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FINAL REPORT - PART 2 OF 2

SEISMIC WAVE VELOCITY AS A MEANS OF IN-PLACE DENSITY MEASUREMENT

Project HR - 114 of the
Iowa Highway Research Board
conducted by
Engineering Research Institute,
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for
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in cooperation with Federal Highway
Administration Bureau of Public Roads

Co-Project Directors
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ENGINEERING RESEARCH INSTITUTE
IOWA STATE UNIVERSITY AMES

SEISMIC WAVE VELOCITY AS A MEANS OF IN-PLACE DENSITY MEASUREMENT

J. M. Hoover and R. L. Handy

INTRODUCTION

As noted in Part 1 of this report, the objective of the investigation was to apply principles of first-arrival seismic refraction to the problem of more quickly determining in-place dry density in highway materials. Part 1 of the report indicated the following generalized conclusions based on laboratory and limited field tests:

1. Seismic velocity versus moisture content curves for laboratory compacted soil specimens were similar in shape to dry density versus moisture content curves but peaked out at a lower moisture content.
2. The method did not appear usable for measurements of density when the moisture content greatly exceeded the optimum for compaction.
3. Seismic tests should be conducted immediately after compaction or the results may be meaningless due to an apparent gradual absorption of pore water into expandable interlayer regions of the clays, thus flattening the velocity versus moisture content curve.

Part 2 of the report, contained herein, presents the results of both additional laboratory development of test techniques, plus extensive field test data. For the benefit of the reader and to avoid unnecessary repetition of information, all figures, tables and references are numbered in a sequence continuing from Part 1.

EQUIPMENT MODIFICATION

As noted in Part 1, modifications to the first timing system used in the project (Model MD-3 Refraction Timing Unit, Fig. 1) consisted primarily of changing the impact source, the energy coupling with the soil, and the timing circuitry, in an attempt to accomplish the following:

a. Utilize the timer with laboratory specimens with a maximum travel distance of 4-1/3 in.

b. Improve reproducibility of results.

Use of a miniature drop hammer gave some improvement, but most of the modifications failed to alleviate the problems. A major difficulty was in adapting the geophone to detect reliable first-arrival waves through a laboratory Proctor specimen.

The second refraction system, a Model 217 Micro-Seismic Timer, Figs. 2, 3, and 4 employed a stable oscillator measuring time in microseconds and a crystal phonograph cartridge and needle as the detector. This gave much more reproducible results when a flathead wire pin was driven flush into the soil and the needle pickup was placed in direct contact with the head of the pin.

During the initial portion of the field tests presented later in this report, it was noted that the impact source and the use of pins or no pins at the pickup had a definite effect on reproducibility of results. It was therefore decided to develop a more constant energy input to maintain a more constant initial amplitude at the impact source, so the amplitude received by the needle would trigger the threshold of the timer at the same instant of energy pulse.

Mereu et al.,[13] using steel spheres both as couplers and falling impact weights, proposed a relationship between the amplitude of the seismic wave and the velocity attained by the embedded coupler after impact:

$$A = K V_c$$

where

A = amplitude of seismic wave

K = a proportionality constant

V_c = maximum speed of the embedded coupler.

Using simple collision theory the above expression becomes

$$A = K(1 + e) \frac{m}{M + m} u$$

where

e = coefficient of restitution between coupler and impact device

m = mass of impact device

M = mass of coupler

u = speed of falling weight at time of impact.

Using the principles noted above, but employing an impact device consisting of a rotating instrument rather than a falling weight, the expression becomes

$$A = K(1 + e) \frac{m}{M(\frac{a}{r})^2 + m} (a\omega)$$

where

a = distance from point of gyration to point of impact

r = radius of gyration with respect to the axis of gyration

ω = angular velocity.

A rotating hammer was constructed, utilizing much the same drop action principle as a liquid limit device, except that the cup was replaced by a steel bar, the tip of which dropped on a steel sphere embedded in the soil.

A series of tests was conducted using a beam sample of soil, an oscilloscope, the rotating hammer, several sizes of spherical couplers, and the Micro-Seismic Timer pickup unit, Fig. 3. Wave shapes were repeatable for each combination of coupler and same relative position of impact source and pickup unit.

Since an oscilloscope is not the most desirable apparatus for field testing purposes, a similar study was conducted in cooperation with the ERI Electronics Shop, substituting the timer for the oscilloscope. It was determined that the threshold level of the timer was too wide to provide the amplitude discrimination required to accomplish fully consistent timer readings.

Consequently, the rotating hammer was found unsuitable for use in the field test program then underway, and was abandoned in favor of continued field use of the small brass hammer.

FIELD TESTS

In cooperation with Iowa State Highway Commission and various County Engineer personnel, twenty-six field tests were conducted throughout the state. Table 3 presents a summary of the general location, pavement structure, tests conducted, and classification of materials involved. Note that the soils encountered ranged from A-1-a to muck classifications, and included asphalt-treated base materials.

The concept of this portion of the project was to establish, as realistically as possible, the conditions of test encountered by field inspectors. The following procedures were adopted.

1. Seismic test. Conducted with the Model 217 Micro-Seismic Timer, using the hand-held brass hammer as impact source on a 3/4-in. diam. steel ball coupler. Contact between pickup needle and soil was a flathead pin. Triggering of the timer unit was created by completion of electrical circuitry at the instant of impact between hammer and coupler as shown in Fig. 2 with the exception that the aluminum foil was eliminated, one side of the circuit being connected directly to the ball. The ball was initially forced one-half its diameter into the material to be tested. A series of 10 to 15 blows and observed times, in microseconds, were recorded for each 3.00-in. distance up to 2.00 ft from impact source to pickup unit. The pickup unit was maintained in one position, while the coupler was moved the required distances.*

*It was evident early in the field tests that considerable time was required to move and adjust the pickup unit so that its needle was in proper contact with each pin.

Table 3. Field test sites, materials, and classifications.

Sample no.	Location	Pavement structure	Generalized material	Material additives	No. of seismic tests	No. of in-place density tests	L.L. (%)	P.I (%)	AASHO Classification
1	Carroll Co.	Base	Soil-agg.	Asphalt emulsion	2	2	N.D.[b]	N.D.[b]	N.D.[b]
2	Story Co. I-35	Subgrade	Till	—	7	5	20.6	6.2	A-4(2)
3	Wright Co.	Subgrade	Soil-peat-agg.	—	9	5	62.2	32.3	A-7-6(13)
4	Polk Co.	Base	Soil-agg.	Primed	6	2	24.3	9.9	A-4(1)
5	Polk Co.	Base	Soil-agg.	Primed	6	3	30.5	12.2	A-6(2)
6	Cerro Gordo	Subgrade	Soil-agg.	—	6	3	—	N.P.	A-1-a
7	Cerro Gordo	Base	Soil-agg.	—	4	2	31.0	10.2	A-4(1)
8	Howard Co.	Sub-base	Soil-agg.	—	6	3	36.8	14.7	A-6(7)
9	Fayette Co.	Base	Soil-agg.	—	6	3	32.3	14.4	A-2-6(1)
10	Fayette Co.	Base	Hot-mix	Asphalt	15	10[a]	N.D.[b]	N.D.[b]	N.D.[b]
11	Polk-D.M. Freeway	Base	Soil-agg.	—	9	7	—	N.P.	A-1-a
12	Cherokee Co.	Base	Soil-agg.	Primed	10	4	37.8	15.6	A-6(2)
13	Cherokee Co.	Base	Soil-agg.	—	30	20[a]	31.3	11.3	A-2-6(0)
14	Plymouth Co.	Base	Cold-mix	Asphalt	6	3-3[a]	N.D.[b]	N.D.[b]	N.D.[b]
15	Sioux Co.	Sub-base	Soil-agg.	—	4	3	39.1	16.6	A-6(4)
16	Hamilton Co.	Base	Soil-agg.	—	12	4-5[a]	22.6	6.1	A-2-4
17	Louisa Co.	Levee	Organic clay[c]	—	3[c]	—	N.D.[b]	N.D.[b]	N.D.[b]
18	Mahaska Co.	Sub-base	Clayey silt	Primed	6	3	46.9	20.5	A-7-6(4)
19	Mahaska Co.	Base	Hot-mix	Asphalt	5[d]	—	N.D.[b]	N.D.[b]	N.D.[b]
20	Clark Co. Ia. 34	Embankment	Clay	—	4	3	41.2	21.7	A-7-6(7)
21	Adair Co.	Sub-base	Clayey sand	—	5	1	27.3	12.1	A-2-6(0)
22	Adair Co.	Base	Hot-mix	Asphalt	5	5[a]	N.D.[b]	N.D.[b]	N.D.[b]
23	Adair Co.	Base	Soil-agg.	Primed	3	2	N.D.[b]	N.D.[b]	N.D.[b]
24	Mills Co.	Embankment	Loess	—	7	7	33.4	13.6	A-6(9)
25	Pottawattamie Co. I-29	Embankment	Loess	—	3	3	36.0	12.3	A-6(9)
26	Harrison I-29	Shoulder base	Sand	—	10	10	—	N.P.	A-1-b

[a] Obtained from inspector — all other in-place tests by rubber balloon.
[b] N.D. = Not determined due to additive content.
[c] Muck. No test completed.
[d] No in-place density data available. Velocities measured as 5391, 5736, 5985, 6048 and 4926 fps.

2. For most sample locations, in-place density tests were conducted using a Rainhart Volumeter rubber balloon device. Duplicate moisture content determinations were made on the materials dug from each hole. Densities of most of the asphalt-treated materials were obtained from county inspectors.
3. With the exception of the asphalt-treated materials, enough additional material was removed from each seismic test location to run a standard Proctor (AASHO T-99) moisture-density curve on site. The Proctor mold was mounted on a concrete block and the standard hammer was hand-held. Two 1-gal. containers of each material were also obtained and returned to Ames for additional tests.
4. All tests were conducted immediately following compaction with the exception of location number 24.

A small mobile lab van was utilized as a field laboratory and provided transportation for the two-man field crew throughout the state.

