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FINAL REPORT - PART 1 OF 2
SEISMIC WAVE VELOCITY AS A MEANS OF
IN-PLACE DENSITY MEASUREMENT

Project HR - 114 of the Iowa Highway
Research Board

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Engineering Research Institute, Iowa
State University
for

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Administration Bureau of Public Roads

Co-Project Directors

J.M. Hoover, Associate Professor of Civil Engineering
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Contribution No. 68 - 8a of the Soil
Research Laboratory

*The opinions, findings and conclusions
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ENGINEERING RESEARCH INSTITUTE
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SEISMIC WAVE VELOCITY AS A MEANS OF IN-PLACE DENSITY MEASUREMENT

J. M. Hogan and R. L. Handy

INTRODUCTION

The objective of this investigation was to apply principles of first-arrival seismic refraction to the problem of determining in-place dry density in a soil embankment. The seismic refraction technique is a method by which velocity of a seismic wave is obtained by measuring the time for the wave to travel between known distances measured on the ground surface. The laboratory method of study involved correlation of results of seismic wave measurements with conventional dry density and moisture content measurements of several soils. Field seismic measurements were correlated to in-place moisture-density determinations. The ultimate goal was an economic improvement in construction control testing, since the time required to perform an in-place seismic measurement on an embankment is much less than that required for conventional moisture-density determination.

REVIEW OF LITERATURE

Seismic test methods are based upon properties of a material that govern the propagation and dissipation of stress waves. The theory of transmission of impulses through a solid body was first examined in connection with propagation of earthquake waves¹. Other investigations have centered on theoretical considerations and experimental results related to waves produced in a soil mass by vibrating foundation loads². There have been two general approaches to the study of soil properties by

dynamic methods. One involves the application of a vibrational load to the soil, while the second is based upon inducing a single sonic pulse. A summary of the results obtained by different applications of the vibratory method to the study of in-place properties of highway structural components has been reported by Jones and Whiffen³. Investigations utilizing the vibratory method have generally been directed towards problems of road design. There is no general agreement on the most pertinent dynamic properties, and a satisfactory general method of road design has not been developed.

Goetz applied sonic testing techniques to specimens of asphaltic concrete to study the correlation between resonant frequency and asphalt content⁴. A problem with such measurements is that resonant frequency is a function of specimen size, in addition to the physical properties of the specimen. Other studies relate resonant frequency of portland cement concrete to strength and durability⁵.

Numerous engineering applications have utilized velocity measurements of a single sonic pulse. For materials such as concrete, asphalt, wood, metals, and polymers, the technique provides a means of quality testing. Whitehurst summarized pulse velocity techniques and equipment for testing concrete structures to detect cracks and deterioration^{5,6}. Leslie investigated samples of soil, wood and concrete by using pulse techniques, and found that maximum velocity occurred in a silty clay at conditions of optimum moisture content and maximum dry density⁷. Manke and Gallaway showed that for a natural clay and a silty clay, maximum velocity occurred slightly on the dry side of optimum moisture content⁸. The effects of confining pressure and temperature were also studied. As

confining pressure increased, pulse velocity generally increased. Above freezing, temperature had little or no effect, and below freezing, the wave velocity greatly increased for soils that contained moisture.

Moore studied the relation of seismic wave velocity to degree of densification for several soils and crushed stone⁹. Tests were conducted under both field and laboratory conditions and results showed a comparatively straight-line relation of seismic wave velocity to increasing density. The equipment used was a Model MD-1 seismic unit manufactured by Geophysical Specialties Division of Minnetech Labs, Inc., Minneapolis, Minnesota. The relationship of seismic velocity to amount of compaction given an in-place soil was studied at the Illinois Institute of Technology Research Institute. Seismic equipment similar to that mentioned above was used, and results showed velocity generally increases with number of passes of compaction equipment¹⁰.

Phelps and Cantor developed a microseismic refraction system to study concrete deterioration under asphalt overlays¹¹. This approach enabled the thickness of the overlying asphalt to be determined and the quantity of the underlying concrete to be estimated by a nondestructive test. The length of the refraction line was about 3 ft, whereas the common length for a shallow subsurface investigation is often 100 to 200 ft.

METHODS

The first part of the investigation was to develop a technique applicable for measuring seismic velocities at small distances in both laboratory and field. An advantage of determining velocity from a distance-time graph is elimination of inaccuracies due to delays in the

timing system. A relationship of pulse velocity to dry density and moisture content was obtained by laboratory measurements on standard and modified AASHO compaction samples.

Equipment used for making shallow subsurface seismic investigations consists of three components; i.e., seismic timer, transducer, and impact source. The timer measures elapsed time for a seismic wave to travel from the impact source to the transducer. For geophysical studies the impact source can be a sledge hammer or explosive charge, and the transducer is usually a geophone. When a hammer is used, energy is often transmitted into the ground through a steel plate or ball.

The investigation began by using a Model MD-3 refraction timing system obtained from Geophysical Specialties Division of Minmetech Labs, Inc., Minneapolis, Minnesota, Fig. 1. Because of the short seismic line length required, some equipment modifications were made: a tack hammer was used, and the energy couple was a 5/8-in. diameter steel ball bearing. To make sure the timer started counting exactly when the hammer blow generated the seismic wave, the timing circuit was modified to close at the contact of the hammer and the ball bearing. This equipment gave acceptable results in the field where a 3-ft seismic line was used, but not in the laboratory where maximum distance was about 4-1/2 in. The counter recorded time to the nearest one-tenth millisecond, adequate in the field but inadequate in the laboratory, causing nonreproducibility of results. Part of the latter was thought due to inconsistencies of hammer energy, but a miniature drop hammer failed to alleviate the problem. It was also difficult to adapt the geophone to produce reliable first-arrival detections when mounted on a proctor specimen.

The above described seismic refraction system was similar to that used by R. W. Moore⁹, Bureau of Public Roads, for finding in-place velocities using a 5-ft seismic line and by the Illinois Institute of Technology Research Institute, where the velocity measurements utilized a line 2 ft long¹⁰.

A second refraction system used was a Model 217 Micro-Seismic Timer, available from Dynametric, Inc., Pasadena, California, in which the counter is controlled by a stable oscillator measuring travel time in microseconds, Fig. 2. Common flashlight batteries provide power. The transducer was a phonograph needle mounted in a brass case, supported on three rubber feet, Fig. 3. Needle contact pressure is controlled by a leveling screw attached to one of the feet. The impact device and energy couple were the same as used with the refraction system previously described. Tapping the ball bearing with the small hammer gave reproducible results and a constant energy source was not necessary. This microseismic apparatus allowed the field and laboratory pulse velocity measurements to be made by the same equipment and technique.

Field measurements of microseismic refraction tests were made along a 2-ft line divided into 3-in. stations. To provide good contact between the transducer and soil, a 1-in. flathead wire nail was driven flush into the soil and the needle placed in contact with the nail. At each station the ball bearing was seated into the subgrade to a depth one-half its diameter and was not tapped hard enough during the testing to drive it deeper into the subgrade. At each station 10 first-arrival measurements were recorded. Standard rubber balloon volume measure density and moisture content determinations were then made at midpoint of the seismic

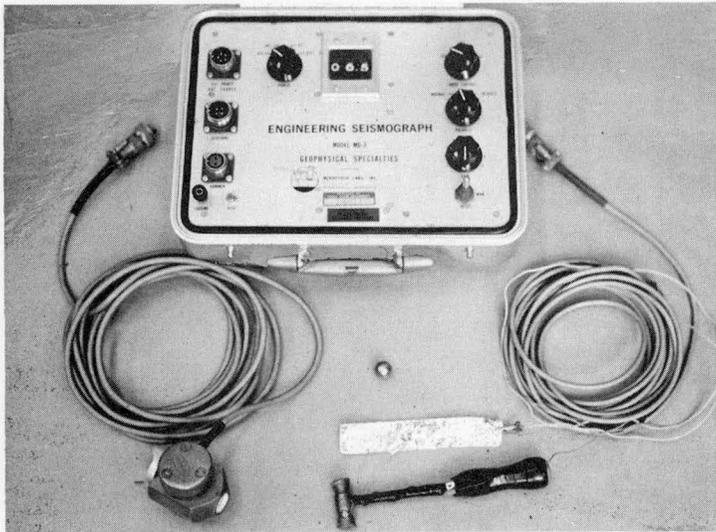


Fig. 1. Geophysical specialties Model MD-3 refraction seismic unit.

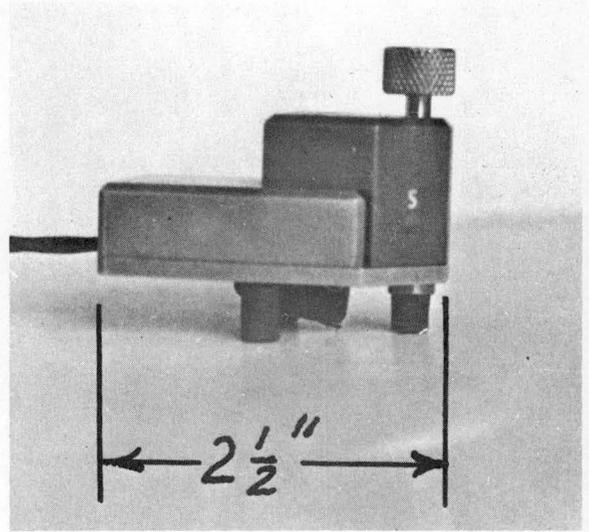


Fig. 3. Dyna Metric ceramic transducer.

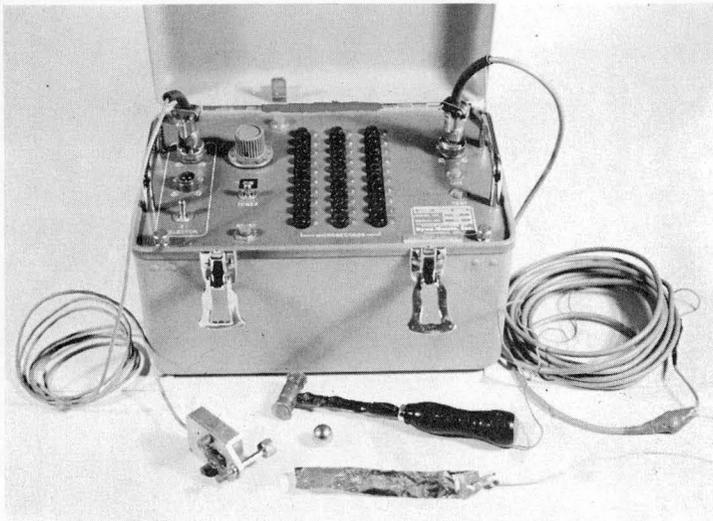


Fig. 2. Dyna Metric Model 217 Micro-seismic Timer.

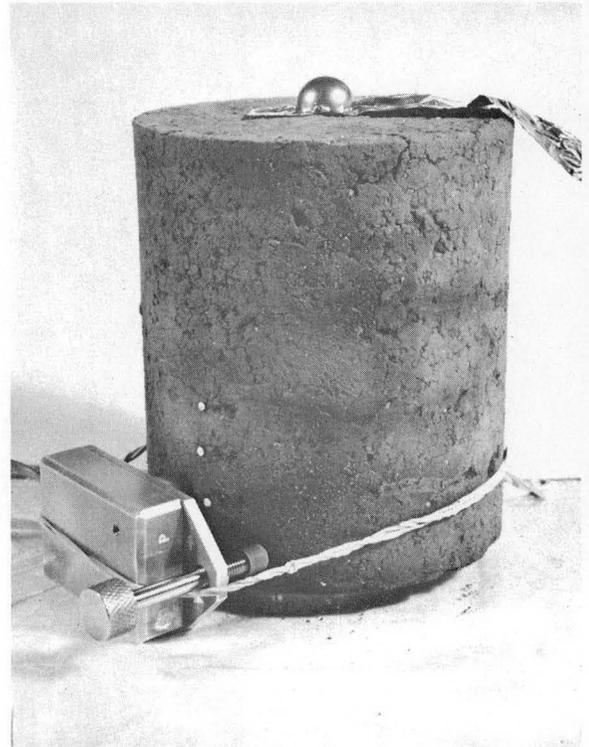


Fig. 4. Laboratory specimen with transducer mounted.

line. Pulse velocities were calculated using data obtained from distance-time plots. Analysis of field velocity plots was accomplished by methods common to shallow seismic investigation.

In the laboratory, standard and modified AASHO compaction tests were performed on soil samples obtained from material used in the field embankment construction¹¹. The specimen size was 4 in. diameter by 4.58 in. high, produced in a split mold in order to minimize specimen disturbance during removal. Two variations of the AASHO compaction procedure were used in molding specimens. Specimens noted as "remolded" were prepared by successive addition of water to the original soil. Specimens noted as "nonremolded" were prepared by adding calculated amounts of water to individual batches of soil. Moisture was added to the nonremolded laboratory soils 24 hours before molding. Initially moisture was added to the remolded soils 24 hours before molding with successive additions of water prior to molding each specimen. Data from these tests were used to express velocity as a function of dry density and moisture content at constant compactive effort and curing time.

For laboratory measurements, each sonic pulse was induced by striking a ball bearing embedded to about one-half its diameter in the center of the specimen. The transducer was attached to the specimen by rubber bands with the needle placed in contact with the head of a straight pin embedded flush into the specimen surface. Four pins, cut to a length of 1/8 in., with heads roughened to provide a better contact surface, were placed in a straight line parallel to the axis of the specimen and spaced at 1/2-in. intervals, with the top pin 2.7 in. below the top of the specimen, Fig. 4. Three such lines were spaced 120 degrees apart on the specimen

surface with travel distances being measured from the bottom of the ball bearing to the heads of the pins. At each transducer location, 10 time measurements were recorded. For each specimen, three pulse velocities were thus computed from the inverse slope of the distance-time plots and the pulse velocity of the specimen was taken as the average value.

THEORY

The elastic properties of matter may be described by various elastic constants. These include:

1. Young's modulus (E), or modulus of elasticity, a measure of the ratio of stress to strain in simple tension or compression.
2. Bulk modulus (k), a measure of the stress-strain ratio under hydrostatic pressure.
3. Shear modulus (n), a measure of the ratio of stress to strain during shear.
4. Poisson's ratio (μ), a measure of the geometric change of shape of a materials mass.

The theory of elasticity indicates that a material can transmit two principal types of seismic waves, longitudinal and transverse, each having different speeds of propagation dependent on the elastic constants.

Longitudinal (compression) waves create a particle motion parallel to the direction of propagation. These waves are similar in effect to sound waves in air. The velocity of longitudinal waves may be determined by

$$V_L = \left[\frac{E}{\rho} \frac{1 - \mu}{1 - \mu - 2\mu^2} \right]^{\frac{1}{2}} \quad (1)$$

where ρ is the density of the material.

