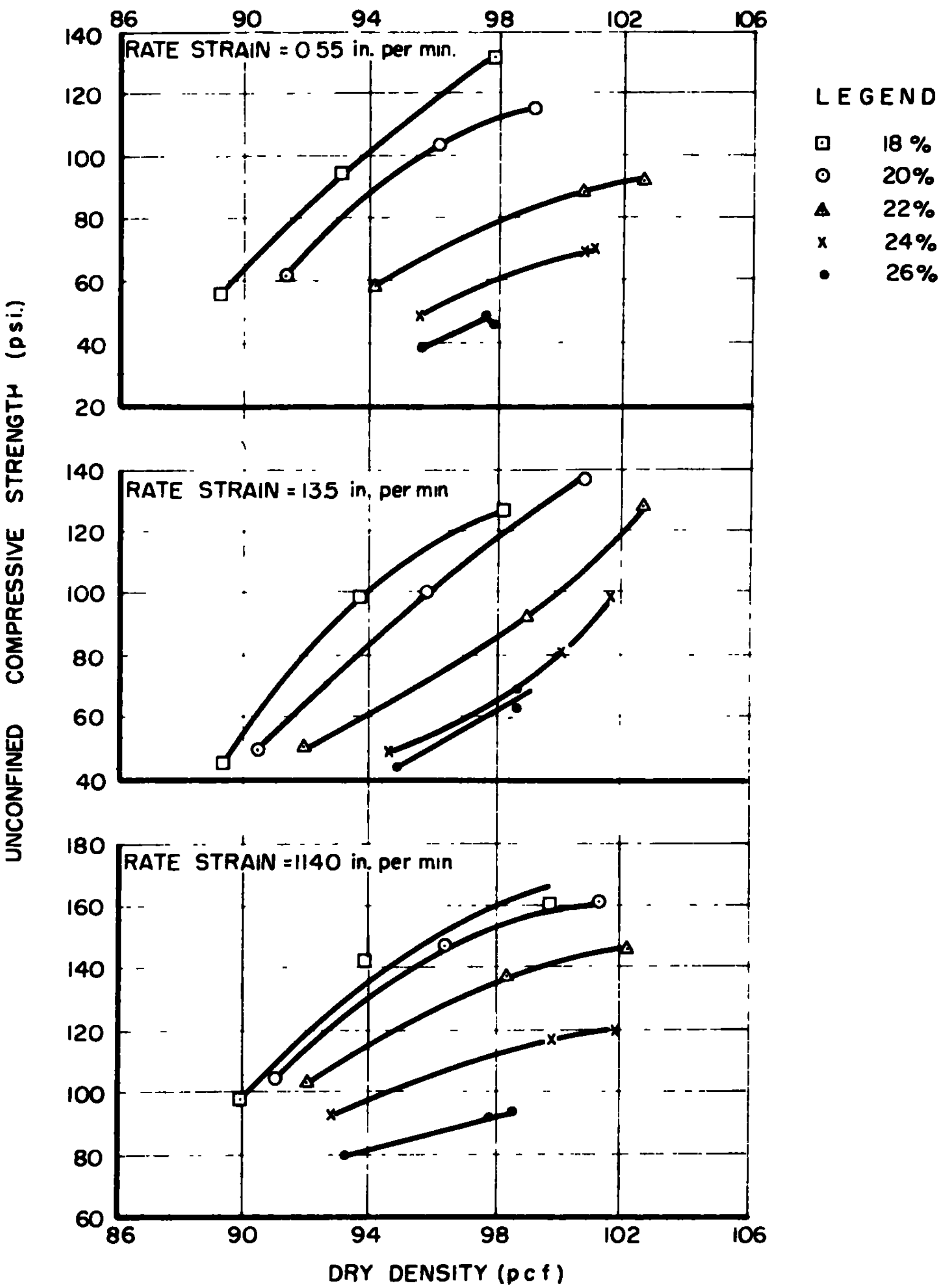


Figure 7. Dry density vs unconfined compressive strength—clay.