Results of those field tests considered of any value are summarized in Figs. 23 through 45. Part (a) (the left half) of each figure presents the field lab moisture-density and moisture-velocity curves for each material noted, whereas part (b) of each figure presents the in-place moisture-density and moisture-velocity data.

At each sample location the above test procedures were utilized as closely as possible. As will be noted in the figures however, occasional variations were made.

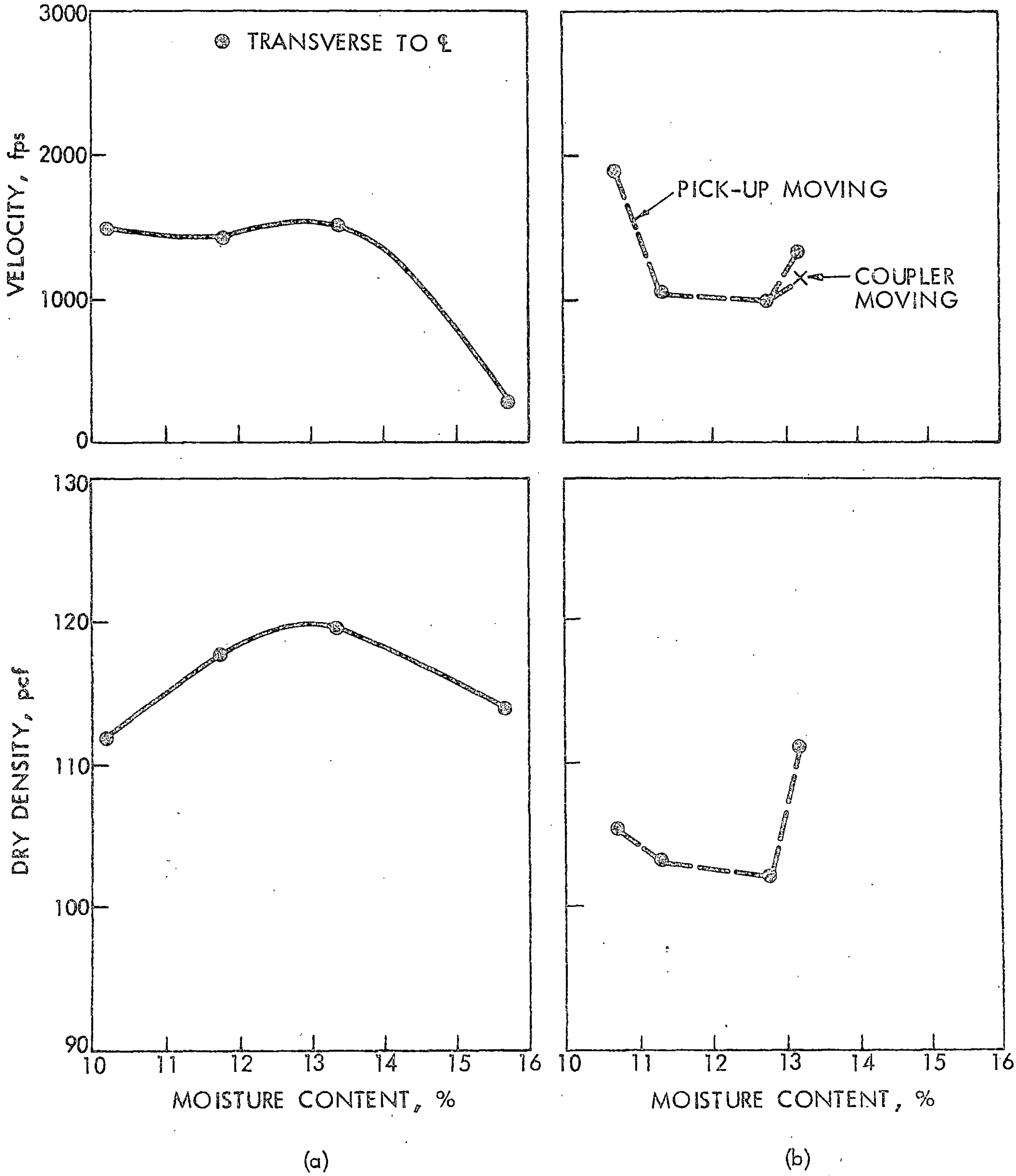


Fig. 23. Field test results, sample location number 2.

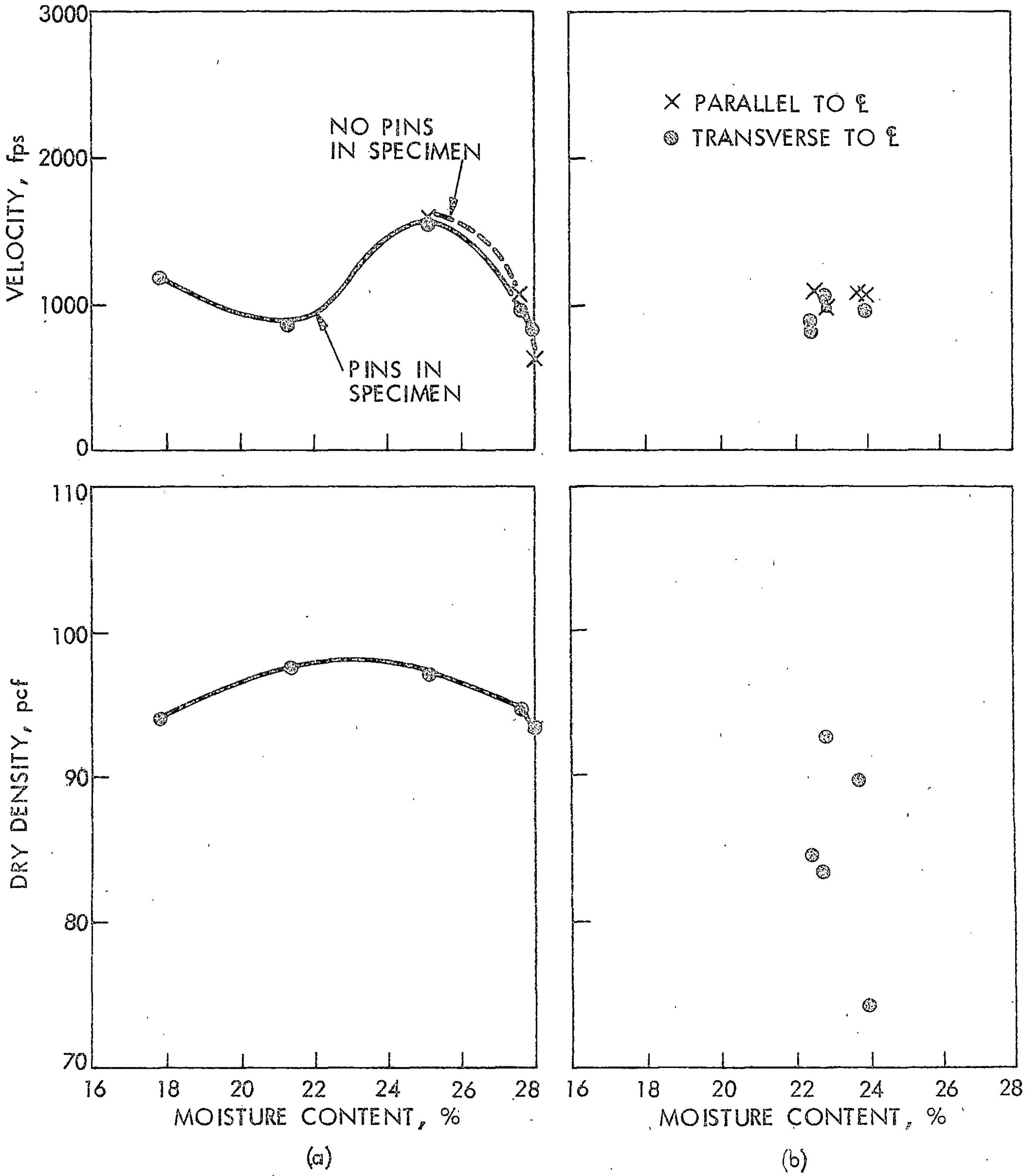


Fig. 24. Field test results, sample location number 3.