Transverse (shear) waves create a particle motion perpendicular to the direction of wave propagation. They may be considered similar to the waves of a vibrating string. The velocity of transverse waves may be determined by

$$V_T = \left[\frac{E}{\rho} \frac{1}{2(1 + \mu)} \right]^{\frac{1}{2}} \quad (2)$$

where again ρ is the density of the material.

Of the three variables, E , ρ , and μ , the latter or Poisson's ratio, is most nearly a constant. If $\mu = 0.5$ there is no volume change under stress -- that is, the volume expansion transverse to the stress equals the volume decrease in the direction of applied stress. In soils μ is about 0.4 to 0.5. Substituting a value of 0.44 into Eqs. (1) and (2) gives:

$$V_L = 1.80 \sqrt{\frac{E}{\rho}}$$

$$V_T = 0.59 \sqrt{\frac{E}{\rho}}$$

or $V_L/V_T = 2.4$. Thus the instruments available, which record first arrival times, will record longitudinal waves unless the receiving instrument can be arranged so longitudinal waves will not affect it.

Let us now re-examine Eq. (1). According to this equation, the higher the density the lower the seismic velocity. This is opposite what was observed in subsequent tests. We therefore may conclude that density is not a major primary factor affecting seismic velocity. Or stated another way, seismic velocity is not a direct measure of soil density, since the effect of changes in density apparently is overridden by changes in the modulus of elasticity E and/or Poisson's ratio μ .

This means that the correlation between density and velocity will be empirical, and will be influenced by anything which will change E and μ .

Possible variations include:

- Moisture content
- Soil microstructure
- Degree of saturation
- Soil minerals
- Structural defects (cracks, spalls).

Thus a correlation may be suitable for a particular soil, moisture content, method of molding, and elapsed time after molding. Hopefully a meaningful correlation will be obtained on laboratory Proctor size specimens for use in the field.

MATERIALS

Initial in-place seismic velocity tests were performed on highway embankments constructed of three types of soil. Material for the laboratory measurements was sampled from the embankment side-slope adjacent to the area of field tests. A description of the materials follows:

Wisconsin age glacial till, an A-4(5) clay loam located in range 23 west, township 83 north. Embankment of south-bound lane of Interstate 35 near junction of US 30. Liquid limit 23, plasticity index 9. Hereafter referred to as I-35 till.

Kansan age glacial till, an A-6(10) silty clay located in range 30 west, township 75 north. Reconstruction embankment of Iowa Highway 92 seven miles east of Greenfield, Iowa. Two weathering variations were

tested, referred to hereafter as Greenfield till-gray or Greenfield till-brown. For gray, liquid limit 30, plasticity index 13; for brown, liquid limit 40, plasticity index 18.

Loess, an A-4(8) silty loam located in range 44 west, township 77 north. Embankments of east and west bound lanes of Interstate-80 one mile east of Loveland, Iowa. Liquid limit 32, plasticity index 6. Referred to hereafter as I-80 loess.

Much of the laboratory developmental work was done on a laboratory loessial soil labeled as 20-2, which is similar to the I-80 loess. Results obtained with the 20-2 loess will be shown with those of the I-80 loess because of the close similarity of the two materials.

LABORATORY RESULTS

Velocities measured in specimens obtained in the standard moisture-density tests were plotted versus moisture content and versus dry density. Typical curves are shown in Figs. 5 and 6.

Moisture Content

It will be noted that the moisture-seismic velocity curves do not peak out at the same place as the moisture-density curves; therefore seismic velocity cannot be used to establish optimum moisture content without some correction. In general a maximum velocity occurred with less than the optimum moisture content and with a correspondingly lower dry density. The average difference in moisture contents for maximum velocity compared to maximum density was $1.2 \pm 0.86\%$, the \pm entry indicating

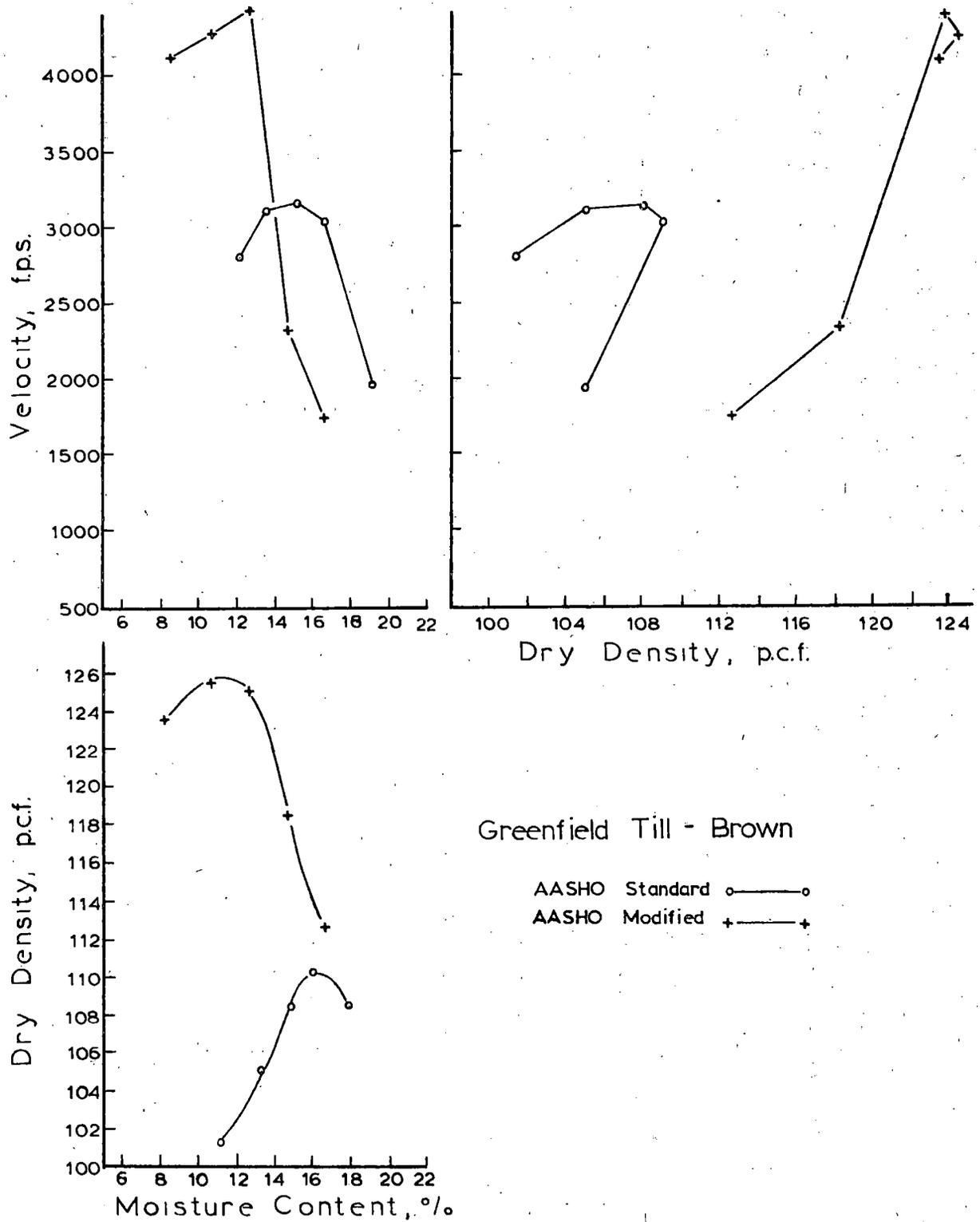


Fig. 5. Greenfield till - brown.

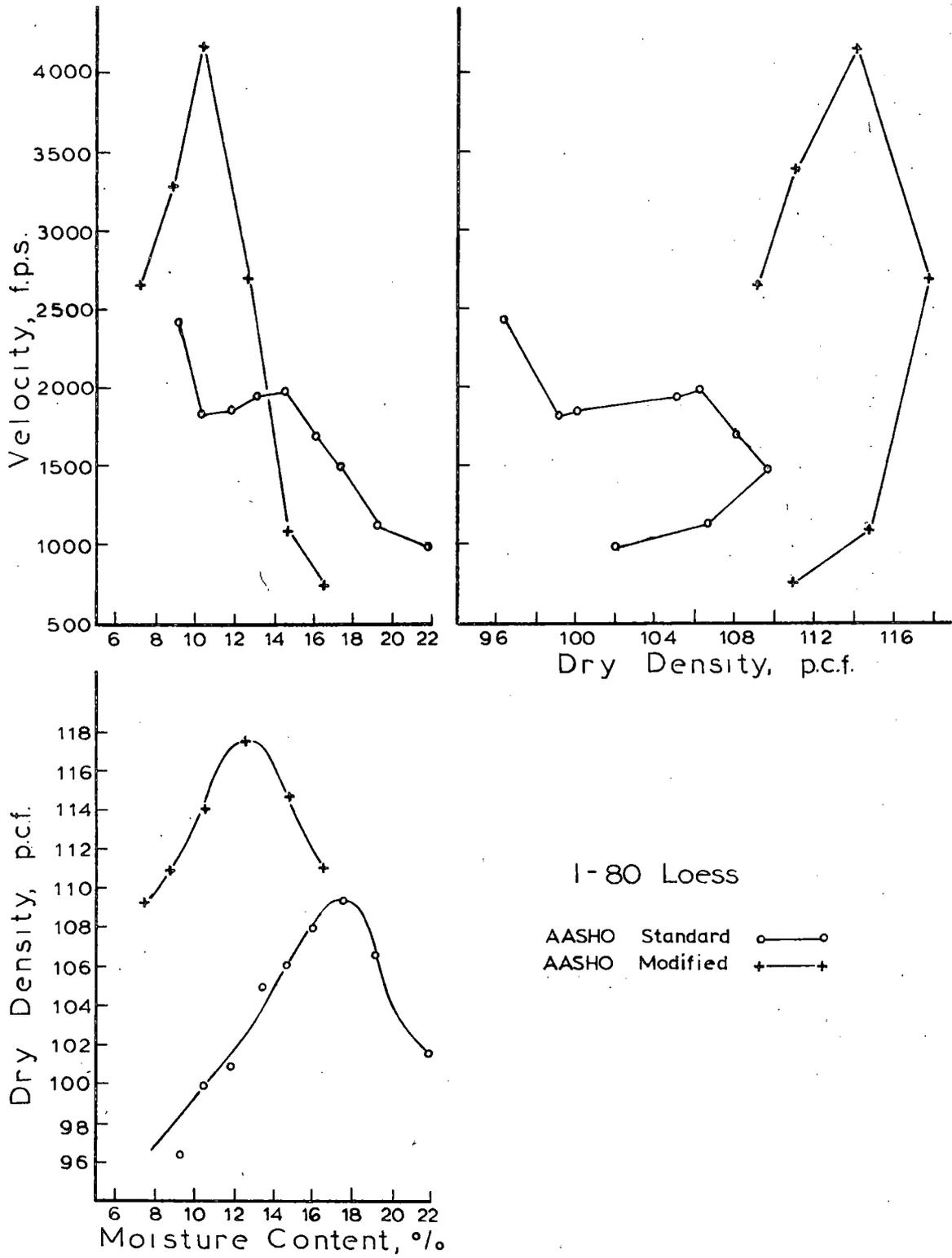


Fig. 6. I-80 loess.

one standard deviation from the mean. Data are shown in Table 1. Seismic velocity could therefore be used to determine the optimum moisture content for maximum density, but there appears to be little advantage in doing so. The difference in optimum moisture contents does not seem to depend on soil type or whether standard or modified compactive effort was used. These results agree with those of Manke and Gallaway in which maximum velocity occurred at a moisture content of about 1.5% less than optimum⁸.

Table 1. Summary of laboratory results.

Soil	Compaction procedure	Max. dry density (pcf)	Dry density at maximum velocity (pcf)	Optimum moisture content (%)	Moisture content at maximum velocity (%)	Maximum velocity (fps)	Velocity at maximum dry density - optimum moisture content (fps)
I-35 till	Standard remolded	123.3	123.3	10.3	10.3	2190	2190 ^(a)
I-35 till	Modified remolded	131.0	131.0	7.9	7.9	3570	3570 ^(a)
I-35 till	Standard not remolded	122.4	121.8	10.8	10.4	3330	2950
I-35 till	Modified not remolded	131.0	130.0	8.8	8.0	4180	2800
Greenfield till - brown	Standard remolded	110.2	107.0	16.0	14.5	3130	3000 ^(a)
Greenfield till - brown	Modified not remolded	125.3	123.8	11.5	12.5	4480	4330 ^(a)
Greenfield till - gray	Standard remolded	116.7	114.6	13.5	11.7	3300	2990 ^(a)
Greenfield till - gray	Modified remolded	127.7	126.6	9.2	8.0	4040	3880 ^(a)
Greenfield till - gray	Standard not remolded	115.3	113.4	14.7	13.1	3388	2610
Greenfield till - gray	Modified not remolded	126.1	124.7	10.4	9.1	4140	3400
I-80 loess	Standard remolded	109.3	106.2	17.5	14.0	1970	1520
I-80 loess	Modified remolded	117.7	114.1	12.5	10.6	4160	2680 ^(a)
I-80 loess	Standard not remolded	106.8	106.5	16.0	15.0	1780	1520
20-2 loess	Standard remolded	107.0	103.5	17.4	16.2	2780	2340 ^(a)
20-2 loess	Modified remolded	116.7	116.7	13.4	13.4	3820	3820 ^(a)
20-2 loess	Standard not remolded	105.8	103.4	17.5	15.4	1830	1250
20-2 loess	Modified not remolded	114.6	112.2	13.8	12.6	3120	2780

^(a) For these tests the velocities were computed from the average of two measurements on each specimen. For all other tests an average of three measurements were used as stated in the development of method section.

Density

The plots on the right in Figs. 5 and 6 show rather conclusively that seismic velocity cannot be used to predict dry density if the moisture content varies, as it does in these graphs. In order for the density to be tested, one must determine the moisture content and go to velocity versus moisture content curves to determine whether the velocity is above or below the appropriate compaction curve.

Discussion

At a given moisture content a higher velocity is not always indicative of a higher density. For example, in both Figs. 5 and 6, at high moisture contents the velocity is lower for modified than for standard compaction. This may be an advantage, since the seismic velocity thus appears to be very sensitive to overcompaction, defined as dispersion of clay due to remolding at too high a moisture content¹². According to theory, overcompaction breaks the flocculated clay structure and allows clay particles to become separated by liquid water, greatly weakening the soil shearing strength. Overcompacted samples sometimes show internal slickensides, or shear planes. This explanation appears to be consistent with the decrease in seismic velocity in this range, since it indicates a large reduction in E, as was found in static tests by Seed and Chan¹². Seismic velocity therefore could be more reliable than density as an indicator of satisfactory compaction, since the density does not ordinarily reflect damages from overcompaction.