Table 4 shows that as the moisture content increases the effect of rate of strain on increasing the strength increases for a given compactive effort. However, it should be noted that this relationship is generally valid for only the dry side of optimum since the data on the wet side are incomplete.

Table 4 also shows that some clay soils may decrease in strength with an increase in rate of strain. This tendency existed at all except one moisture content, the highest, at the lowest compactive effort. In the two higher compactive efforts the condition existed at only one moisture content, in each. Since the latter values are so close to unity, it could be assumed that there was not a decrease and the stress ratio is unity.

However, due to the fact that the stress ratios for the medium transient tests are consistently less than 1.0 this might be a significant trend, for the lowest compactive effort. It can also be noted that a value of the stress ratio greater than 1.0 occurs at nearly the optimum moisture content. This indicates that on the wet side, stress ratios greater than 1.0 would be obtained. Also, it must be recognized that since the stress ratio for the medium transient tests are generally very close to unity, at low moisture contents and low compactive efforts, and since an average curve is drawn through the data obtained this would account for the stress ratio being less than 1.0.

A study of Figure 6 reveals that the higher the compactive effort the greater the effect of a change in moisture content on the strength of the clay soil. For example, as the compactive effort is increased the curves in Figure 6 become farther apart.

It should be noted that the 18 percent moisture content curve in Figure 6 is out of line with the remainder of the data. This is probably because of specimens tested at this moisture content failed, partially at least, by crumbling.

Figure 7 illustrates, qualitatively, that the effect of an increase in density, decreases as the rate of strain increases. This can be noted from the fact that the slopes of the curves for rate of strain equal to 1,140 in. per min are less than those for either 0.55 or 13.5 in. per min.

It is worthy of note that the strength ratio for the clay increases with increasing moisture content while that for the silty clay decreases with increasing moisture content. Also, for a given rate of strain the effect of moisture content on the strength is greater for the silty clay than the clay. However, the latter trend decreases as the compactive effort decreases.

Modulus of Deformation

The data on the modulus of deformation, for both soils tested, was the most difficult to interpret. This was due to the large scattering of the values (Figs. 2 and 3). The latter situation being caused by the difficulty in picking values from the oscilloscope trace. It was quite easy to determine the maximum load, on the specimen, and the strain at which it occurred. However, at low loads it was, in many instances, impossible to accurately determine the load on the specimen and the strain at which it occurred. As a result, in practically all cases, the initial portions of all stress strain curves appeared to be out of line.

Consequently, the modulus of deformation vs moisture content curves, for a given compactive effort and rate of strain can only be used to obtain general trends as indicated by the results shown (Figs. 2 and 3). Since the modulus of deformation vs rate of strain curves (Figs. 8 and 9), for a given moisture content and compactive effort, were obtained from the curves previously indicated they, also, are only of qualitative value.

Silty Clay

Regardless of the scattering of the points in Figure 2 it can be readily seen that moisture content has a tremendous effect on the modulus of deformation of the silty clay. It is also apparent that as the rate of strain increases the effect of moisture on the modulus of deformation also increases.

This rate of change of modulus of deformation with respect to a change in moisture content decreases as the moisture content increases until a point is reached where the compactive effort has a negligible effect on the modulus of deformation. This condition