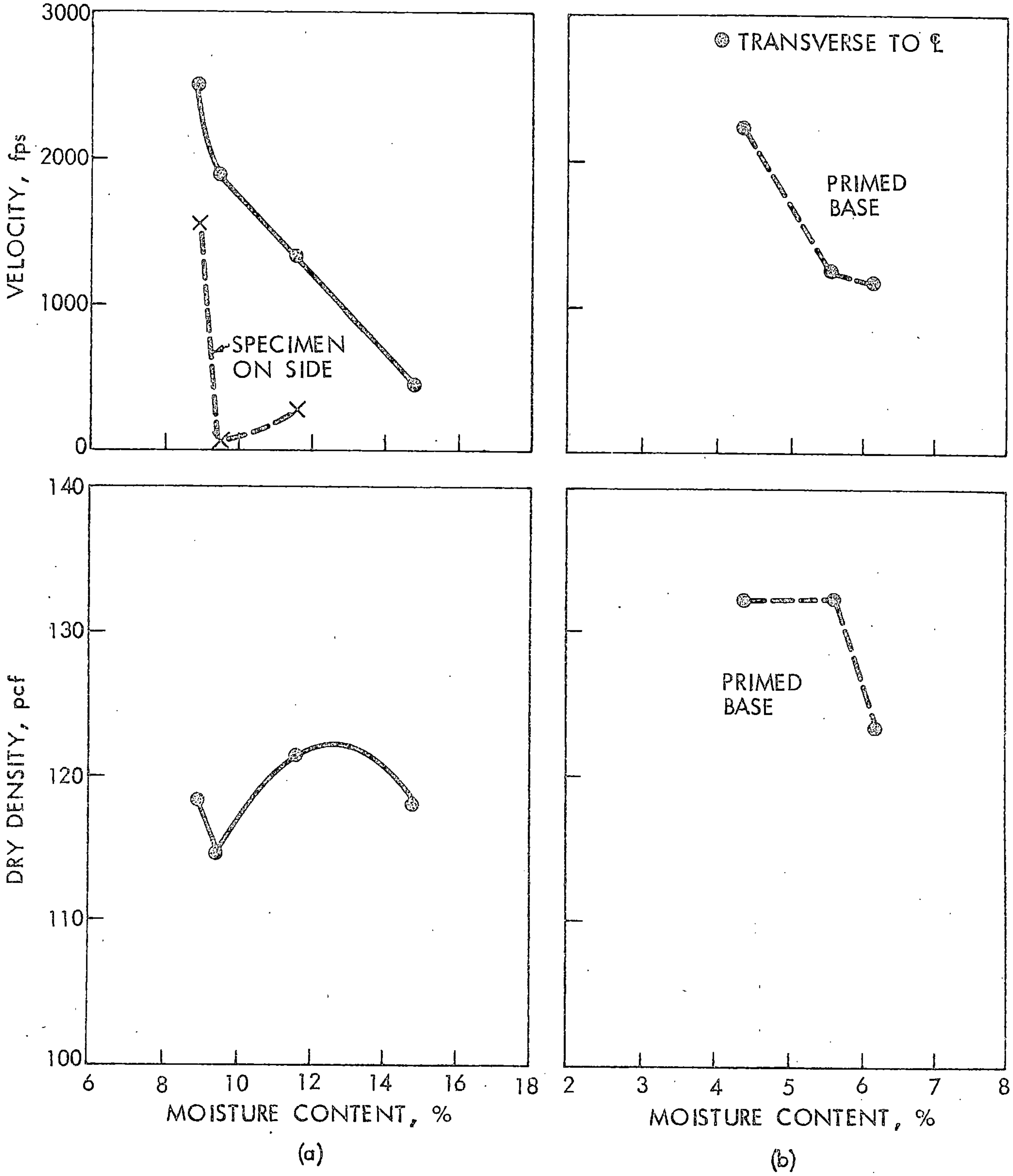


Fig. 25. Field test results, sample location number 4.

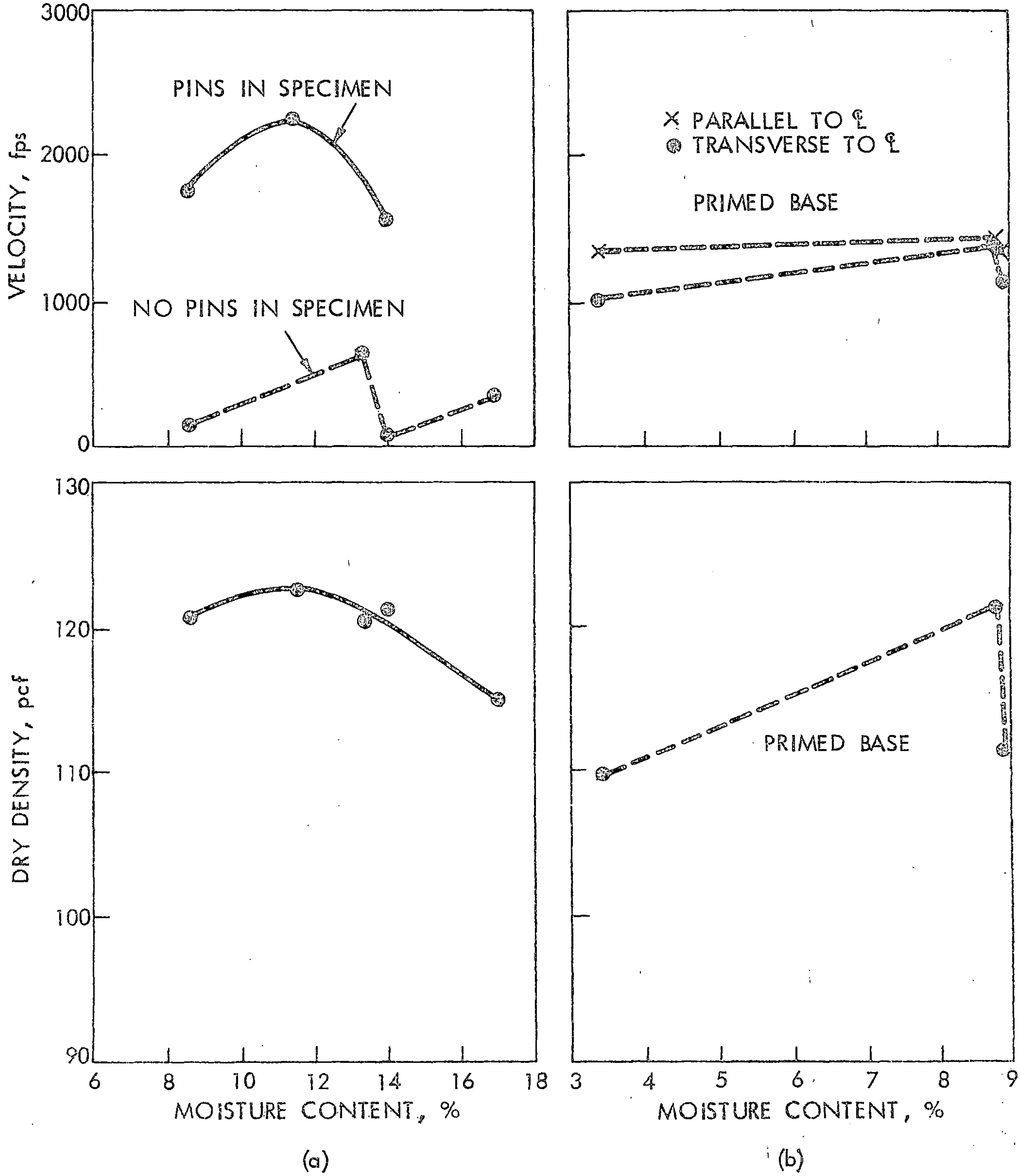


Fig. 26. Field test results, sample location number 5.

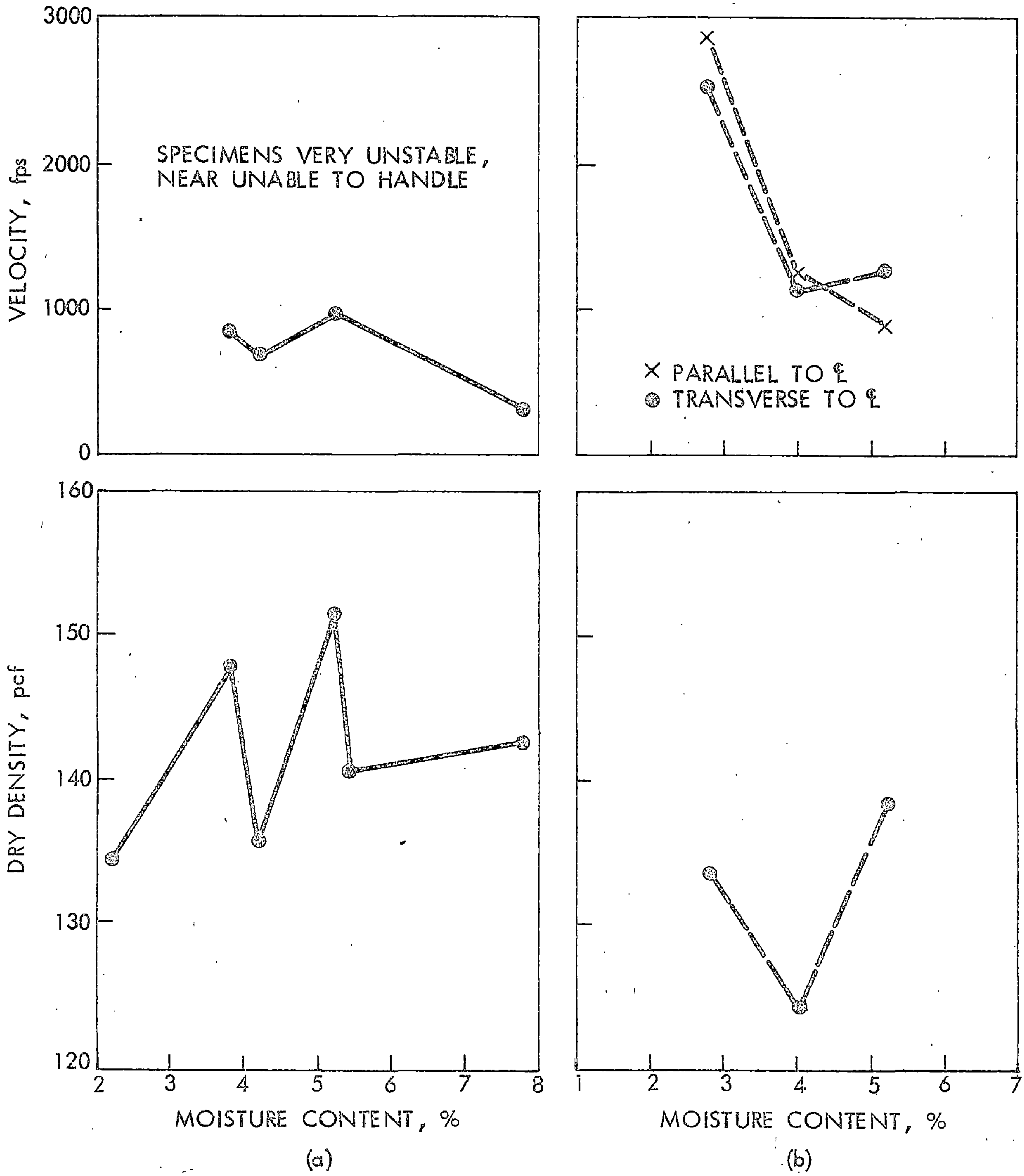


Fig. 27. Field test results, sample location number 6.