Elapsed Time

Another phenomenon discovered more or less by accident was a gradual decline in seismic velocity of laboratory specimens as they were aged. This decrease occurred even though there was no appreciable change in moisture content or density. Typical results are shown in Figs. 7, 8 and 9. Upon aging, the velocity peaks tended to become less pronounced and move to a lower moisture content. The reason for this can only be conjectured, and must relate to a reduction in either E or μ , since ρ remains essentially constant. The reason may relate to a gradual rearrangement of the soil water; the clay mineral in all three soils is montmorillonite, which readily absorbs water by interlayer expansion. Incorporation of pore water into the clay interlayer structure might soften the clay and reduce E and V_L . The opposite effect is expected from thixotropic behavior, or the tendency for remolded and partially dispersed soil clay to reflocculate with time. According to Barkan¹², moist clay has a high V_L . The explanation for the decrease in seismic velocity therefore may relate to a change in μ . According to Eq. (1), if μ should decrease from 0.44 to 0.42, which is not unlikely with a removal of pore water, V_L would become $1.60 \sqrt{E/\rho}$, a decrease of over 10%. (Incidentally the shear wave is much less affected, decreasing less than 1%.) The circumstantial evidence therefore points to small time-dependent reductions in μ gradually reducing the longitudinal wave velocity. The practical significance is that velocity tests should be made the same day that compaction is performed or the velocity will be lowered to the extent that the compaction may not pass a velocity-criterion specification.

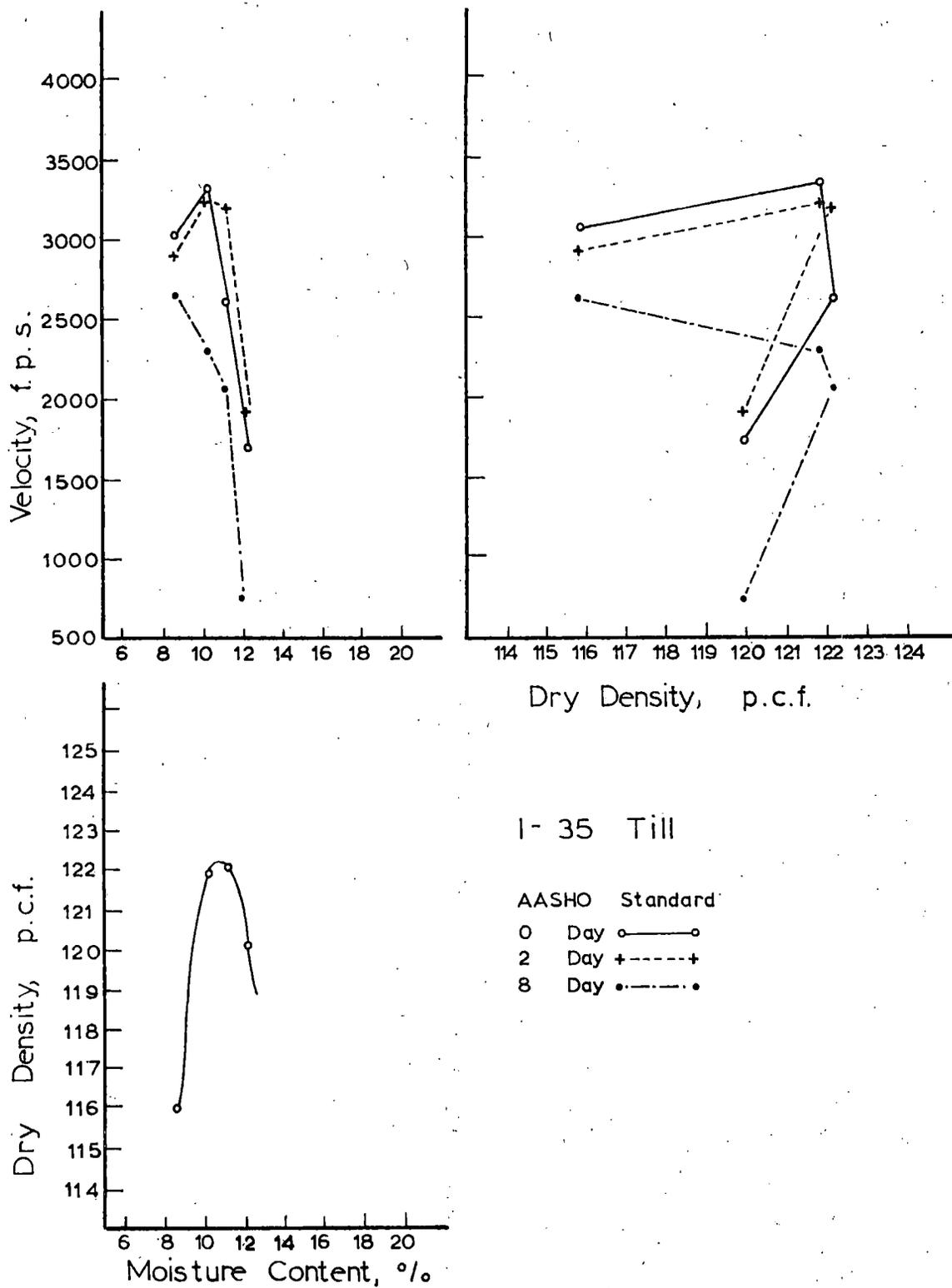
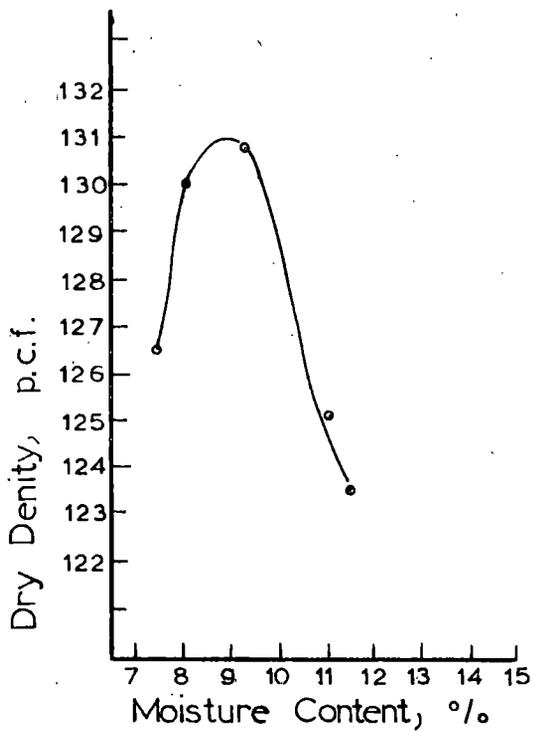
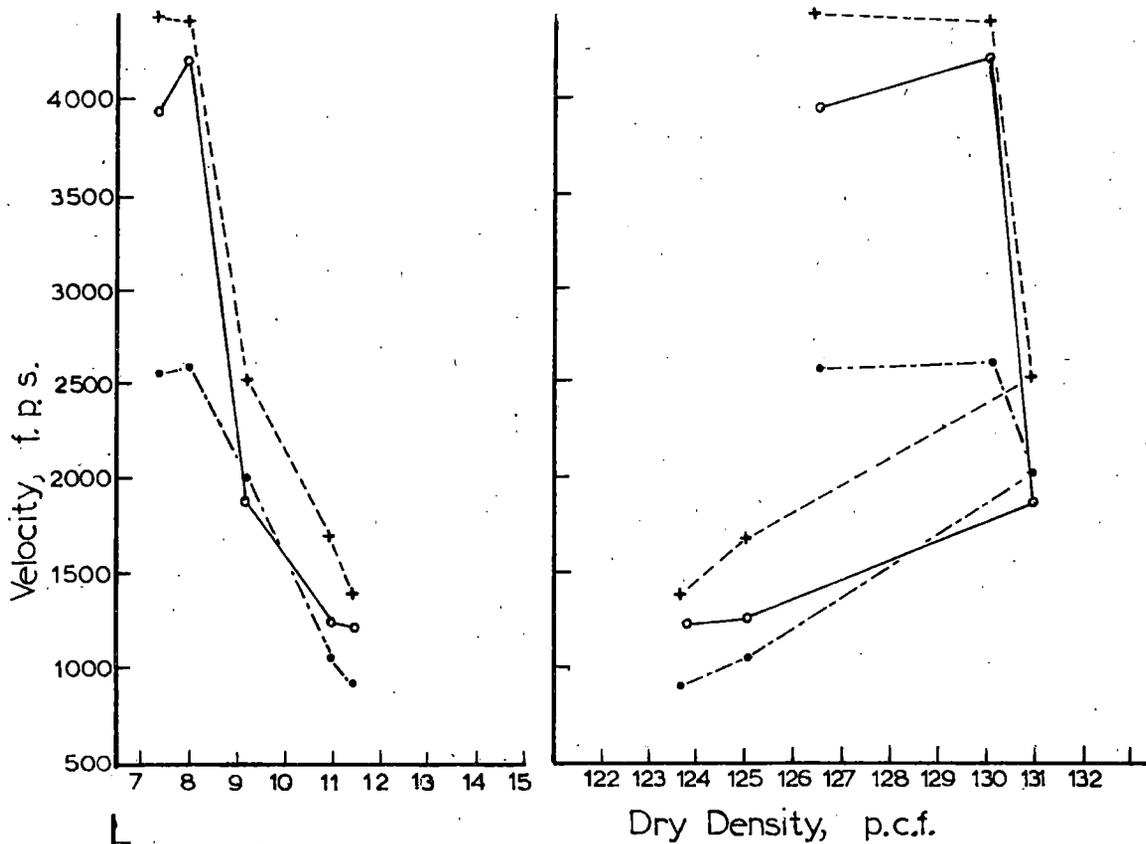


Fig. 7. I-35 till.

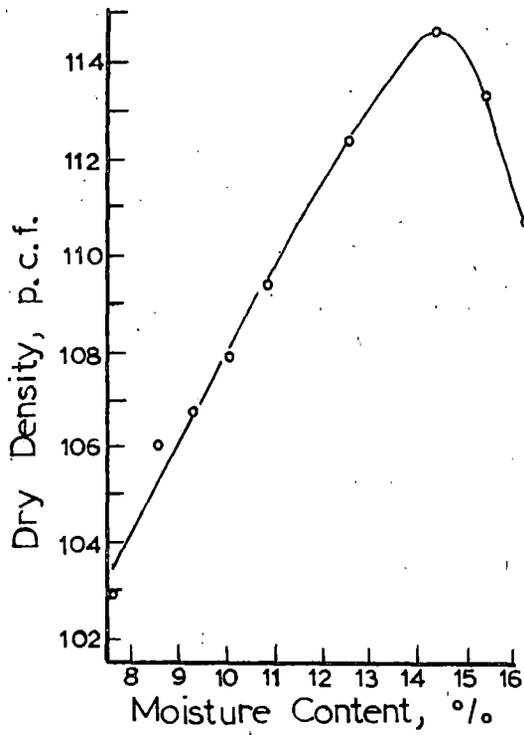
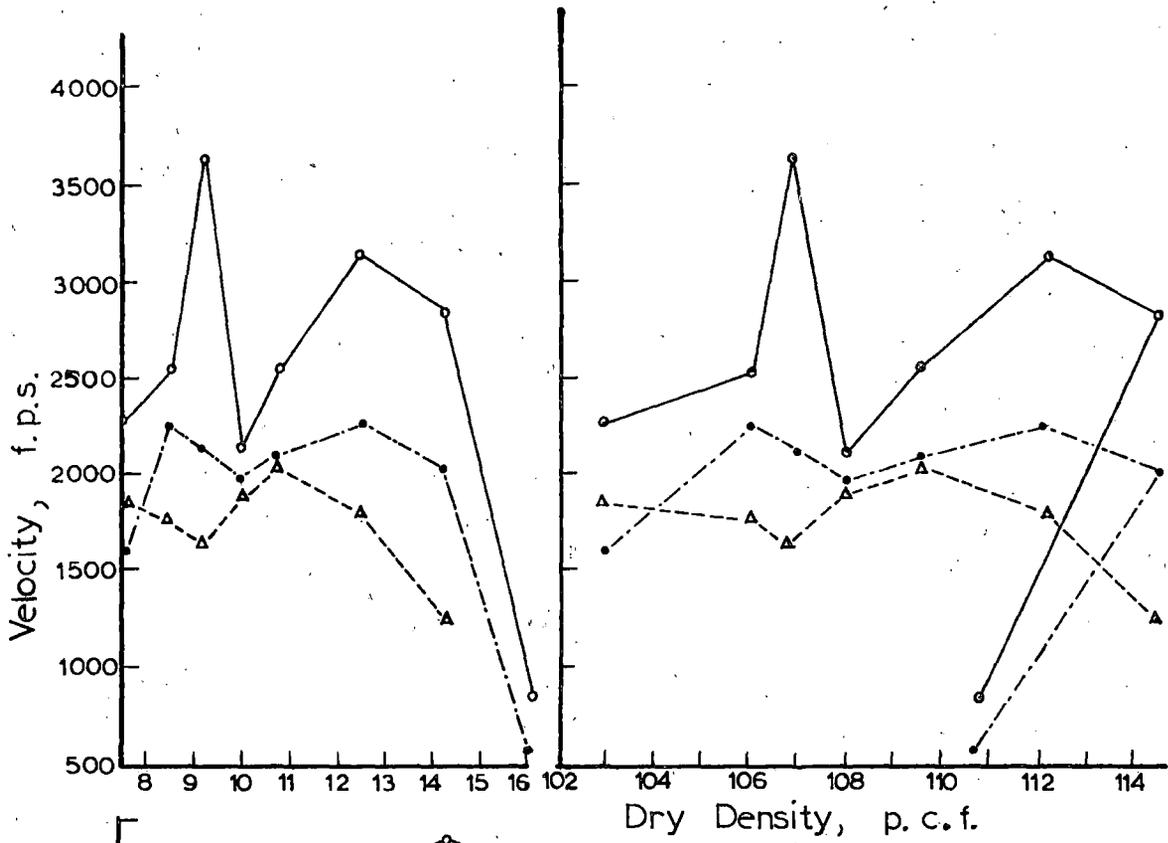


I-35 Till

AASHO Modified:

- 0 Day ○—○
- 2 Day +---+
- 7 Day ●-.-●

Fig. 8. I-35 till.



20 - 2 Loess

AASHO Modified :
 0 Day ○—○
 2 Day ▲---▲
 9 Day ●-●

Fig. 9. 20-2 loess.

FIELD DATA

Results from 35 field tests are shown in Figs. 10 - 18. The velocities obtained from these graphs are shown in Table 2.

In order to convert the velocity measurements to densities, the laboratory moisture-density and moisture-velocity curves with standard and modified compactive efforts were interpolated for intermediate compactive efforts, as shown in Figs. 19 - 22. The curves for remolded soils were used since they were less erratic, probably because of more uniform pulverization. The compactive efforts were arbitrarily numbered 1 through 5, 1 indicating standard Proctor and 5 modified Proctor compaction. Each measured velocity and moisture content was then entered on the moisture-velocity graphs and the compactive effort estimated. The compactive effort and the moisture content were then entered on the moisture-density curves to estimate dry density.