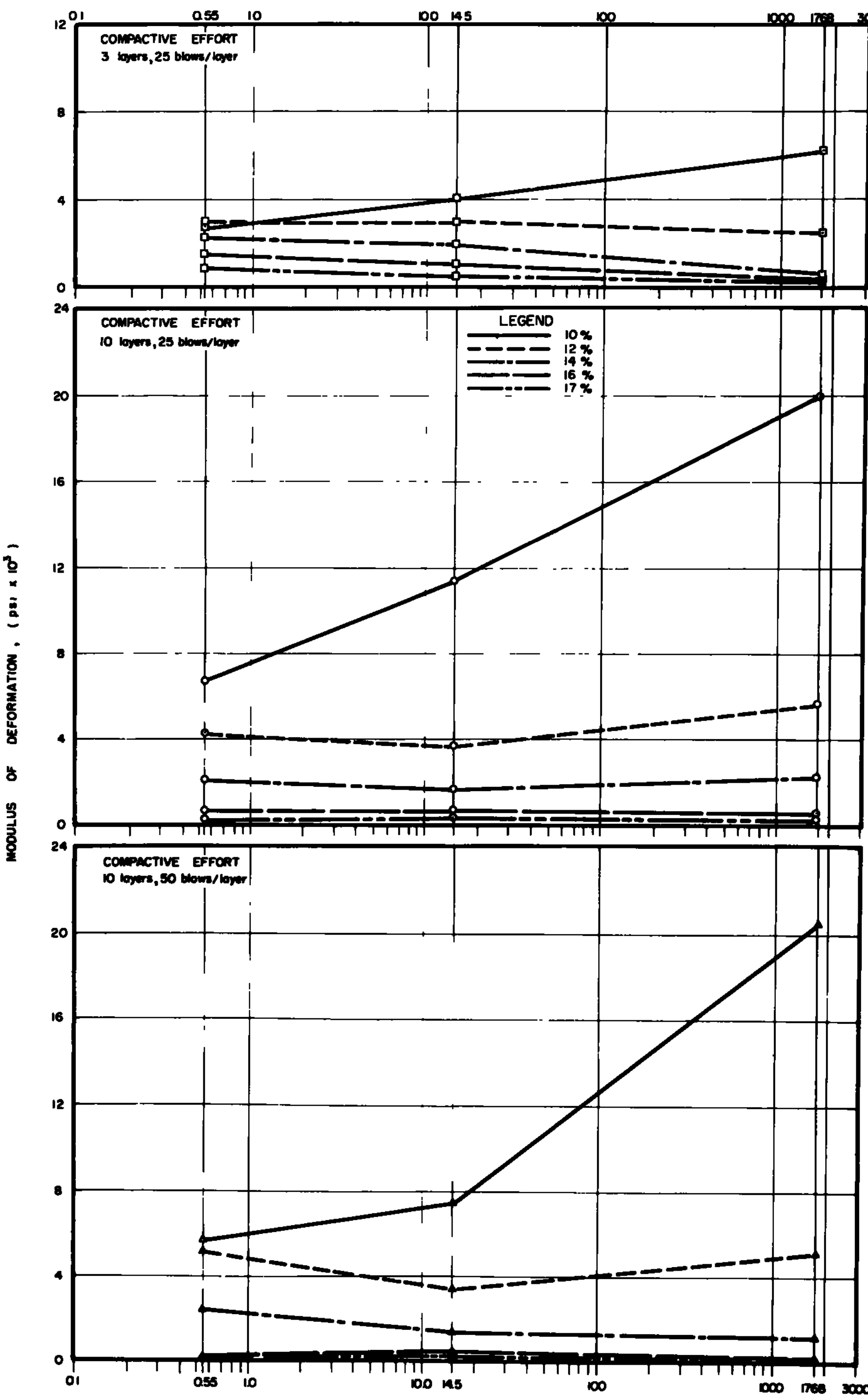


Figure 8. Rate of strain vs modulus of deformation—silty clay.

occurs on the dry side of optimum for the slow and medium transient tests, for all compactive efforts, and approximately at optimum for the fast transient tests.

In fact, if a soil is to be compacted at a moisture content which approximates the O.M.C. for standard compaction, considering the fast transient test conditions, it appears that use of a compactive effort greater than Standard Proctor is not warranted. Considering the fact that a subgrade usually gains approximately 2 percent moisture before coming to equilibrium with its natural surroundings, this would make compaction at an effort greater than standard AASHO impractical, unless methods of preventing an increase in moisture content were provided. The latter statement is assuming that the modulus of deformation is to be used as the criterion of strength.