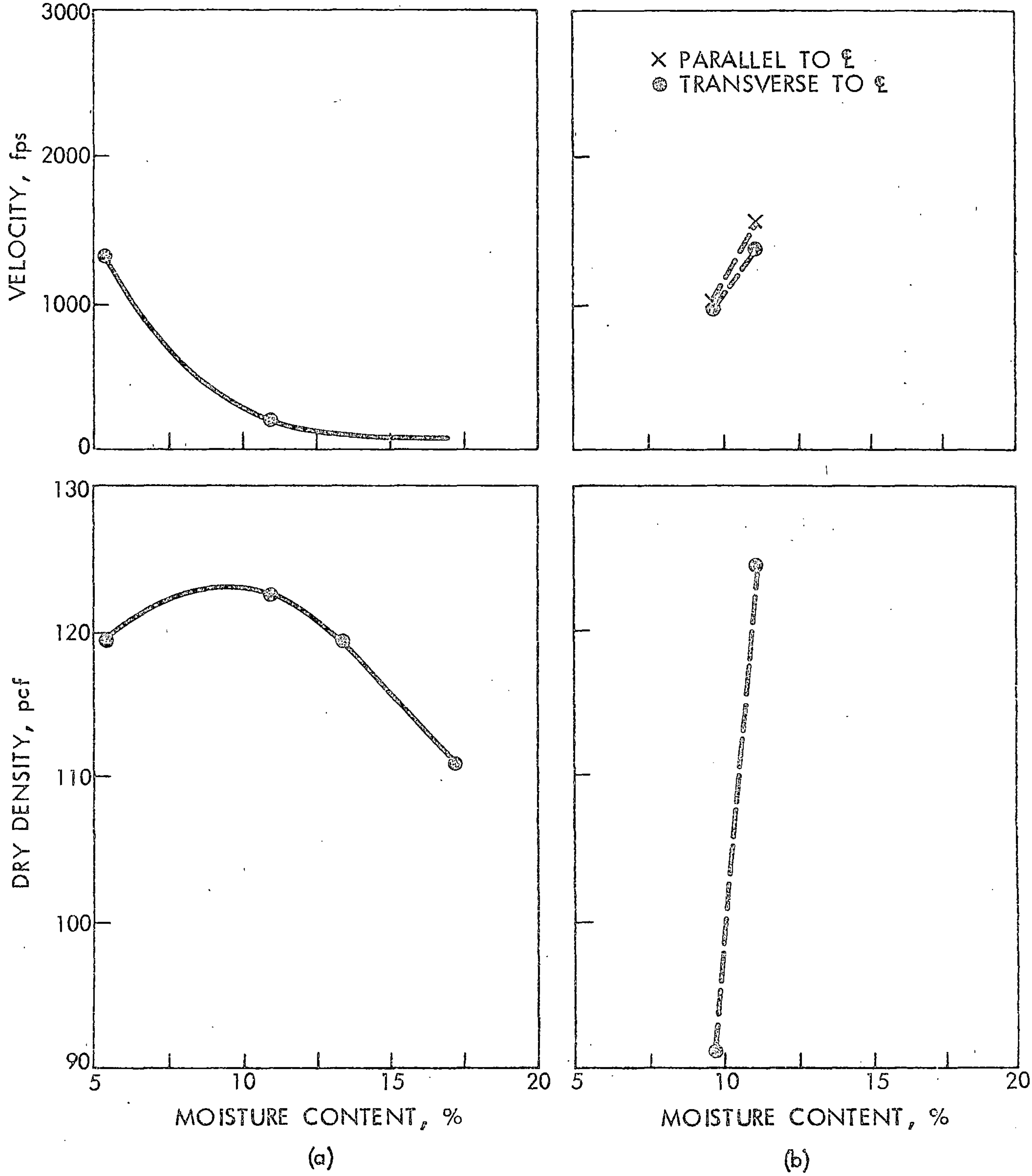


Fig. 28. Field test results, sample location number 7.

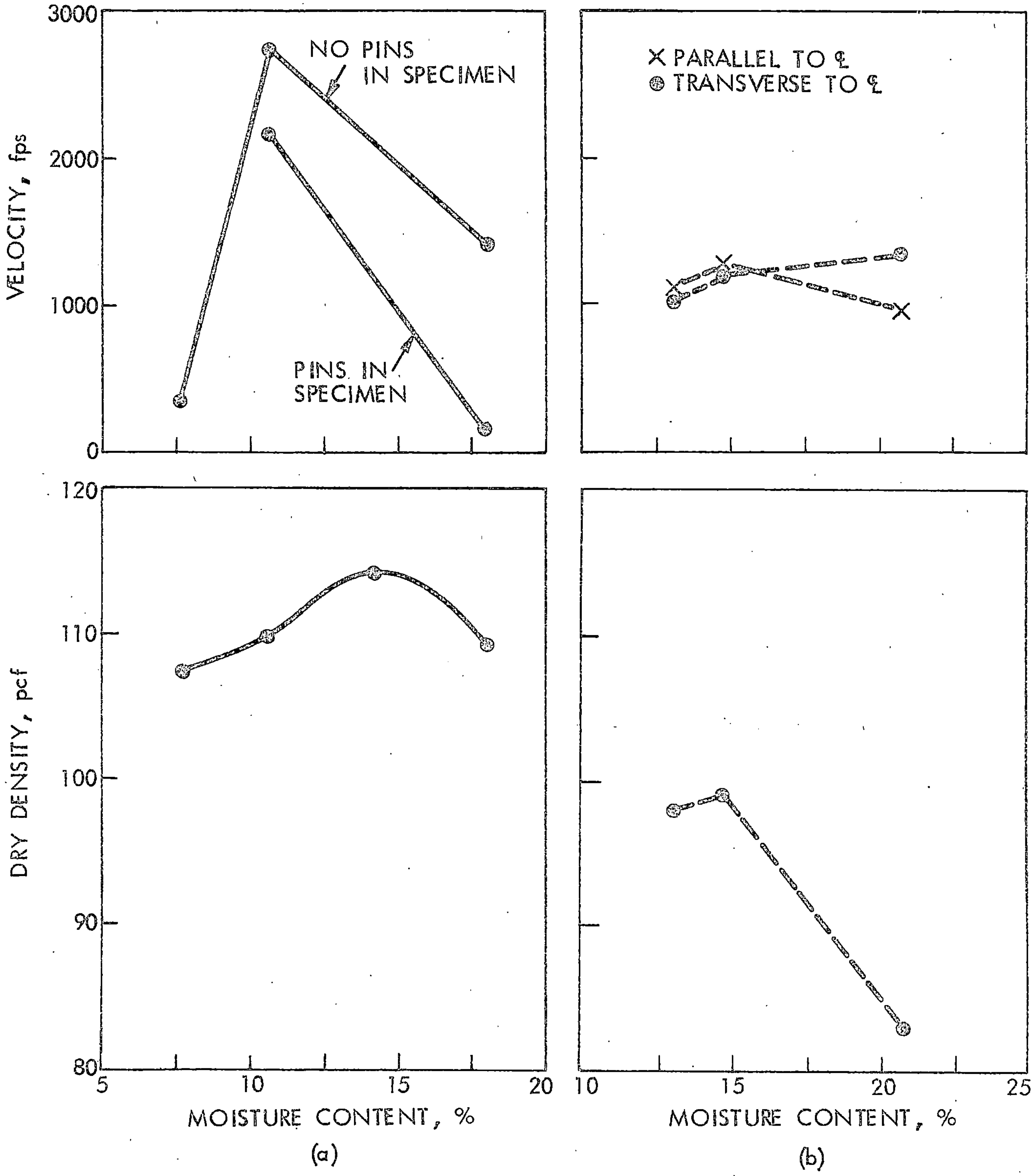


Fig. 29. Field test results, sample location number 8.

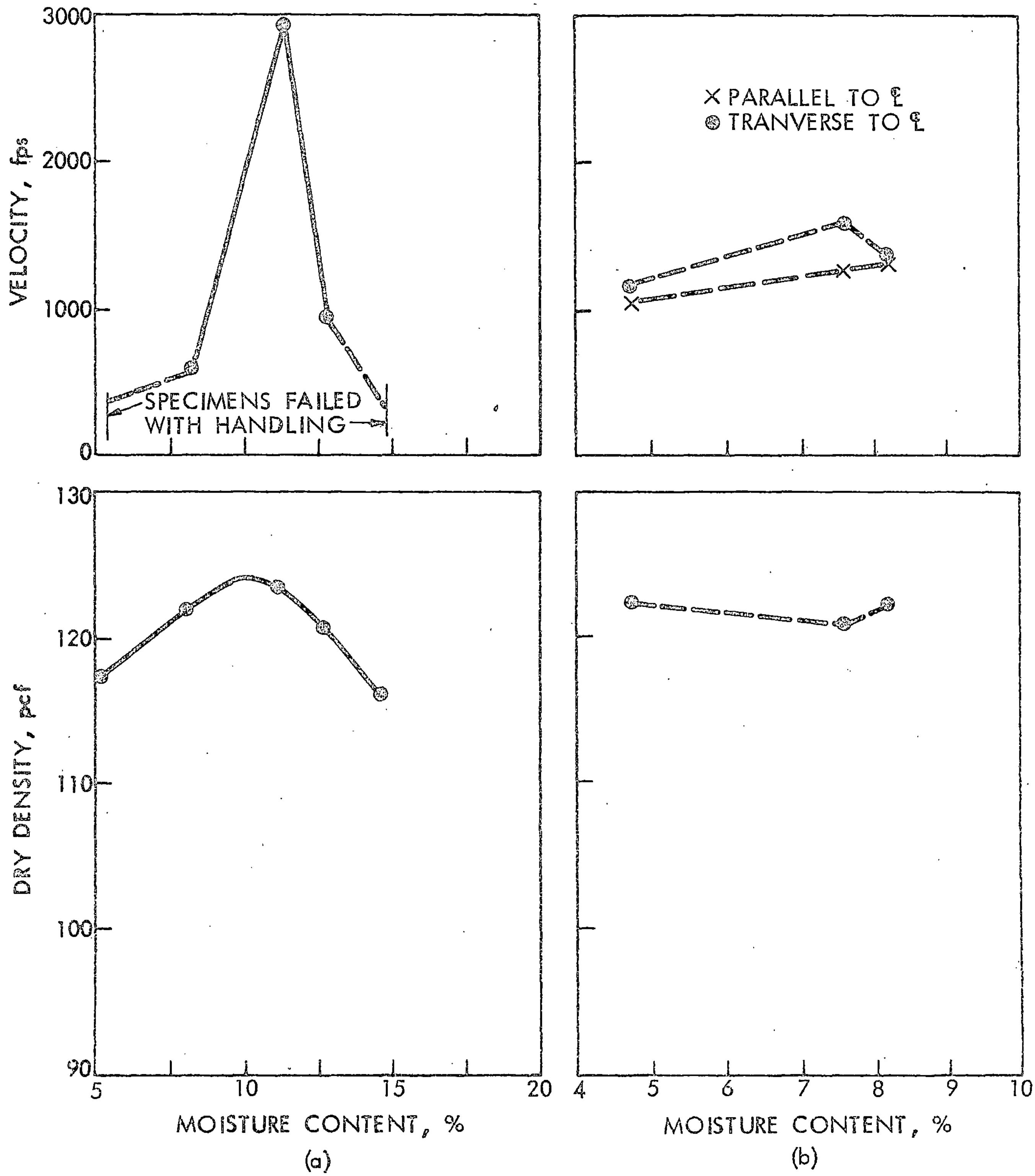


Fig. 30. Field test results, sample location number 9.