As seen in Table 2, in almost every instance the density inferred from seismic data were lower than that actually measured in the field. Exceptions are noted in parentheses, and all occur at high moisture contents where there is an inverse relationship between velocity and compactive effort. Thus in all cases the field velocities were too low, probably because no attempt was made to test immediately following compaction. Exceptions were tests 30 to 32, which were tested immediately after compaction. Unfortunately, in many of the tests the moisture content was high enough to be in the region of an inverse velocity-compactive effort relationship, indicated by crossing of the lines at the right in Fig. 11. Interpolation of compactive efforts is not appropriate in this region, since the velocity probably peaks out at some intermediate effort before overcompaction occurs.

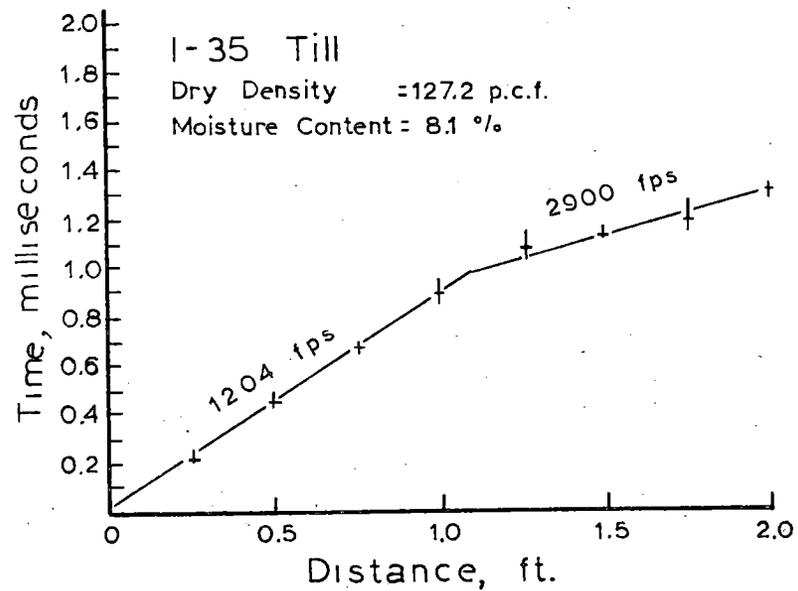
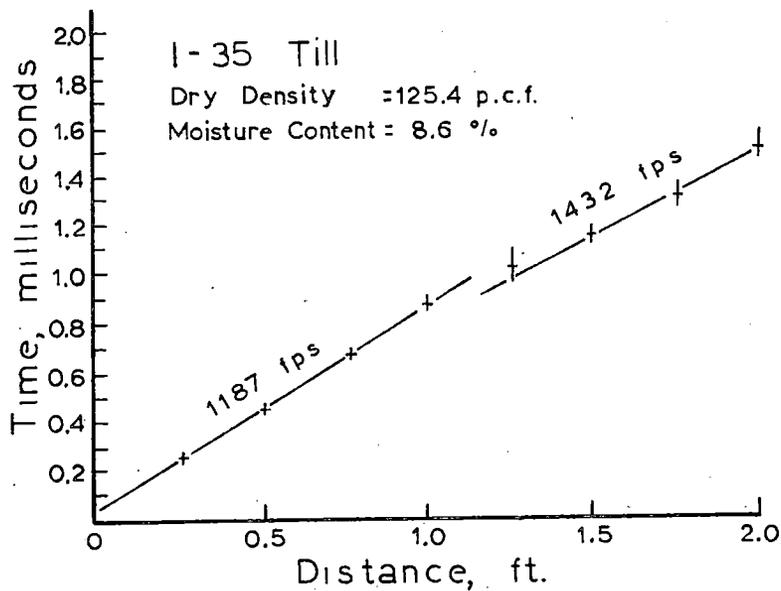
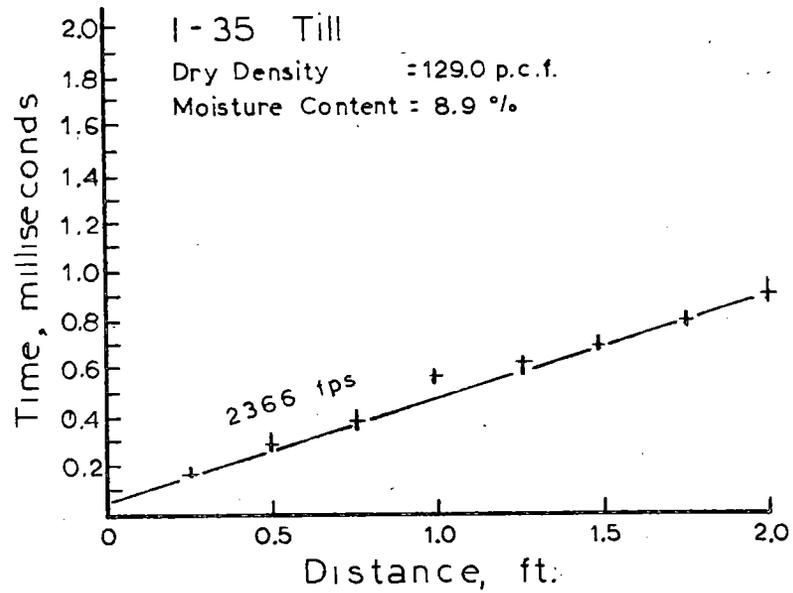
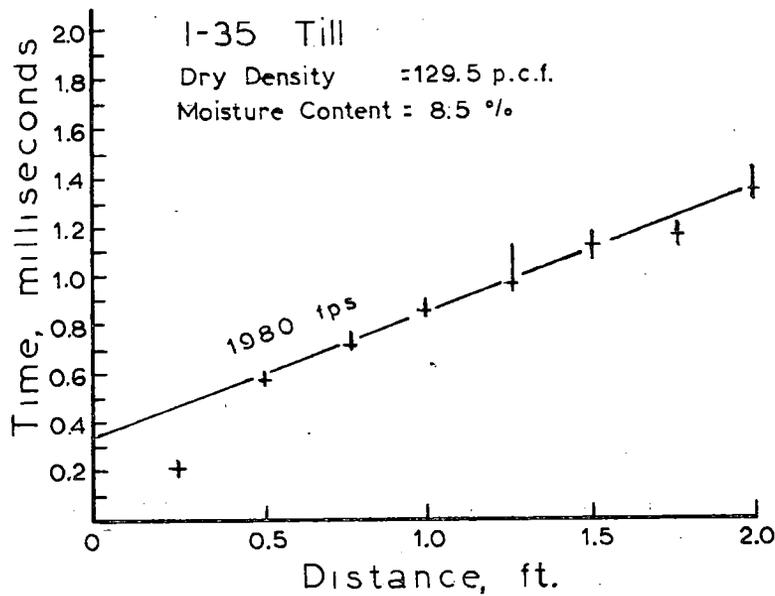


Fig. 10. I-35 till.

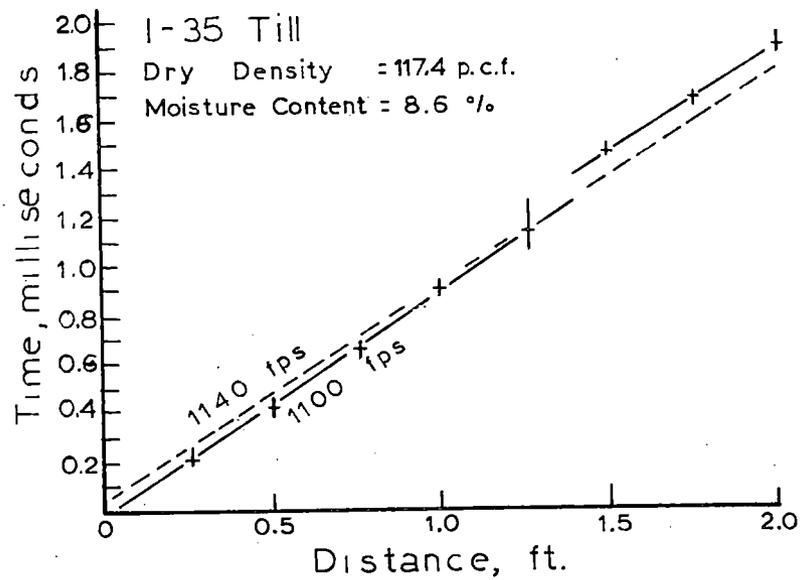
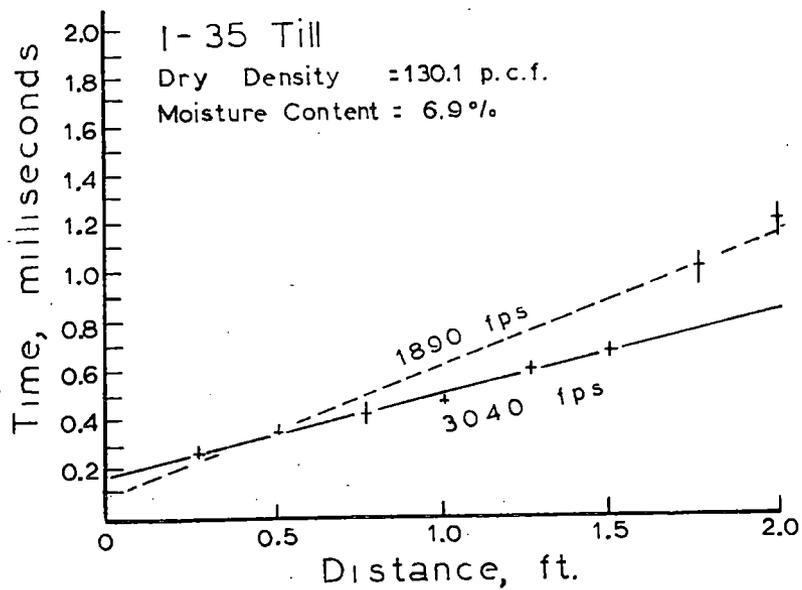
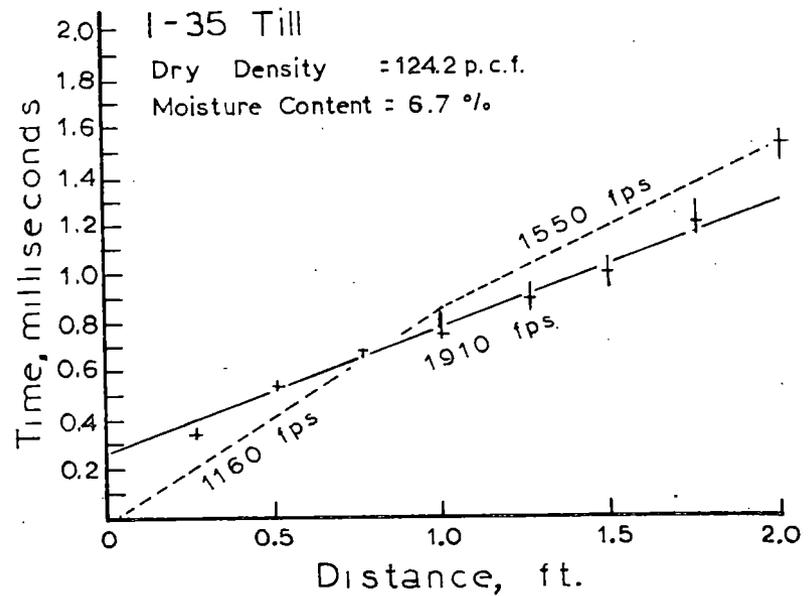
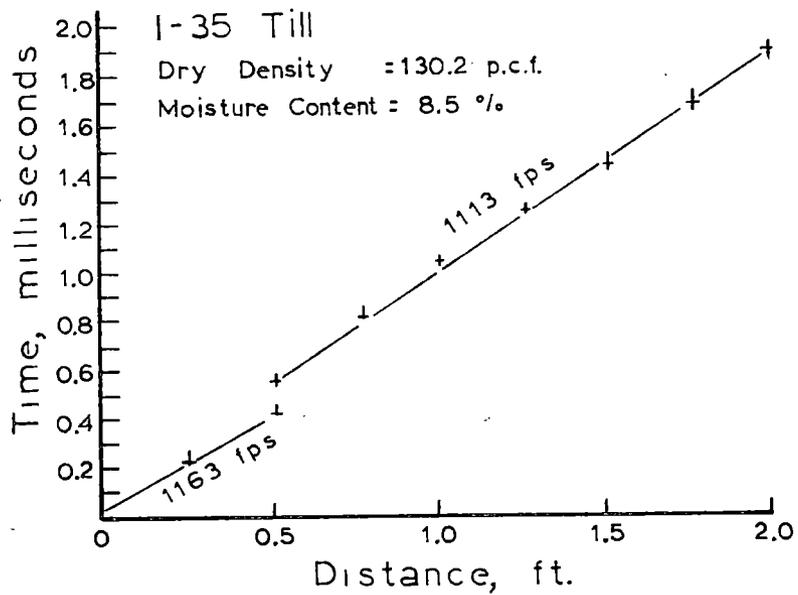


Fig. 11. I-35 till.