Considering the moisture content range tested it appears a significant increase in modulus of deformation due to an increase in rate of strain was obtained only for the specimens compacted at about 10 percent moisture (Fig. 8). This is true regardless of the compactive effort. Also, on the basis of Figure 8 it can be easily seen that moisture content has a much more significant effect on the modulus of deformation than does rate of strain.

TABLE 5

SUMMARY OF MODULUS OF DEFORMATION DATA—SILTY CLAY

Rate Strain	Compactive Effort: 3 Layers/25 Blows		10 Layers/25 Blows		10 Layers/50 Blows	
	Moisture Content = 10%					
	M_D (psi)	M_D Ratio	M_D (psi)	M_D Ratio	M_D (psi)	M_D Ratio
0.55 in./min.	2,700	1.00	6,700	1.00	5,700	1.00
14.5 in./min.	3,900	1.46	11,300	1.69	7,400	1.30
1768 in./min.	6,200	2.30	20,000	3.22	20,600	3.61
	Moisture Content = 12%					
	M_D (psi)	M_D Ratio	M_D (psi)	M_D Ratio	M_D (psi)	M_D Ratio
0.55 in./min.	2,900	1.00	4,200	1.00	5,200	1.00
14.5 in./min.	2,950	1.02	3,600	0.86	3,400	0.65
1768 in./min.	2,400	0.83	5,600	1.33	5,200	1.00
	Moisture Content = 14%					
	M_D (psi)	M_D Ratio	M_D (psi)	M_D Ratio	M_D (psi)	M_D Ratio
0.55 in./min.	2,200	1.00	2,050	1.00	2,500	1.00
14.5 in./min.	1,950	0.88	1,600	0.78	1,400	0.56
1768 in./min.	550	0.25	2,250	1.10	1,250	0.50
	Moisture Content = 16%					
	M_D (psi)	M_D Ratio	M_D (psi)	M_D Ratio	M_D (psi)	M_D Ratio
0.55 in./min.	1,040	1.00	600	1.00	150	1.00
14.5 in./min.	1,000	0.96	600	1.00	500	3.33
1768 in./min.	250	0.24	550	0.92	150	1.00
	Moisture Content = 17%					
	M_D (psi)	M_D Ratio	M_D (psi)	M_D Ratio	M_D (psi)	M_D Ratio
0.55 in./min.	800	1.00	200	1.00	75	1.00
14.5 in./min.	450	0.56	350	1.75	200	2.67
1768 in./min.	200	0.25	200	1.00	50	0.67

As regards moisture contents of 12 percent or above it appears that an increase in the rate of strain will not produce an increase in the modulus of deformation. From Figure 8 and Table 5 it can be seen that for certain moisture contents there appears to