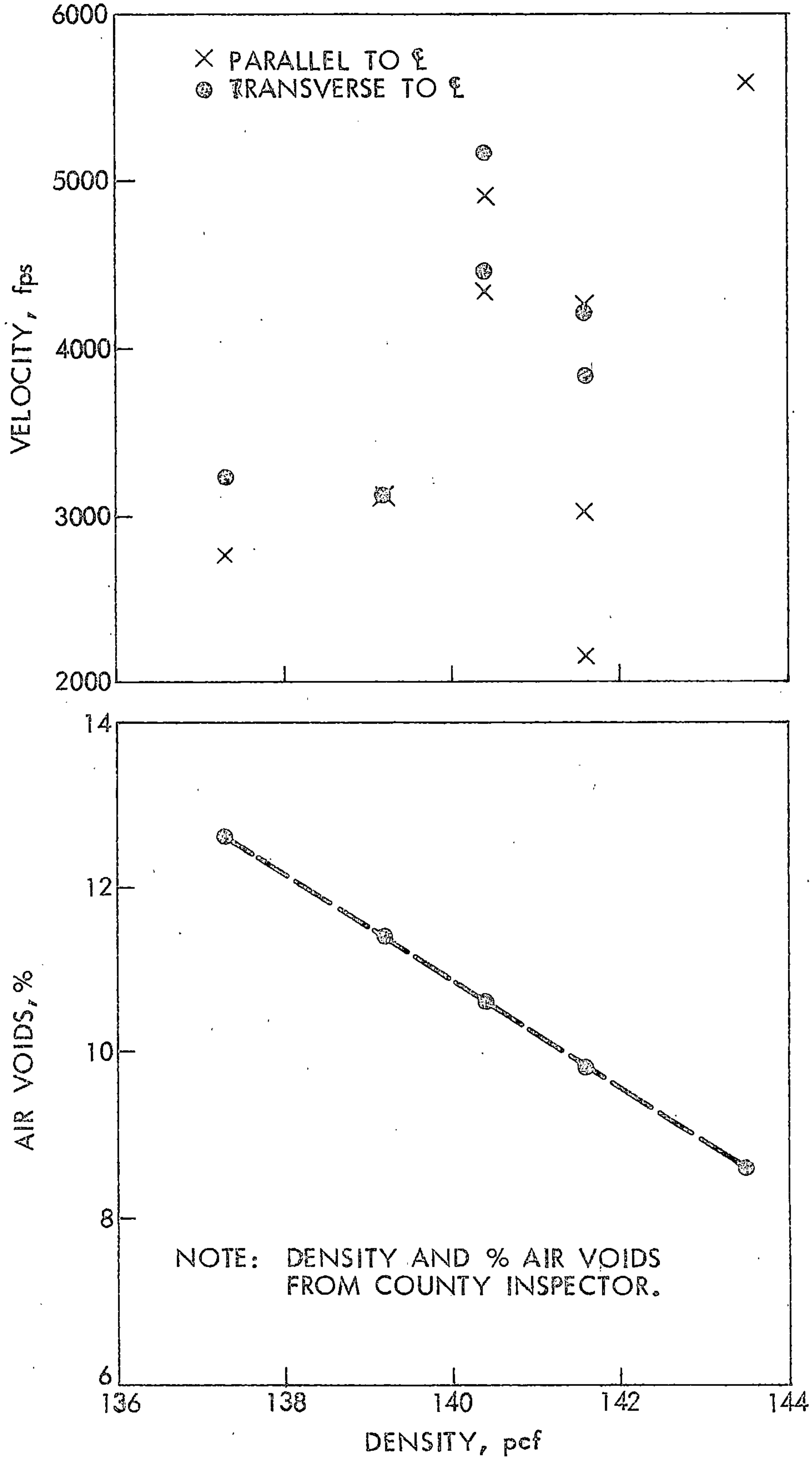


Fig. 31. Field test results, sample location number 10.

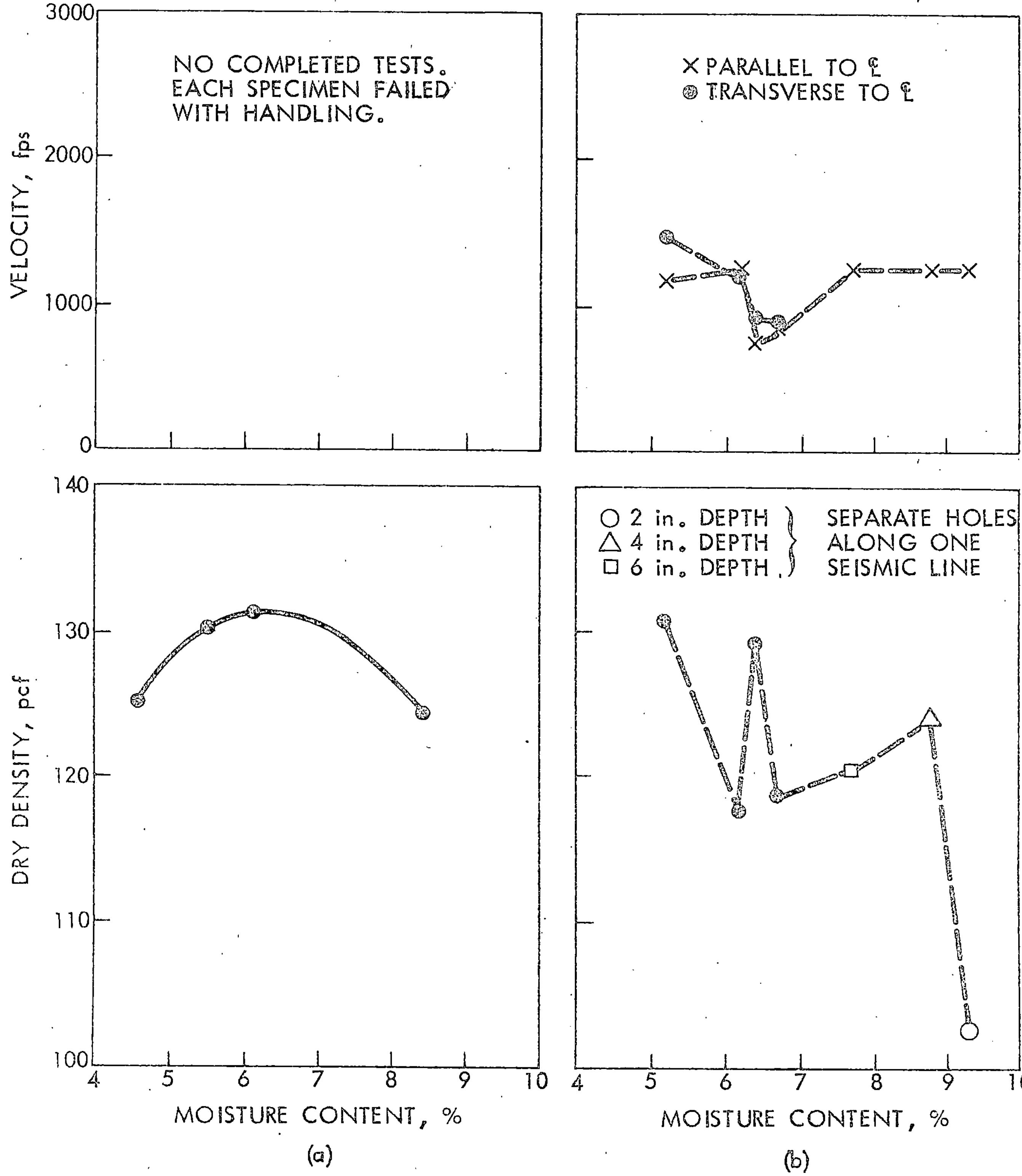


Fig. 32. Field test results, sample location number 11.