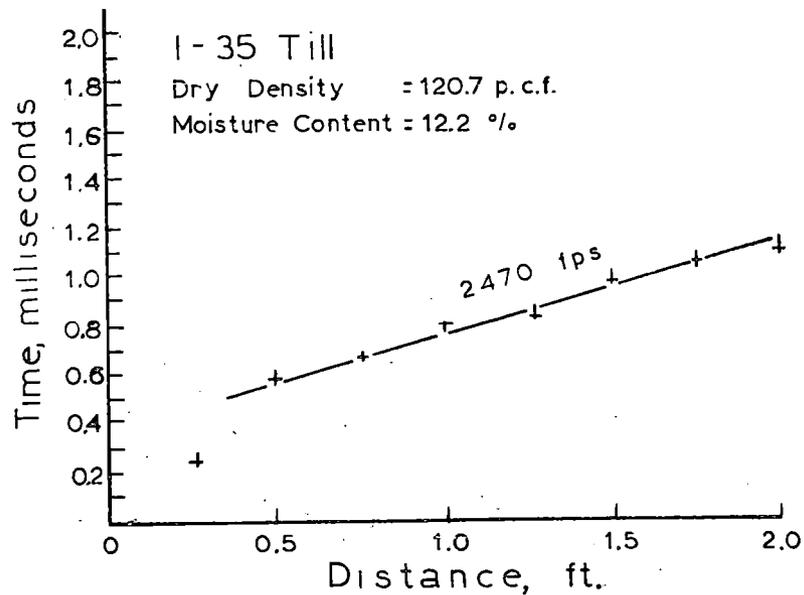
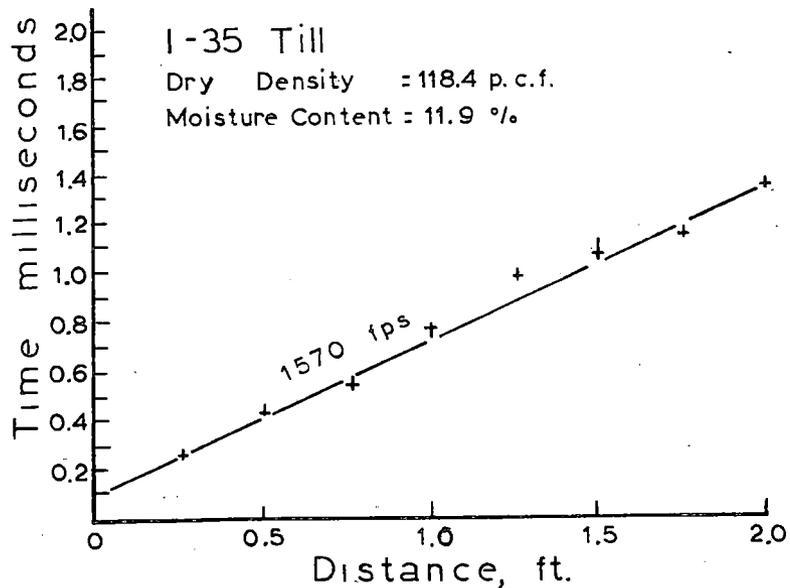
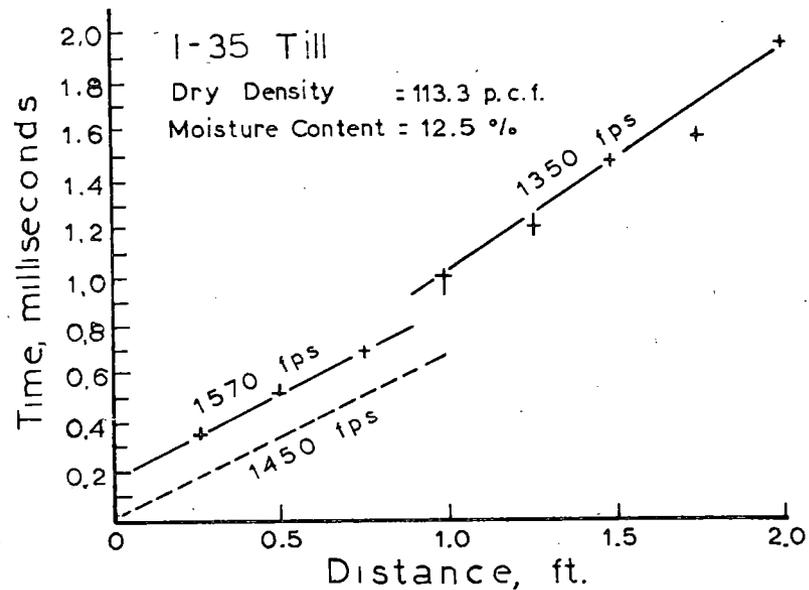
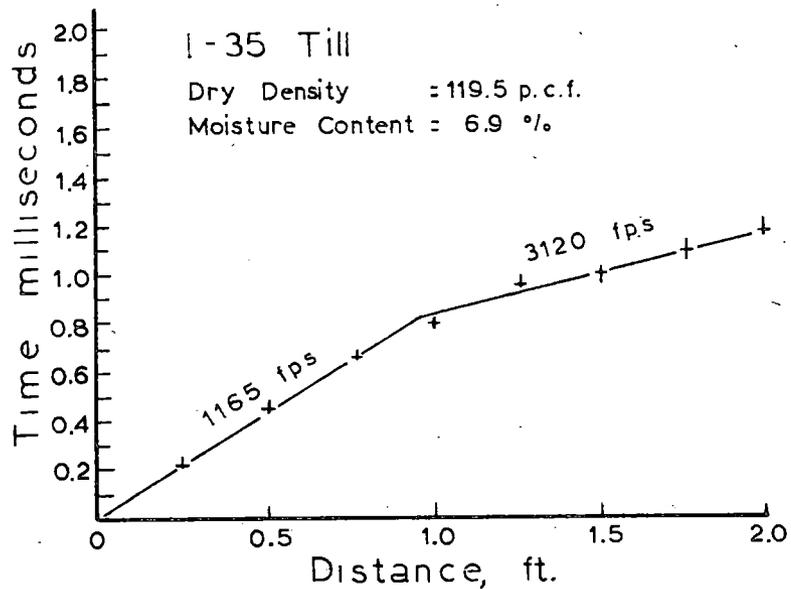


Fig. 12. I-35 till.

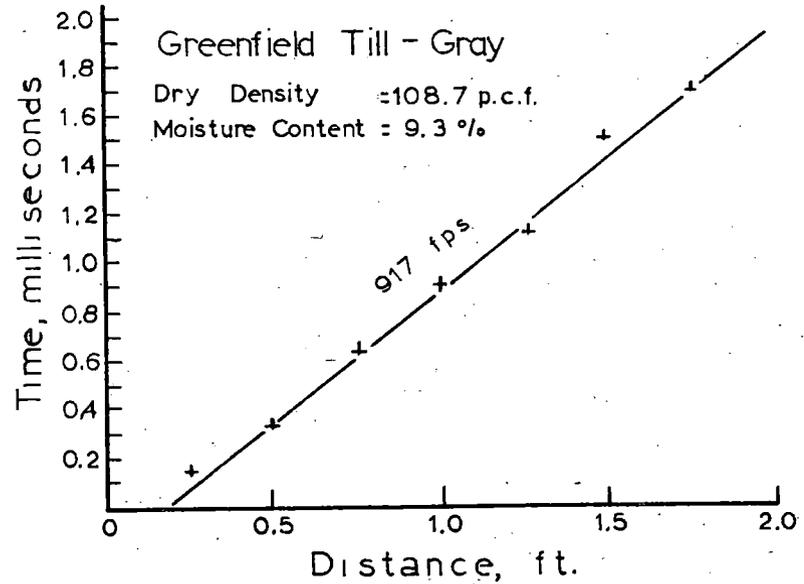
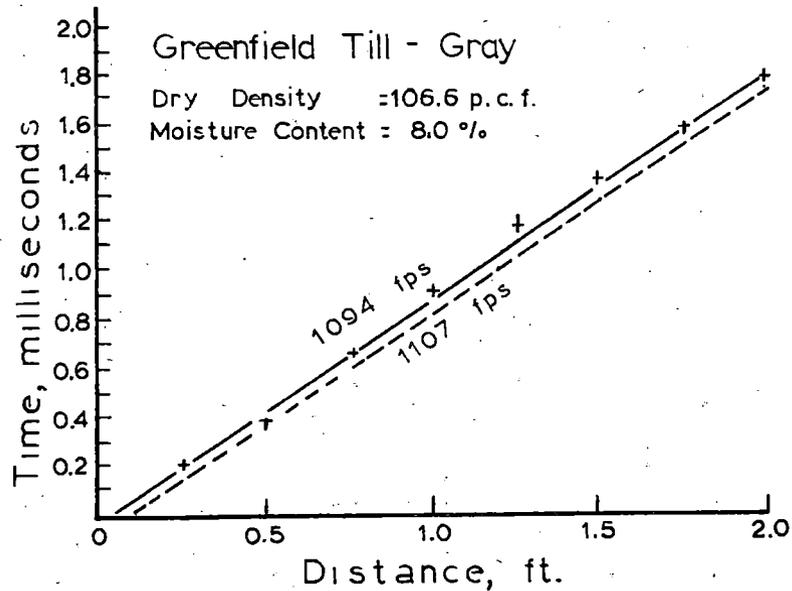
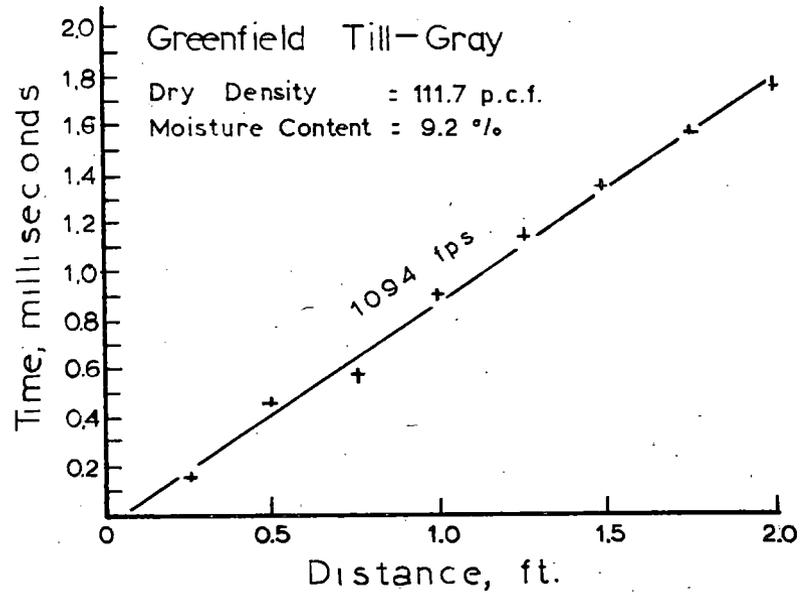
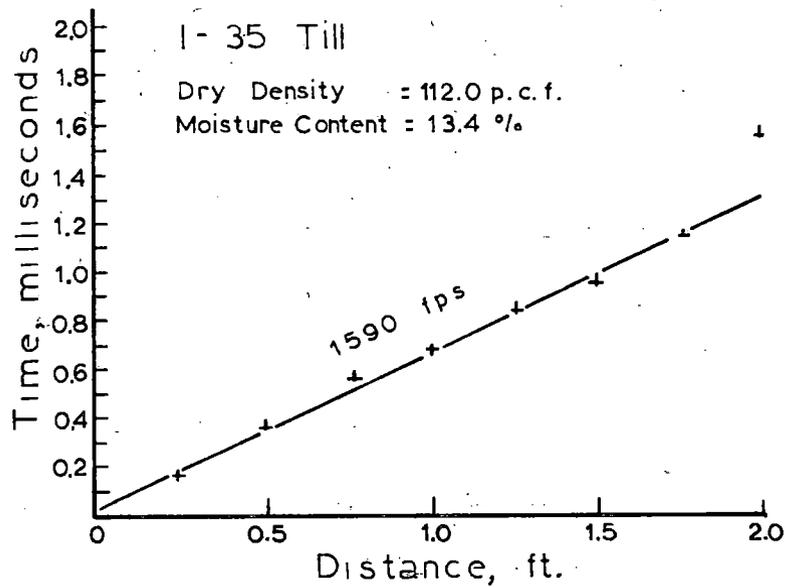


Fig. 13. I-35 till and Greenfield till - gray.

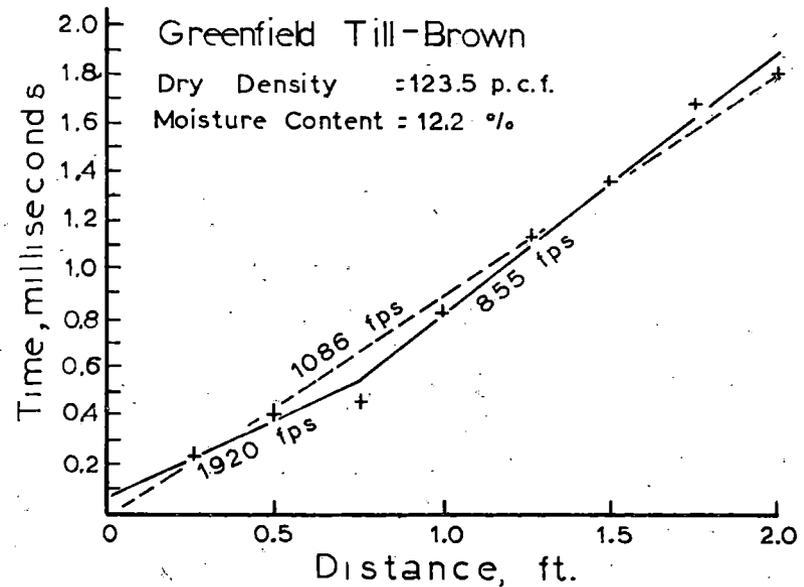
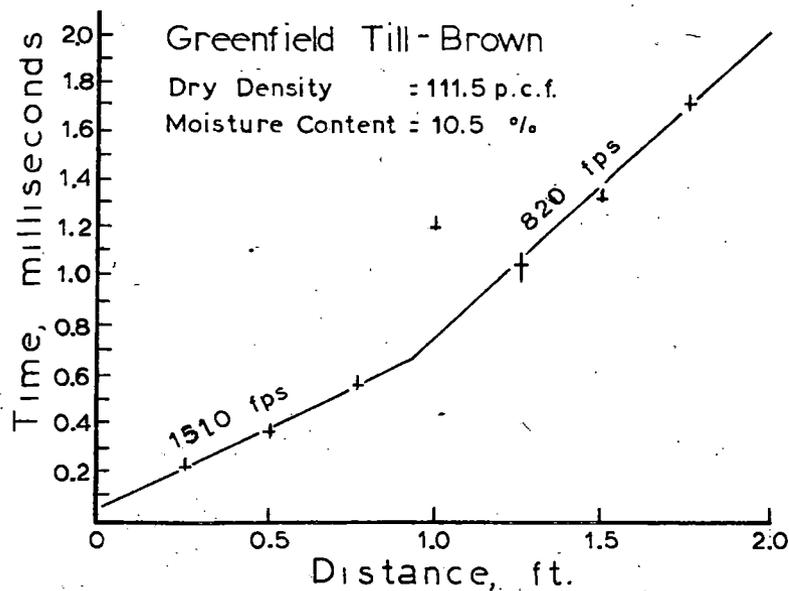
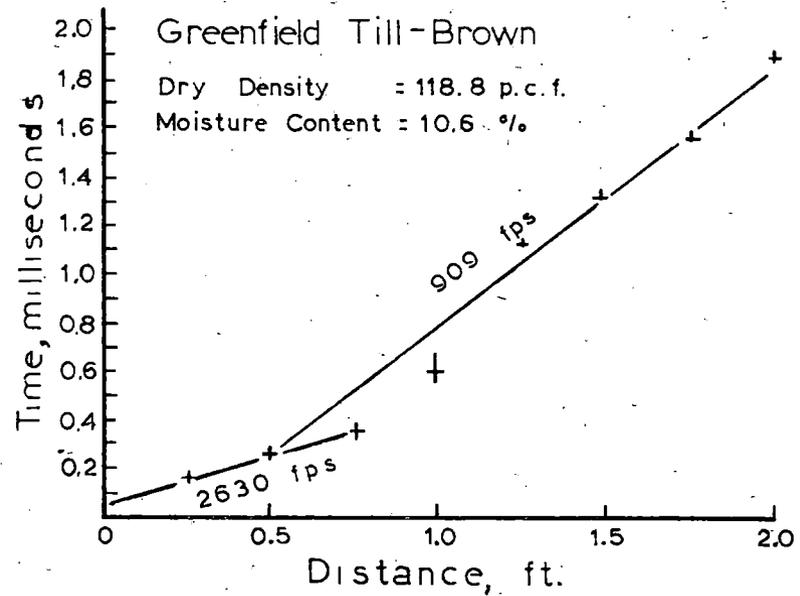
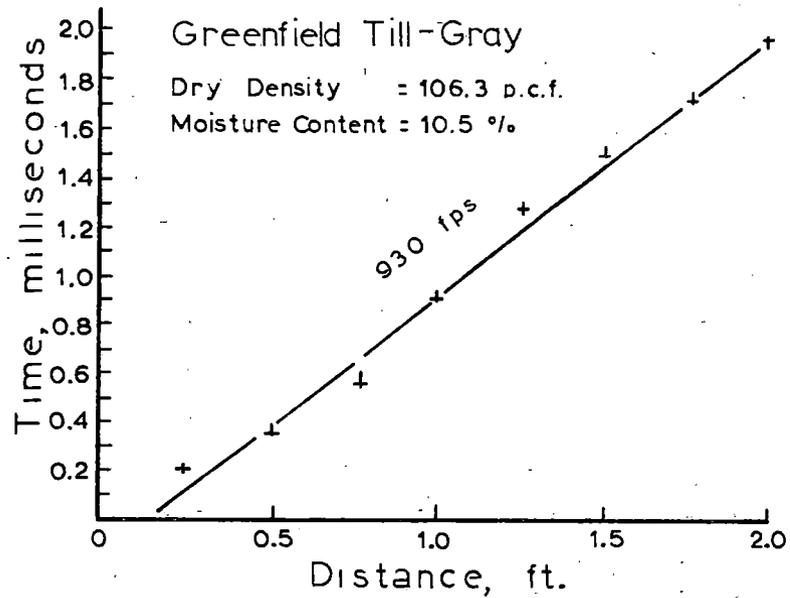