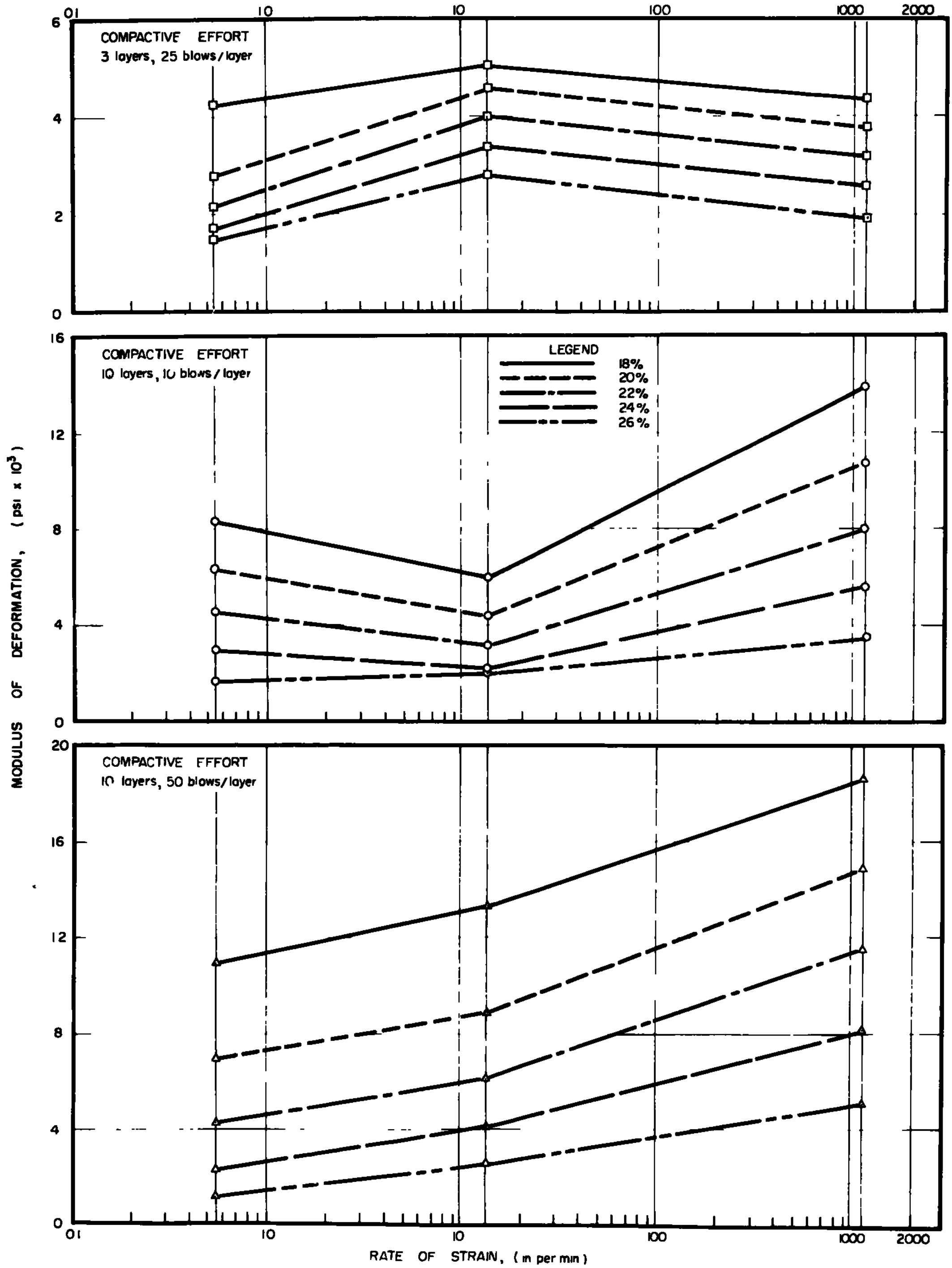


Figure 9. Rate of strain vs modulus of deformation—clay.

be a decrease in the modulus of deformation with an increase in the rate of strain. This can probably be attributed to the scattering of data. Also, the scattering of data might be the reason there was a significant increase in modulus of deformation with rate of strain for the 10 percent moisture content specimens.

Table 5 indicates an important trend. For a given compactive effort and rate of strain the M_D ratio decreases with increasing moisture content. There was, however, too much variability of data to make quantitative comparisons between various compactive efforts.