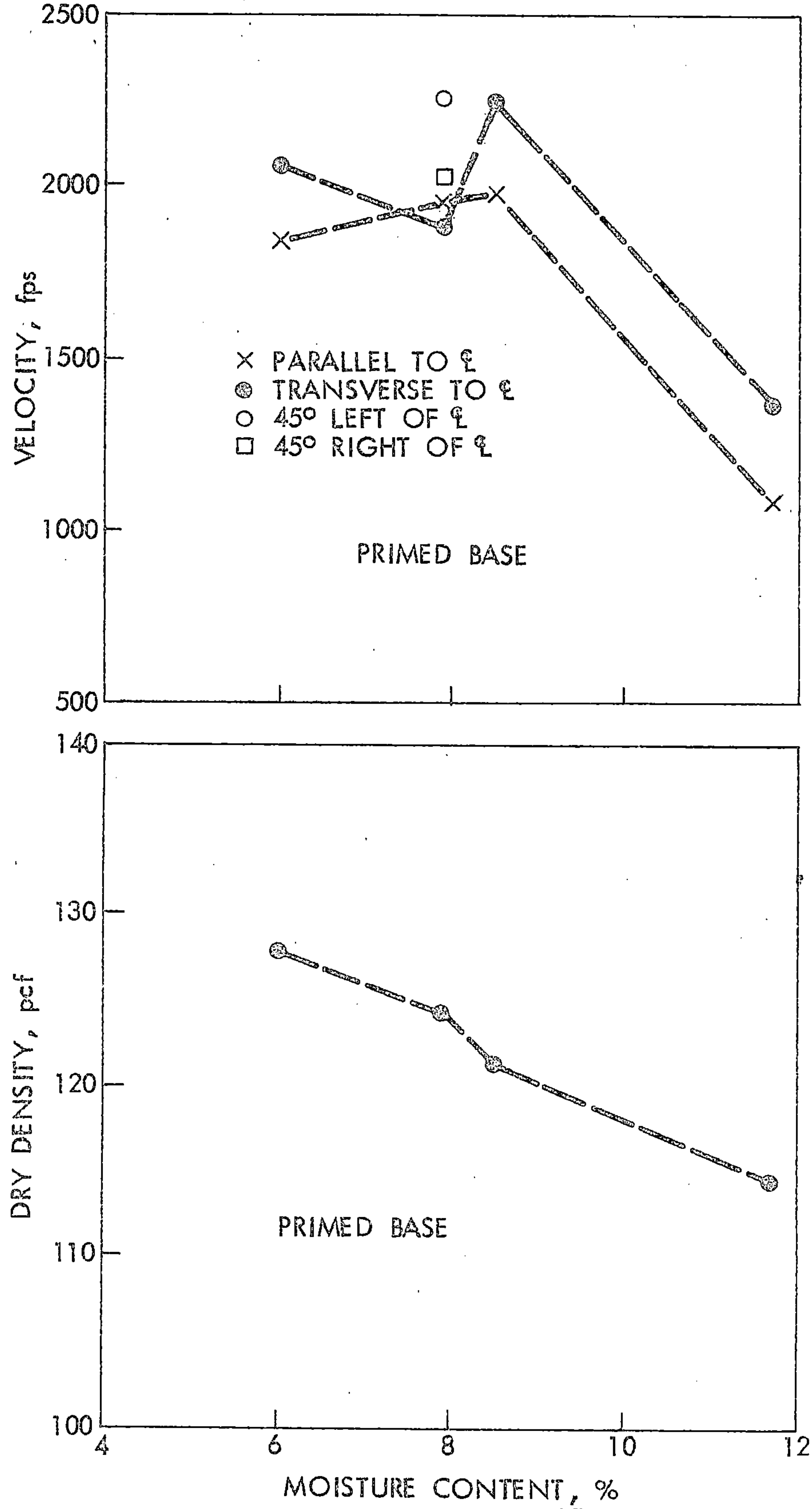


Fig. 33. Field test results, sample location number 12.

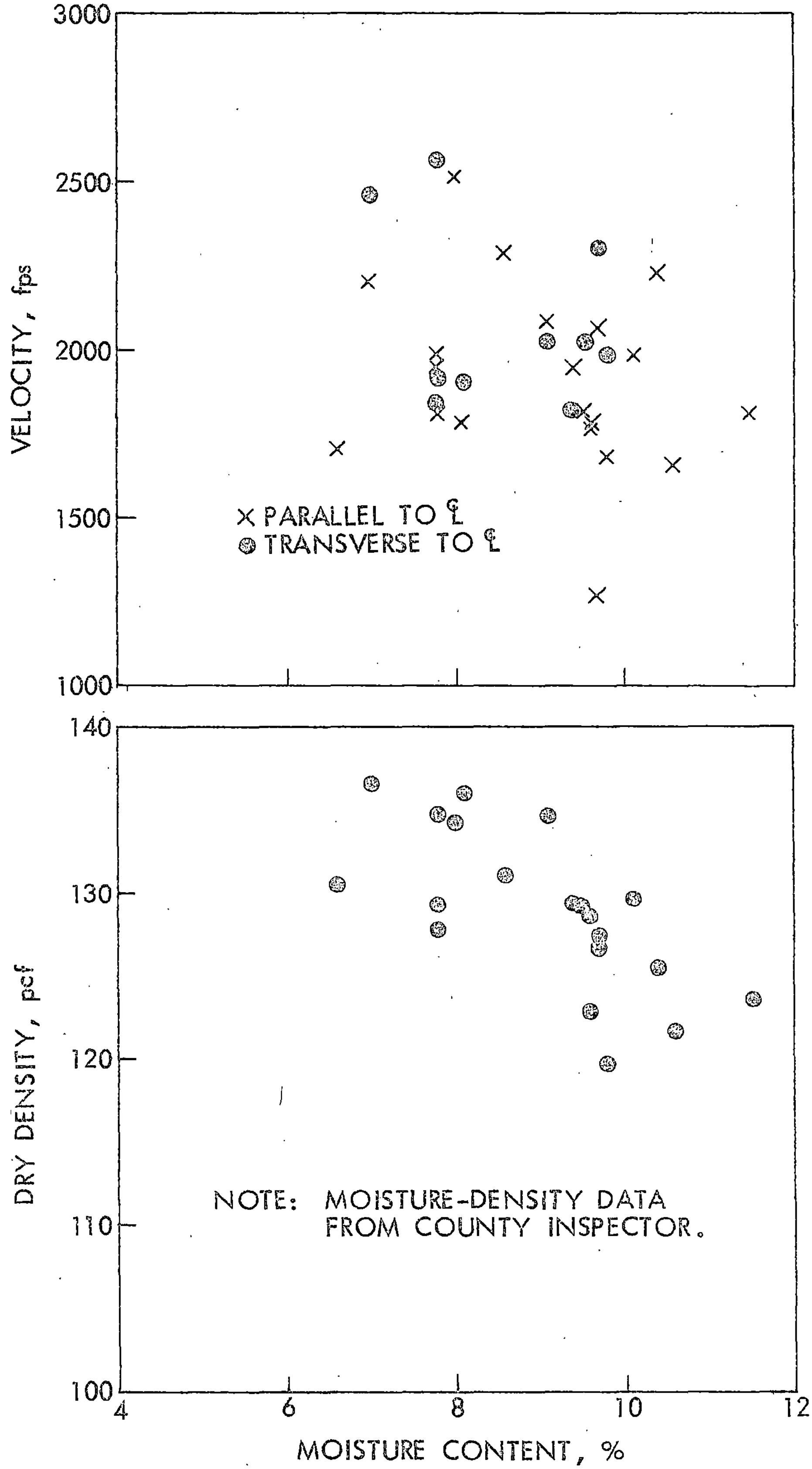


Fig. 34. Field test results, sample location number 13.

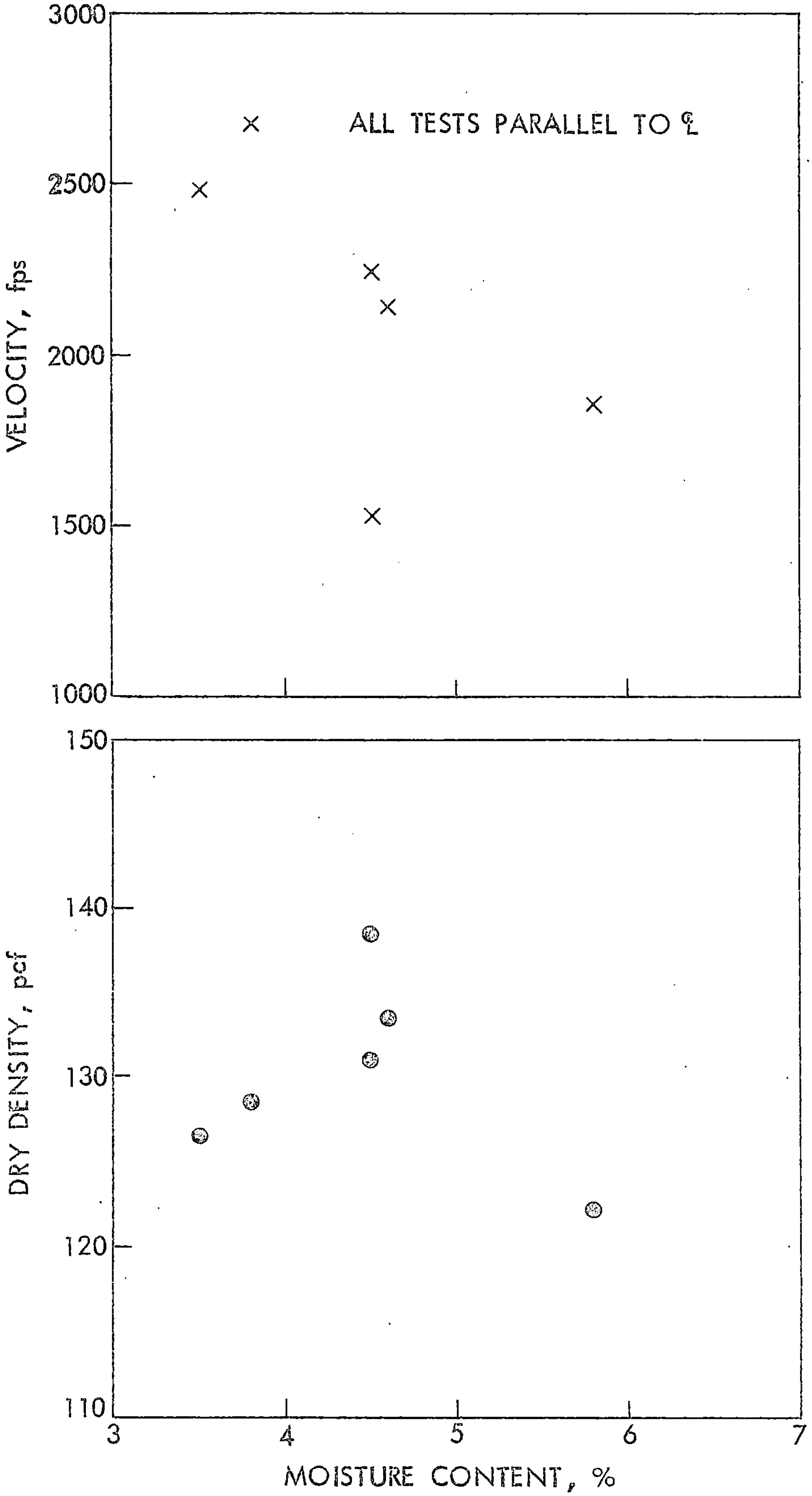


Fig. 35. Field test results, sample location number 14.