Fig. 14. Greenfield till - gray and brown.

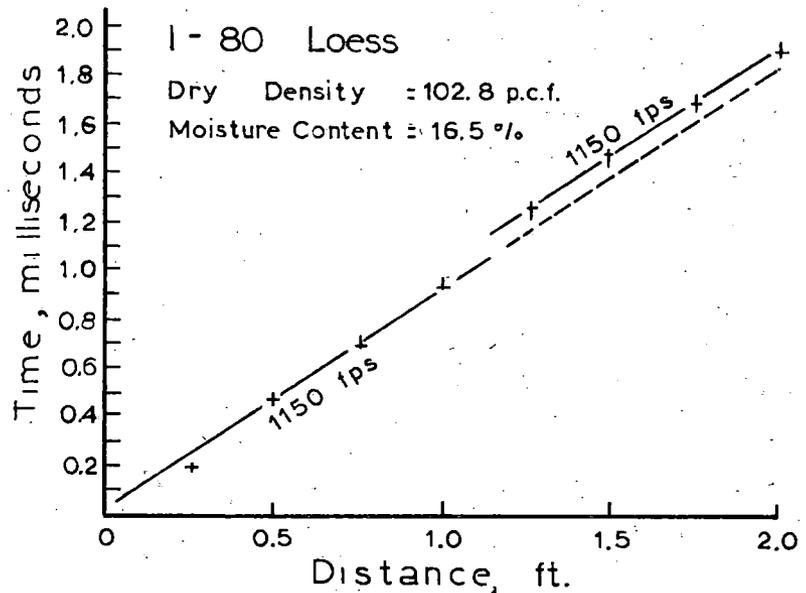
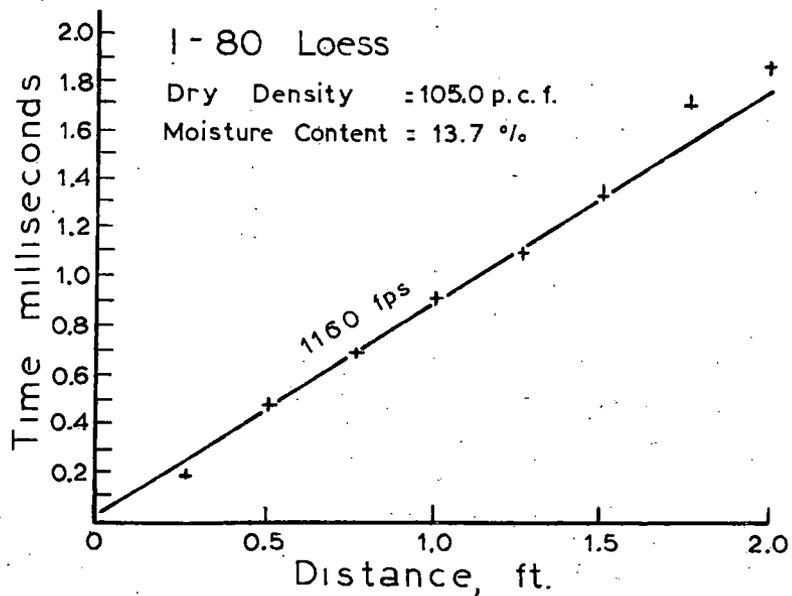
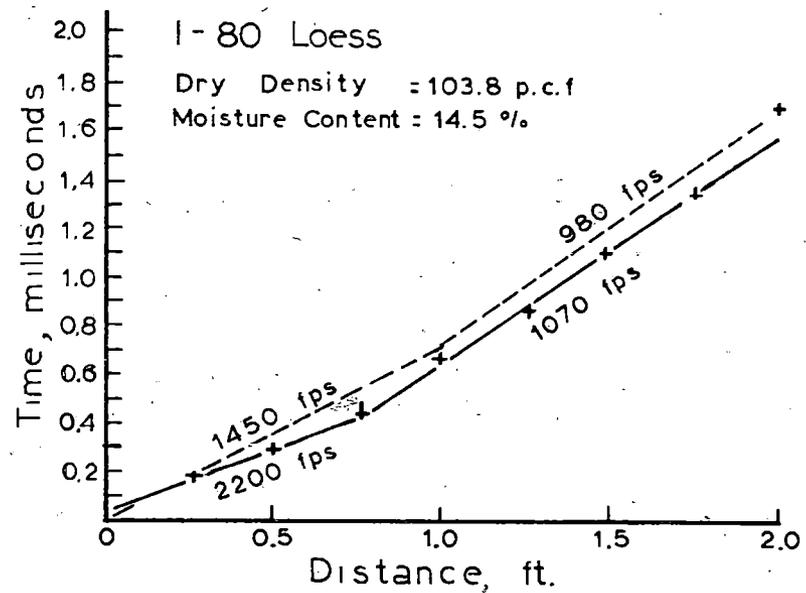
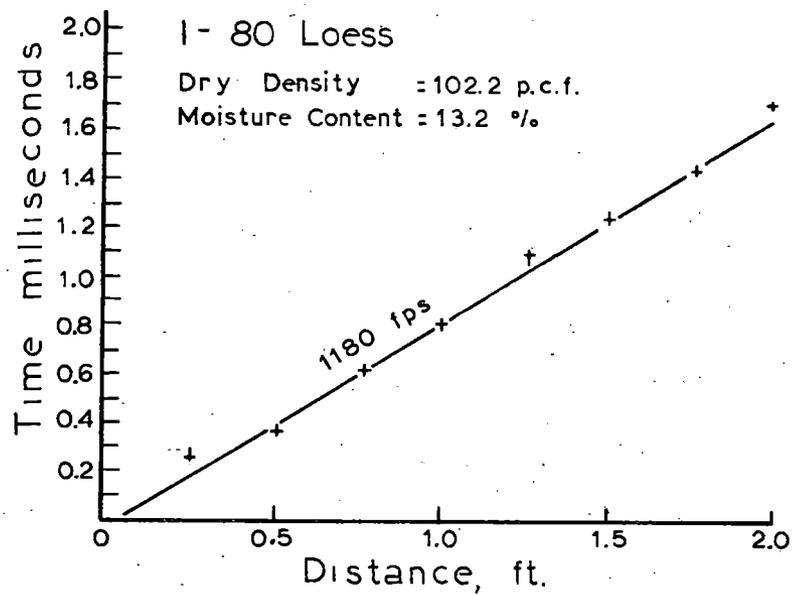


Fig. 15. I-80 loess.

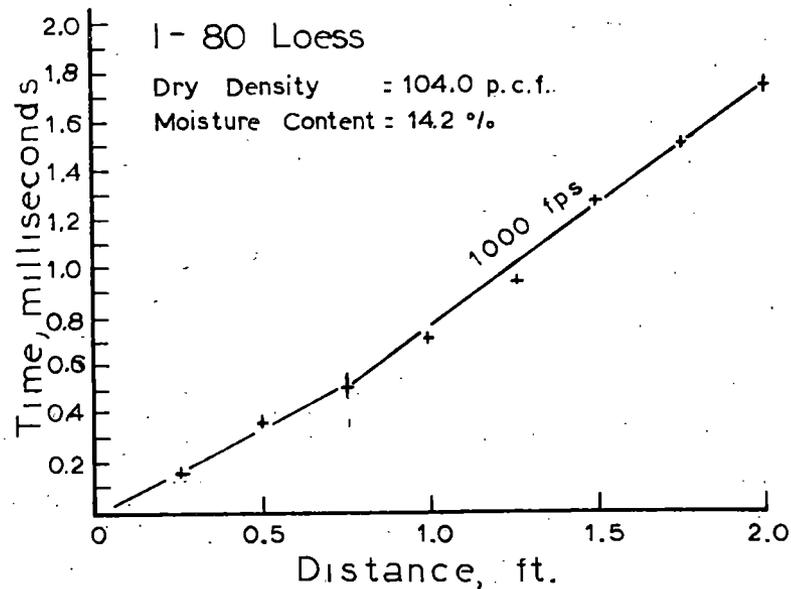
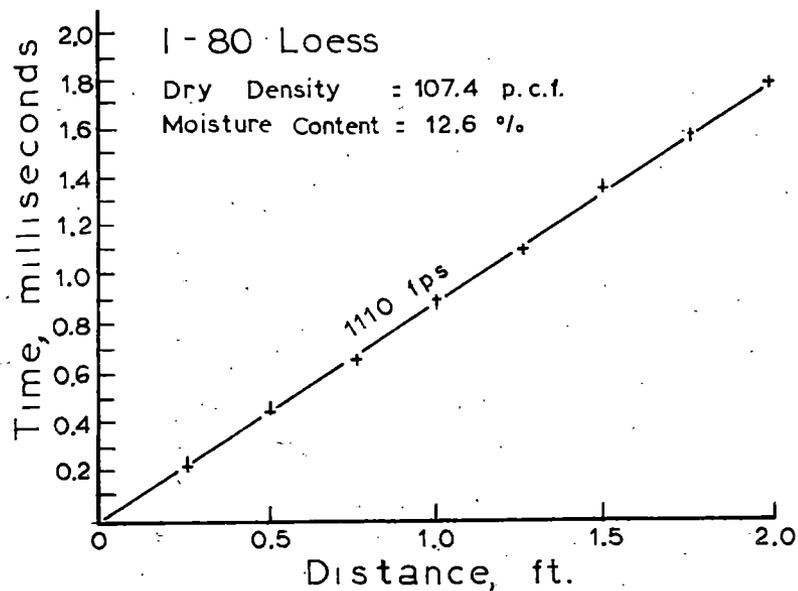
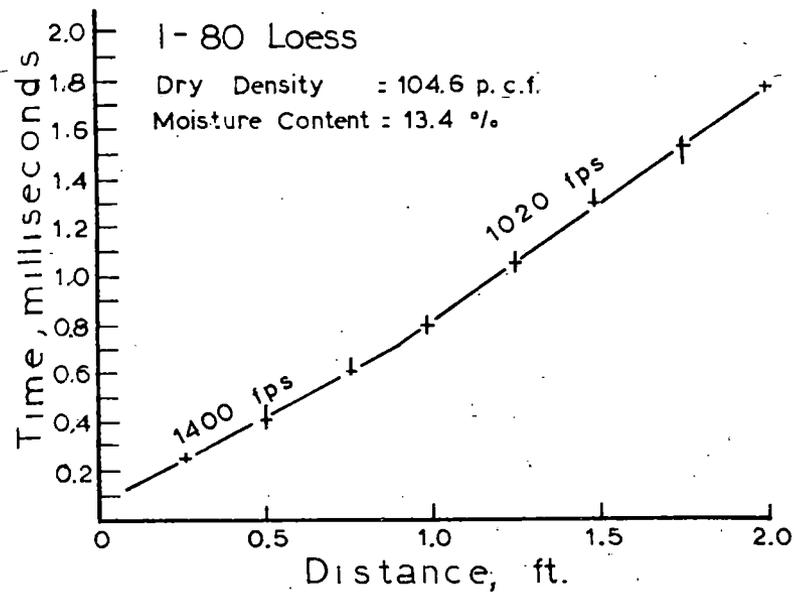
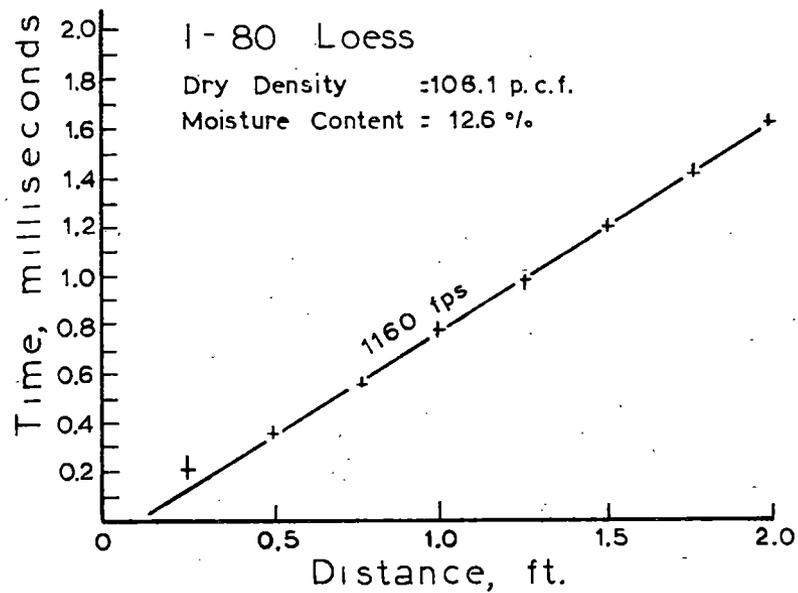


Fig. 16. I-80 loess.