Clay

In the clay soil there was also a substantial decrease in the modulus of deformation for a given increase in moisture content at a given rate of strain (Fig. 9). This condition was more pronounced the higher the compactive effort and the greater the rate of strain. On the basis of the data given, at moisture contents approximating the optimum

TABLE 6

SUMMARY OF MODULUS OF DEFORMATION DATA — CLAY

Rate Strain	Compactive Effort: 3 Layers/25 Blows		10 Layers/25 Blows		10 Layers/50 Blows	
	Moisture Content = 18%					
	M_D (psi)	M_D Ratio	M_D (psi)	M_D Ratio	M_D (psi)	M_D Ratio
0.55 in./min.	4,300	1.00	8,300	1.00	10,900	1.00
13.5 in./min.	5,100	1.19	6,000	0.72	13,400	1.23
1140 in./min.	4,400	1.02	13,900	1.68	18,700	1.71
	Moisture Content = 20%					
	M_D (psi)	M_D Ratio	M_D (psi)	M_D Ratio	M_D (psi)	M_D Ratio
0.55 in./min.	2,800	1.00	6,300	1.00	7,000	1.00
13.5 in./min.	4,600	1.64	4,400	0.70	8,900	1.27
1140 in./min.	3,800	1.36	10,700	1.70	15,000	2.14
	Moisture Content = 22%					
	M_D (psi)	M_D Ratio	M_D (psi)	M_D Ratio	M_D (psi)	M_D Ratio
0.55 in./min.	2,200	1.00	4,500	1.00	4,200	1.00
13.5 in./min.	4,000	1.80	3,100	0.69	6,200	1.48
1140 in./min.	3,200	1.45	8,000	1.78	11,600	2.76
	Moisture Content = 24%					
	M_D (psi)	M_D Ratio	M_D (psi)	M_D Ratio	M_D (psi)	M_D Ratio
0.55 in./min.	1,700	1.00	3,000	1.00	2,300	1.00
13.5 in./min.	3,400	2.00	2,200	0.73	4,100	1.78
1140 in./min.	2,600	1.53	5,600	1.87	8,300	3.61
	Moisture Content = 26%					
	M_D (psi)	M_D Ratio	M_D (psi)	M_D Ratio	M_D (psi)	M_D Ratio
0.55 in./min.	1,500	1.00	1,600	1.00	1,200	1.00
13.5 in./min.	2,800	1.87	2,000	1.25	2,600	2.17
1140 in./min.	1,900	1.27	3,600	2.25	5,300	4.41

moisture content for Standard AASHO the effect on the modulus of deformation of an increase in compactive effort is negligible. However, as the rate of strain increases the effect of the amount of compactive effort becomes apparent.

From Figure 9 and Table 6 the effect of rate of strain and moisture content on the modulus of deformation can be observed. For all compactive efforts and rates of strain there was a tendency toward an increase in modulus of deformation with an increase in rate of strain. In a few instances, particularly the medium transient tests at the intermediate compactive effort, there was a slight decrease in the modulus of deformation with an increase in rate of strain. This can be attributed to the scattering of the data, and the attempt to draw a representative curve through it. The aforementioned reason was also the cause of the M_D ratios being less than one, in all probability (Table 6).

Consequently, it can be stated that for a given rate of strain the M_D ratio increases with increasing moisture content. Also, the M_D ratio, for a given moisture content and the fast transient test conditions, increased as the compactive effort increased. This tendency was not apparent in the M_D ratio for the medium transient tests.

In the case of the intermediate effort, considering the medium transient tests, the value of the M_D ratio obtained was much less than either of the other two compactive efforts. Also, the caliber of the data did not produce results from which a general trend could be predicted for the medium transient tests; that is, no definable tendency of the variance of the M_D ratio of the medium transient tests at a given moisture content but varying compactive effort.

As can be seen from Figure 9 moisture content has an increasingly important effect on the modulus of deformation the higher the compactive effort. Also, it is shown that significant increases in the modulus of deformation may be obtained by increasing the rate of strain. It should be noted that the higher the compactive effort the greater the effect of rate of strain on M_D.

For the lowest compactive effort, a decrease in M_D for an increase in rate of strain was noted (Fig. 9). This is probably due to the scattering of data and the use of average curves.

Comparison of Clay and Silty Clay

In both the clay and silty clay, a significant increase in unconfined compressive strength occurred with an increase in rate of strain for all compactive efforts and all moisture contents tested. However, with the silty clay, as the moisture content increased, the strength ratio decreased while for the clay the converse was true.