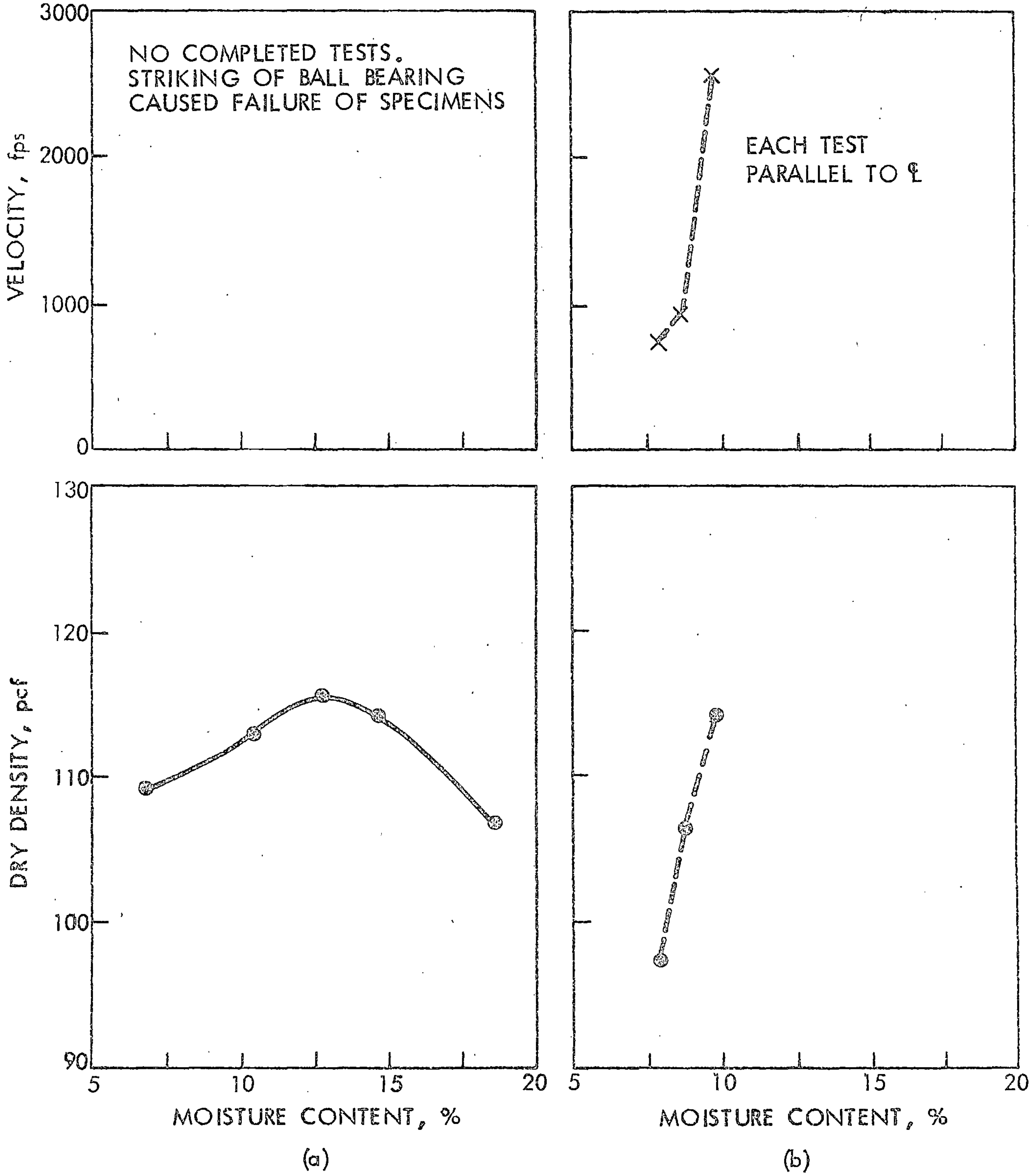


Fig. 36. Field test results, sample location number 15.

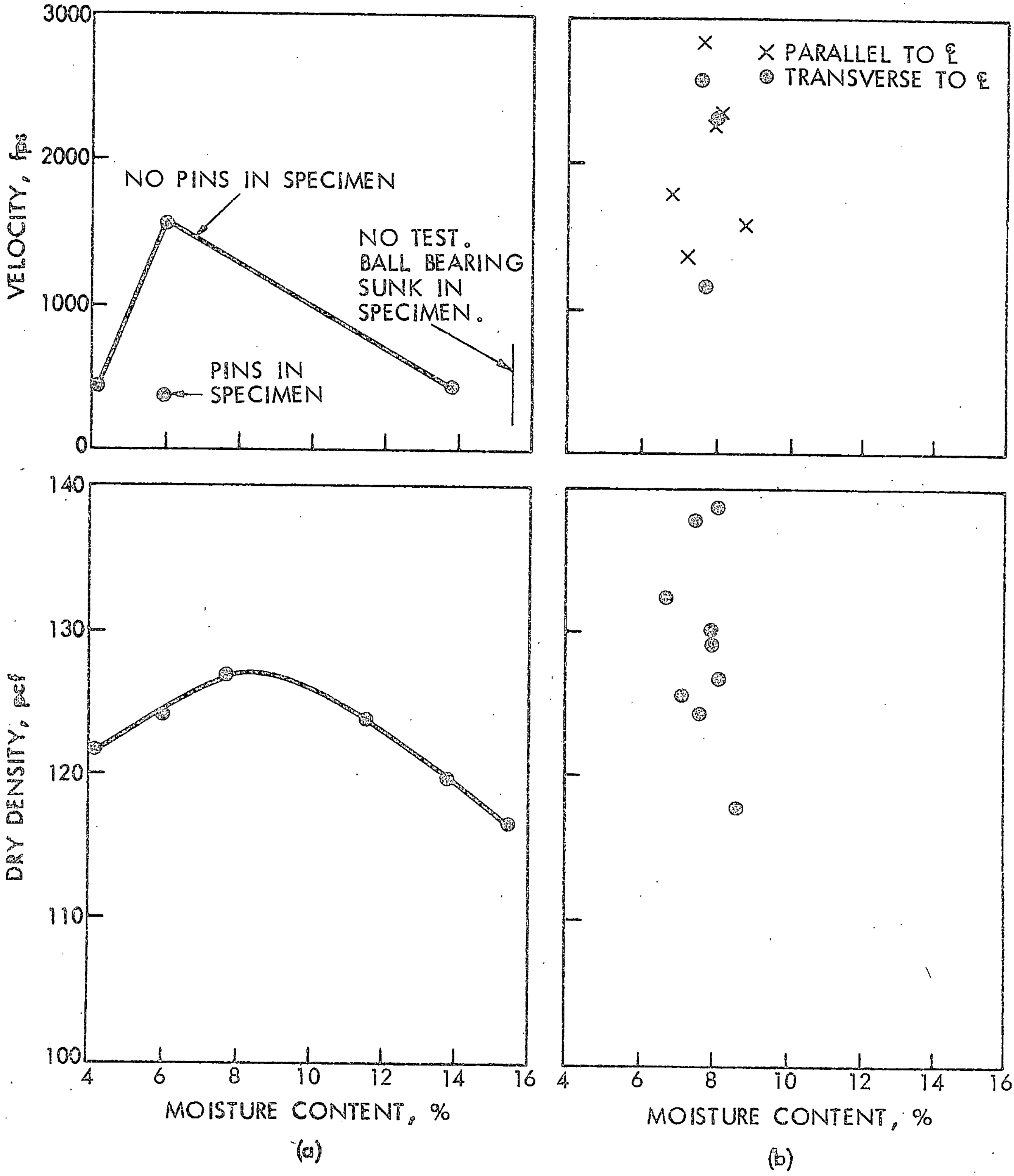


Fig. 37. Field test results, sample location number 16.