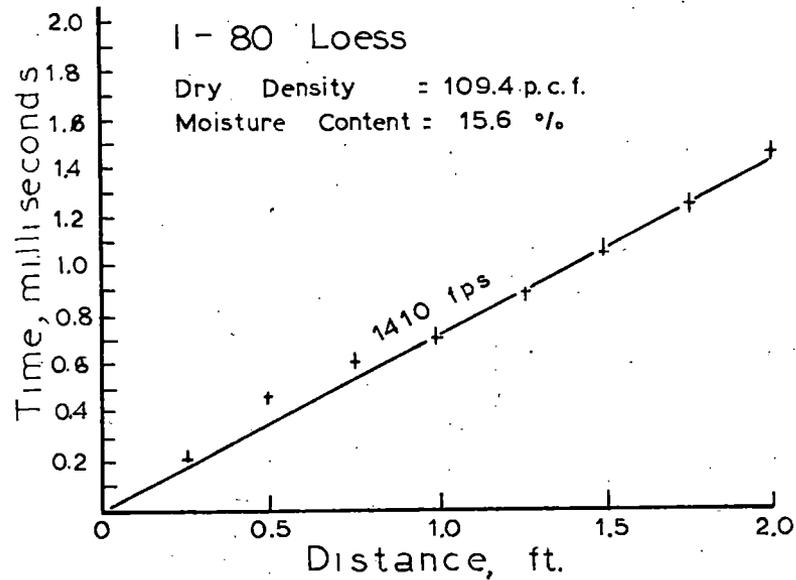
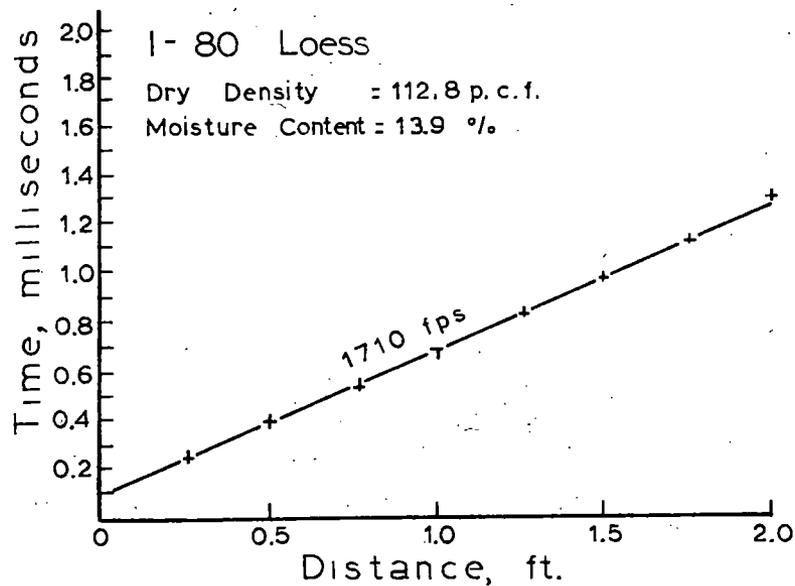
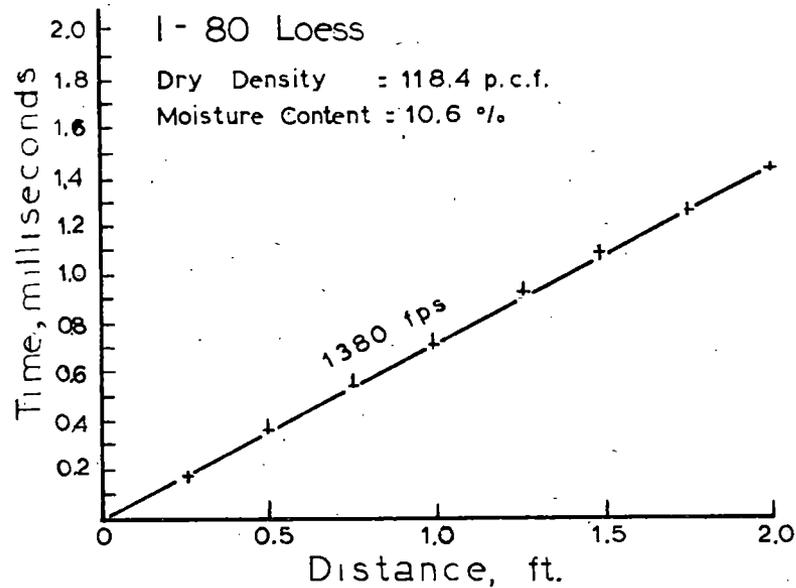
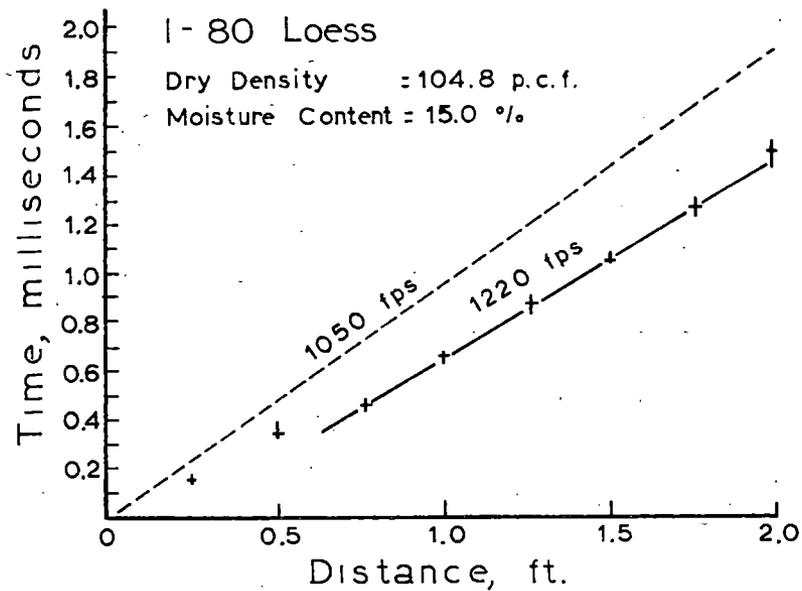


Fig. 17. I-80 loess.

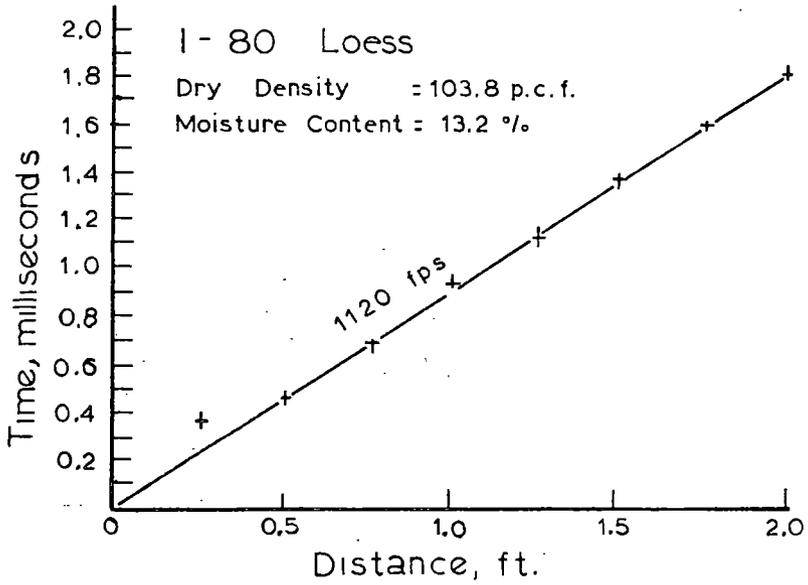
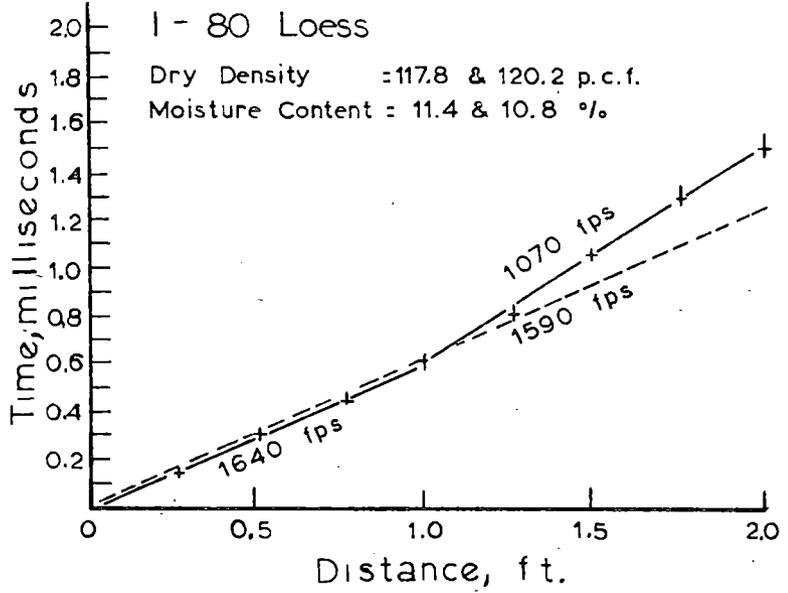
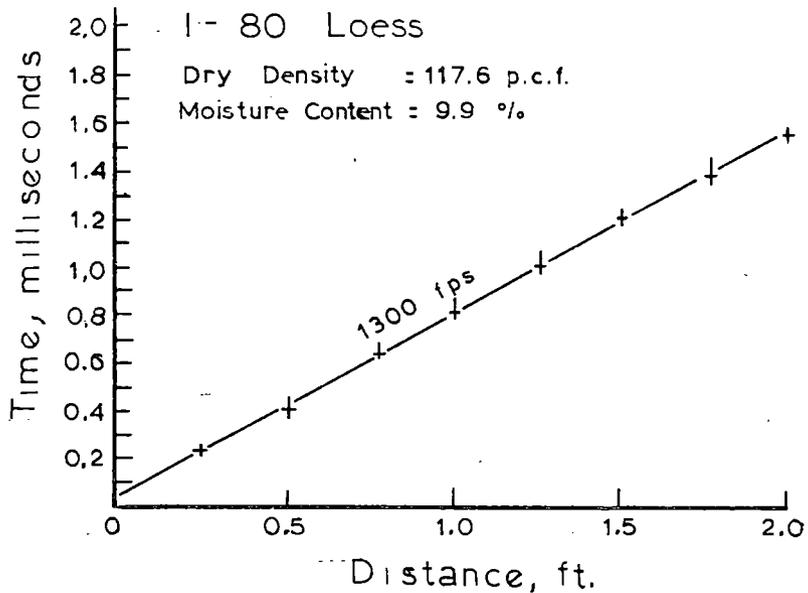


Fig. 18. I-80 loess.

Table 2. Summary of field test results (no correction for delay).

Field test	Velocity (fps)	Soil	Measured moisture content (%)	Compactive effort	Seismic density (pcf)	Measured dry density (pcf)
1	1980	I-35	8.5	1.8	122.4 ^a	129.5
2	2366	I-35	8.9	1.9	123.6 ^a	129.0
3	1187	I-35	8.6	0.4	114 ^a	125.4
4	1204	I-35	8.1	0.7	115 ^a	127.2
5	1163	I-35	8.5	0.5	114 ^a	130.2
6	1910	I-35	6.7	2.1	119 ^a	124.2
7	3040	I-35	6.9	4.6	128.4 ^a	130.1
8	1100	I-35	8.6	0.5	115 ^a	117.4
9	1165	I-35	6.9	1.1	113 ^a	119.5
10	1570	I-35	12.5	< 1	< 119 ^a	113.3
11	1570	I-35	11.9	< 1	< 121 ^a	118.4
12	2470	I-35	12.2	5	121 ^a	120.7
13	1590	I-35	13.4	< 1	< 118 ^a	112.0
14	1094	Grfd gr	10.6	< 1	< 108 ^a	111.7
15	1094	Grfd gr	8.0	< 1	< 108 ^a	106.6
16	917	Grfd gr	9.3	< 1	< 108 ^a	108.7
17	1370	Grfd gr	10.5	< 1	< 108 ^a	106.3
18	2630	Grfd br	10.6	1.5	104 ^a	118.8
19	1510	Grfd br	10.5	< 1	< 101 ^a	111.5
20	1920	Grfd br	12.2	< 1	< 102 ^a	123.5
21	1180	I-80	13.2	< 1	< 102 ^a	102.2
22	2200	I-80	14.5	< 1	< 105 ^a	103.8
23	1160	I-80	13.7	< 1	< 104 ^a	105.0

Table 2. Cont.

Field test	Velocity (fps)	Soil	Measured moisture content (%)	Compactive effort	Seismic density (pcf)	Measured dry density (pcf)
24	1150	I-80	16.5	(3.2)	(111) ^a	102.8
25	1160	I-80	12.6	< 1	< 103 ^a	106.1
26	1400	I-80	13.4	< 1	< 103 ^a	104.6
27	1110	I-80	12.6	< 1	< 103 ^a	107.4
28	1430	I-80	14.2	(5)	(114) ^a	104.0
29	1220	I-80	15.0	(4)	(111) ^a	104.8
30	1380	I-80	10.6	< 1	< 100 ^b	118.4
31	1710	I-80	13.9	(5)	(116) ^b	112.8
32	1410	I-80	15.6	(3)	(112) ^b	109.4
33	1300	I-80	9.9	< 1	< 99 ^a	117.6
34	1640	I-80	10.8	1	100 ^a	117.8
35	1120	I-80	13.2	< 1	< 103 ^a	103.8

^aSeismic density test taken up to several days following field compaction.

^bSeismic density test taken immediately following field compaction.