In both the clay and the silty clay the strength ratios for the fast transient test were greater for the lowest compactive effort. No definite relationship could be established for the medium transient tests between the strength ratios and the compactive effort.

In both the clay and the silty clay the moisture content proved to be more significant than the increase in rate of strain, as regards affecting the unconfined compressive strength. This tendency became less as the compactive effort decreased.

Moisture content has a great effect on the modulus of deformation of the silty clay as well as the clay. This condition was more pronounced the higher the compactive effort and the higher the rate of strain. Furthermore, for the clay soil, increasing the rate of strain produced a measurable increase in the M_D ratio, but this was not the case for the silty clay.

It is worthy to note that the data presented in this report do not give a straight line relationship, on a semi-logarithmic plot, for the variance of strength or modulus of deformation with respect to rate of strain (Figs. 4, 6, 8 and 9). The aforementioned is not surprising due to large number of variables present. Nevertheless, such a relationship can be obtained for certain soils (23).

From Tables 3 and 4 it can be readily seen why the effect of rate of strain is more significant in increasing the strength of the material at low density. This fact may be ascertained by comparing the difference in strength between the fast and slow transient tests for the same moisture content but varying densities. It can be seen that the increase in strength is relatively constant regardless of the compactive effort. Thus, due to the much lower slow transient strength of the material at low density, it is to be expected to show a greater percentage increase in strength for a given increase in rate of strain.

Also, it is interesting to note that the aforementioned difference is less variable, with moisture content, for the clay than the silty clay. This is because the silty clay is much more susceptible to changes in moisture content.

In contrast to Whitman (23), the data show a general trend toward a decrease in the strain at failure with an increase in the rate of strain. This is attributed to the fact that the faster the rate of strain the faster the load is applied which results in the specimen not having the opportunity of deforming greatly before it devlops its maximum shear strength.

Finally, it is of interest to investigate the possibility of thixotropic action affecting the results, since the specimens were tested approximately 24 hr after molding. Both Moretto (27) and Skempton and Northey (25) observed that thixotropic strength regain decreased with decreasing water content below the liquid limit. Also, Seed and Chan (26) showed that thixotropic effects are relatively small, for samples compacted on the dry side of optimum for the compactive effort being used.

It is realized that the thixotropic effect is not a well known phenomenon. Consequently, the results published by one investigator may be used by another only if the material and the test procedures are quite similar. Nevertheless, it was felt that the aforementioned work could be used as a guide to the design of the experiment. Thus, by testing specimens at moisture contents well below the liquid limit and by limiting the time of storage to a maximum of twenty-four hours, it was hoped that the effects of thixotropy would be relatively constant for all tests.

CONCLUSIONS

On the basis of these tests, and for the soils involved, it can be concluded that:

1. As the compactive effort is increased the greater the effect of changes in moisture content on the unconfined compressive strength, regardless of the rate of strain.
2. The lower the compactive effort the greater the effect of rate of strain on the strength. (a) Considering the silty clay, as the moisture content increases the strength ratio tends to decrease; and (b) considering the clay, as the moisture content increases the strength ratio increases.
3. As the rate of strain increases the effect of an increase in dry density, at a given moisture content, on the unconfined compressive strength decreases.
4. Increasing the rate of strain produced a measurable increase in the M_D ratio of the clay soil. (a) For the clay soil, as the moisture content increased the M_D ratio increased for a given compactive effort but the highest compactive effort yielded the greatest increase; and (b) in the silty clay soil there was a tendency toward a decrease in M_D ratio for a given rate of strain and compactive effort.
5. On the basis of these tests it must be concluded that to obtain significant increases in strength or modulus of deformation it takes a rate of strain equivalent to a fast transient test.
6. As the rate of strain decreases there is a tendency for the strain at failure to increase.

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