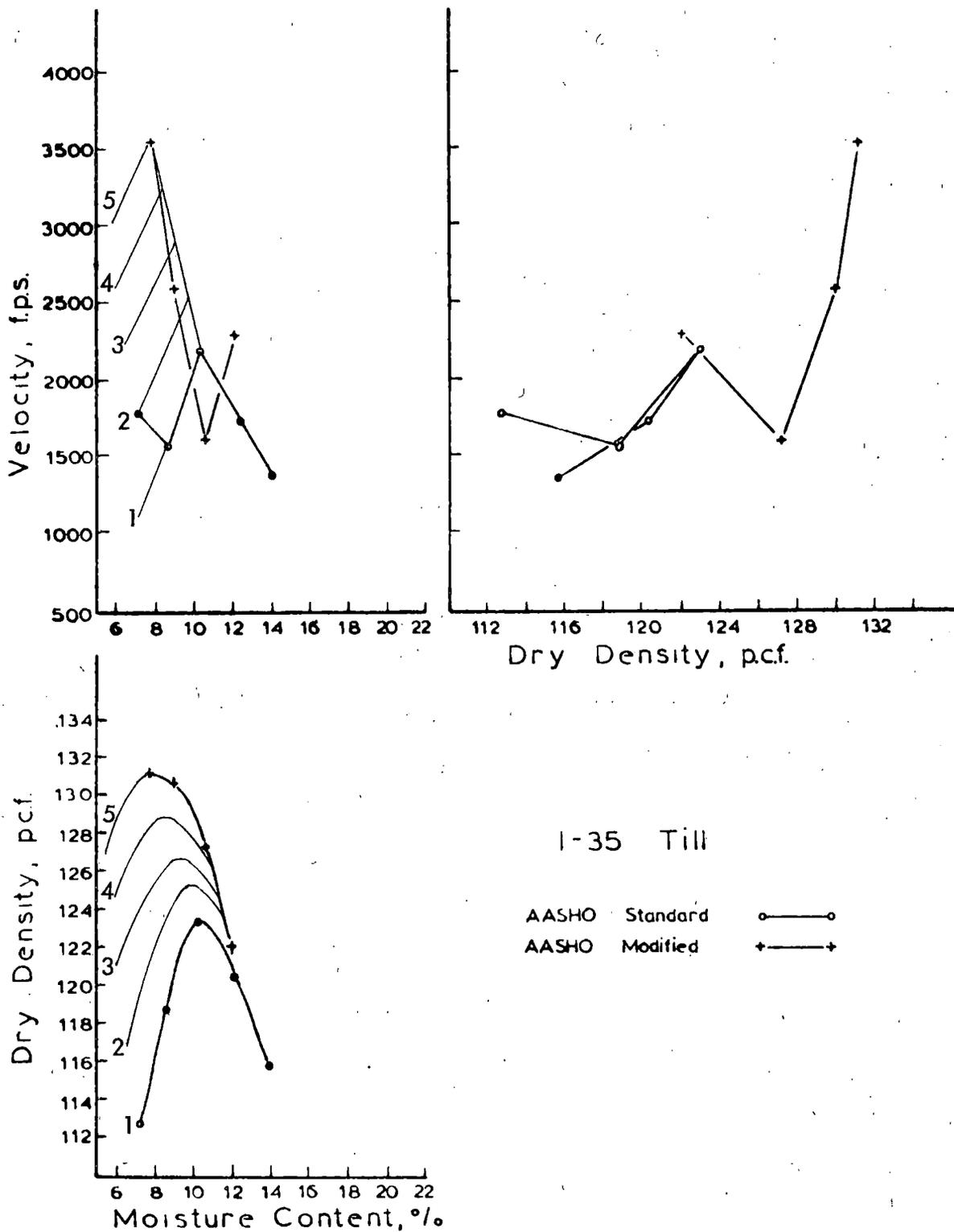


Fig. 19. I-35 till.

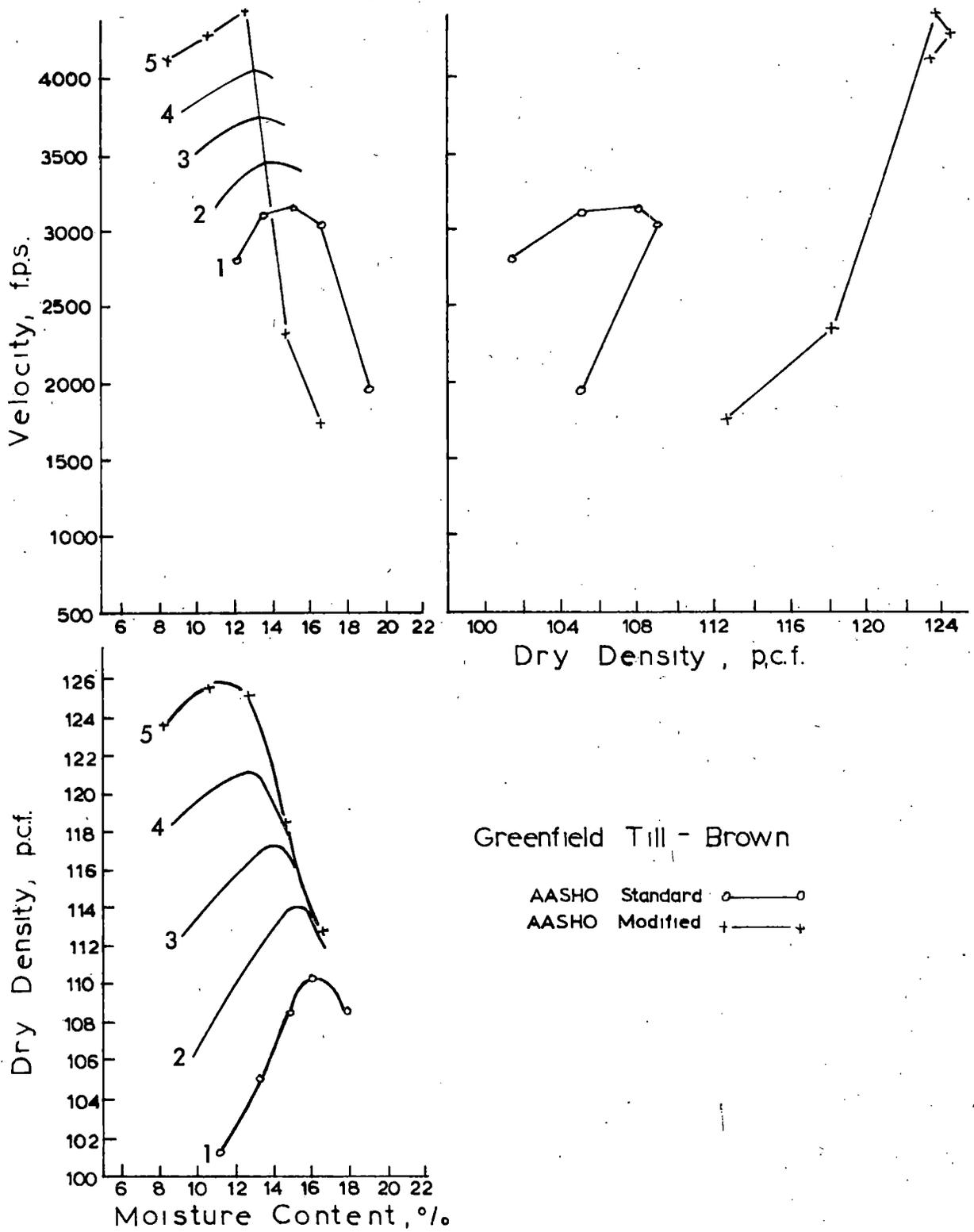


Fig. 20. Greenfield till - brown.

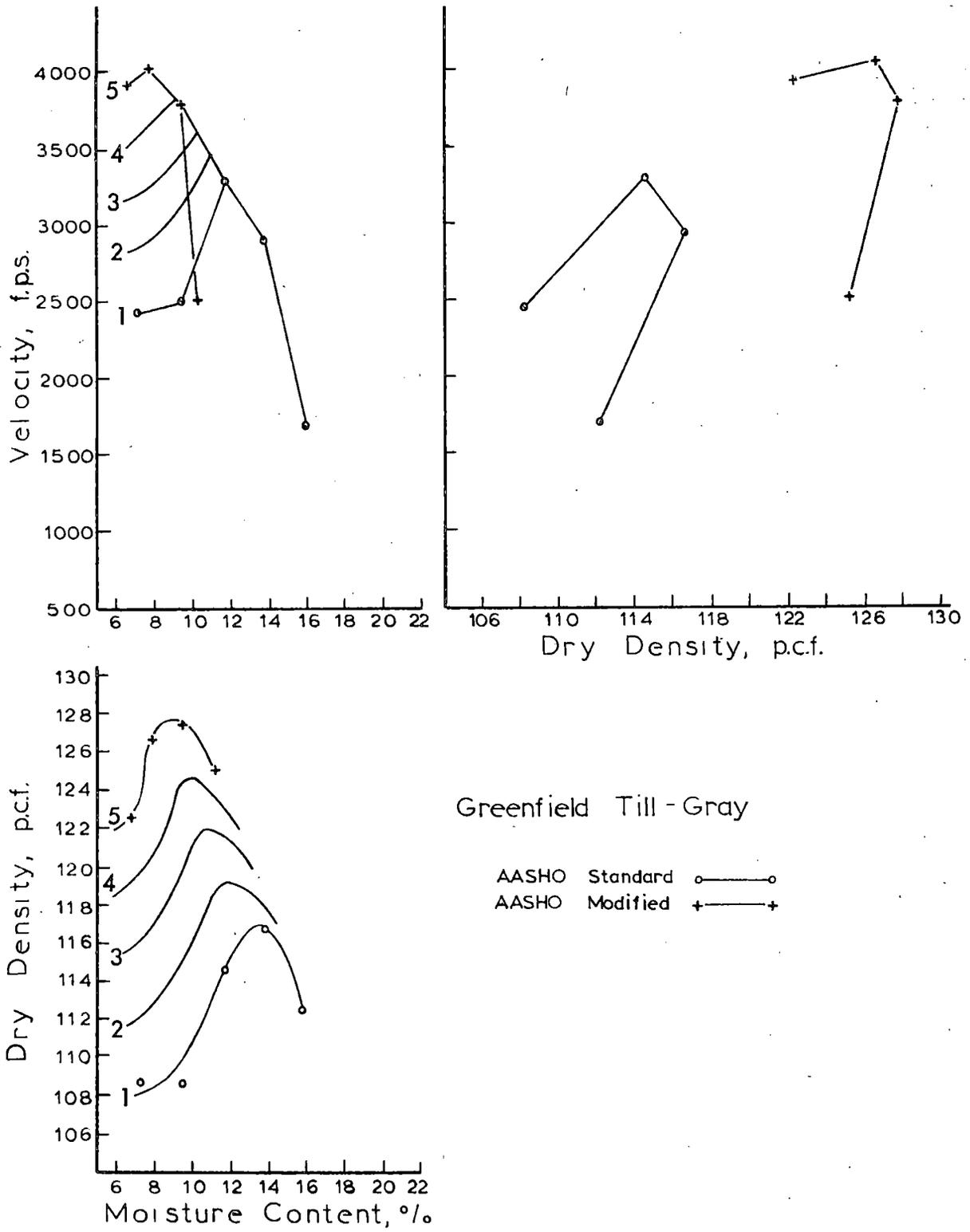


Fig. 21. Greenfield till - gray.

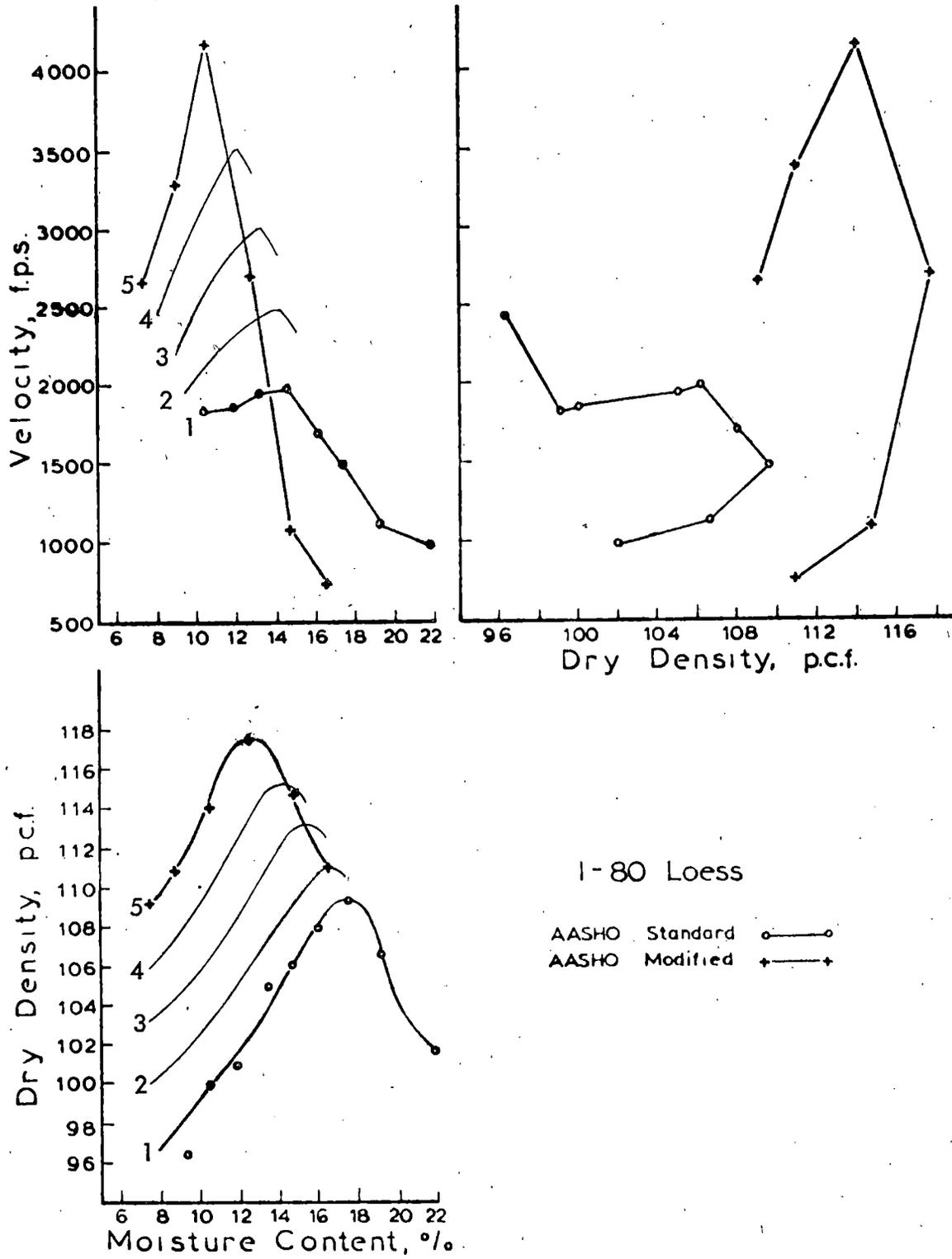


Fig. 22. I-80 loess.

CONCLUSIONS

1. Seismic velocity versus moisture content curves for standard and modified Proctor compacted laboratory soil specimens are similar in shape to dry density versus moisture content curves, but peak with about $1.2 \pm 0.9\%$ lower moisture content, the \pm entry indicating one standard deviation on the mean.
2. The seismic velocity versus moisture content curves are very sensitive to overcompaction, i.e., when compaction proceeds at too high a moisture content, shearing the soil and dispersing the clay. The method therefore does not appear to be usable for measurement of density when the moisture content greatly exceeds the optimum for compaction.
3. Field velocities obtained in this study in all cases are too low for a reliable estimation of field density from laboratory seismic data. Subsequent laboratory tests indicated that the reason is a gradual reduction in velocity upon aging, apparently because of gradual absorption of pore water into the expandable interlayer region of the clay. Seismic tests therefore should be conducted immediately after compaction or the results become meaningless.

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