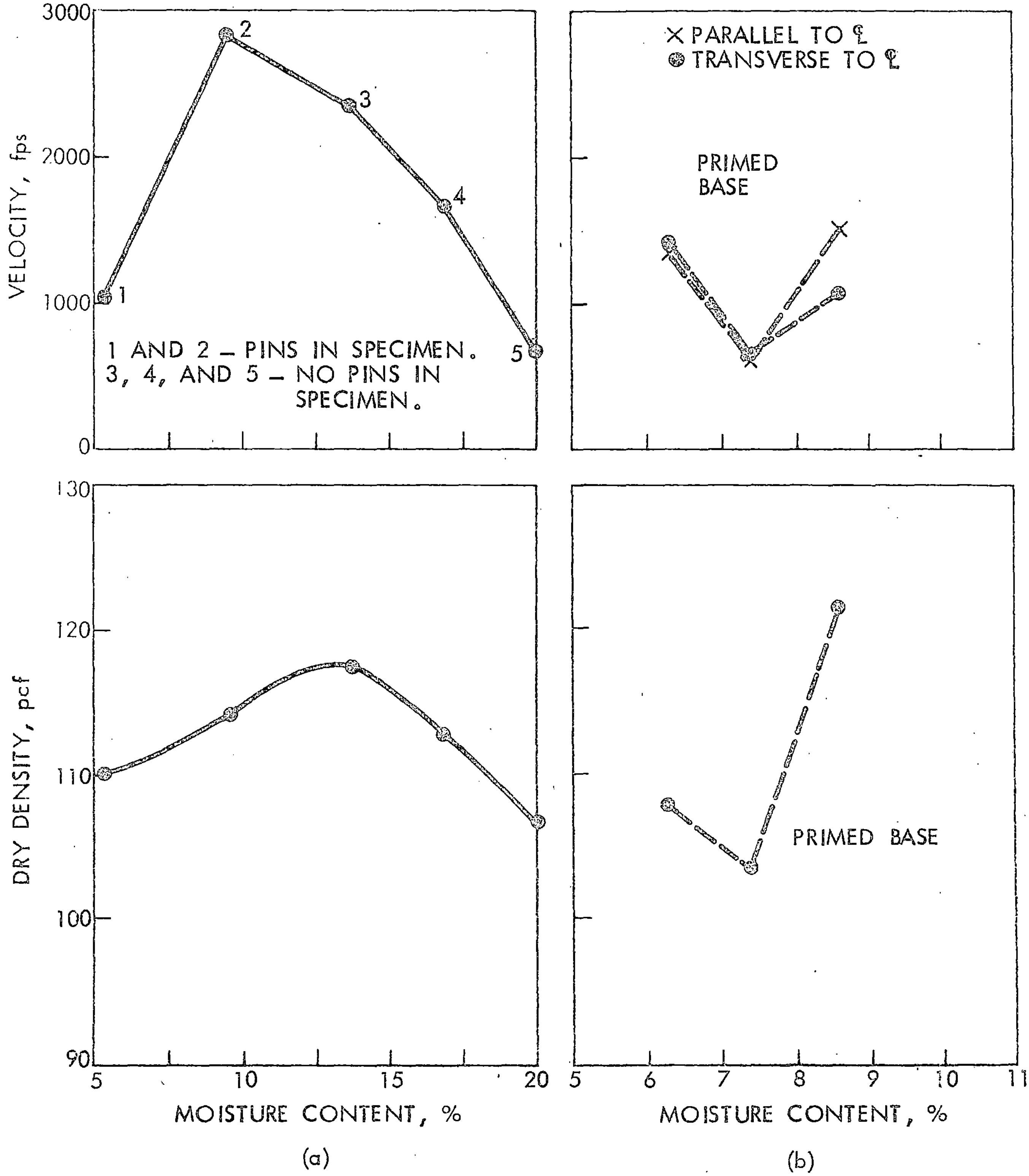


Fig. 38. Field test results, sample location number 18.

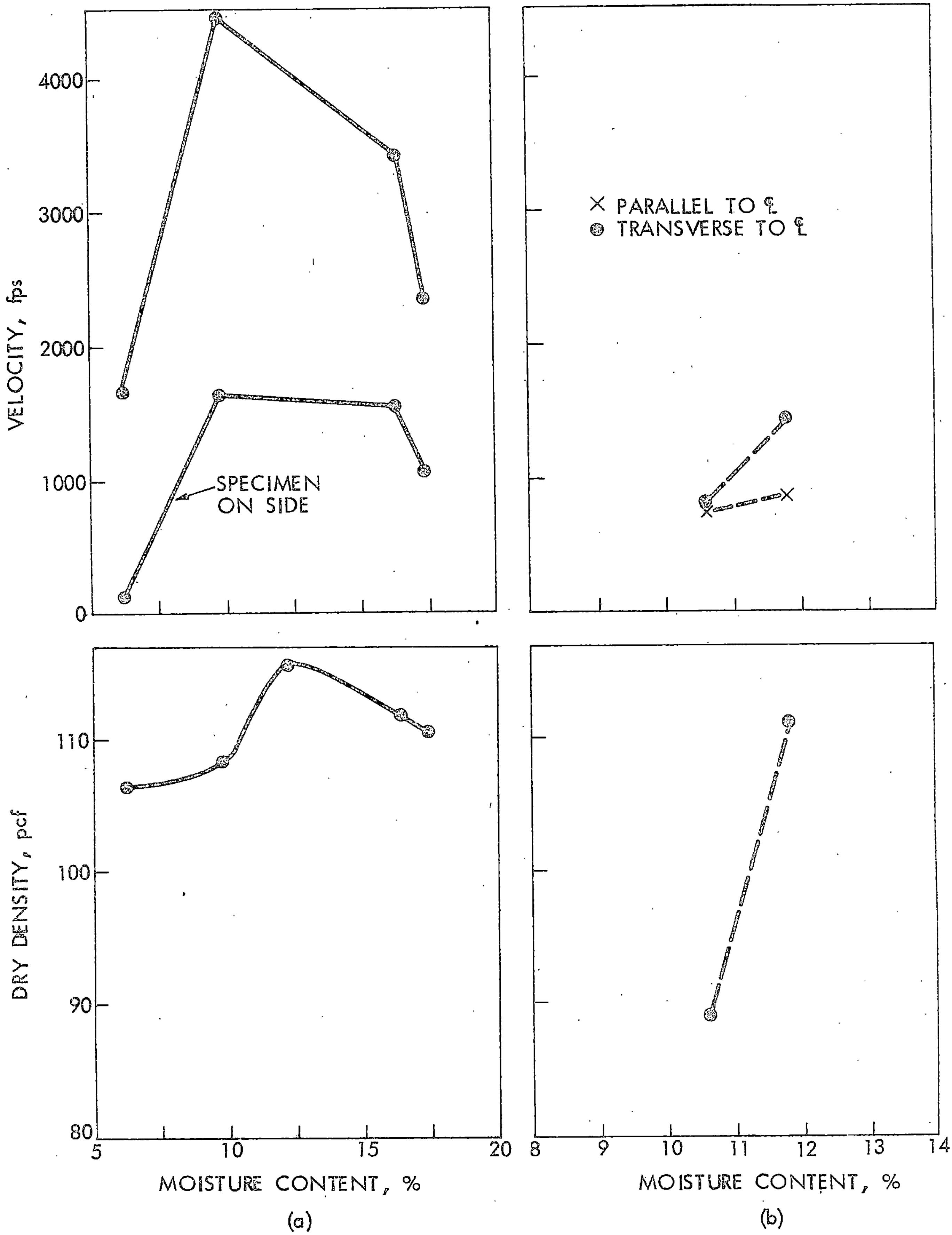


Fig. 39. Field test results, sample location number 20.

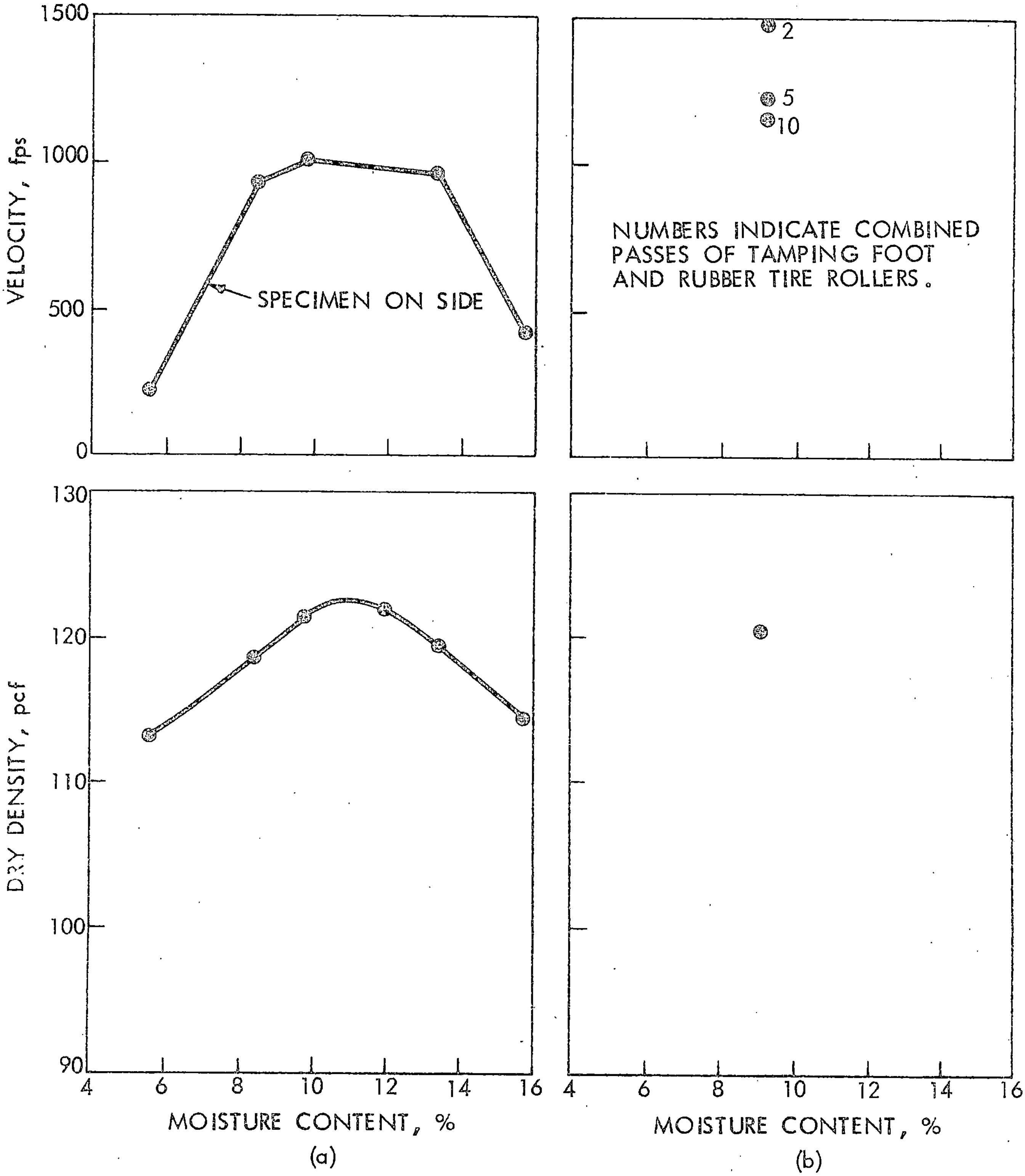


Fig. 40. Field test results, sample location number 21.

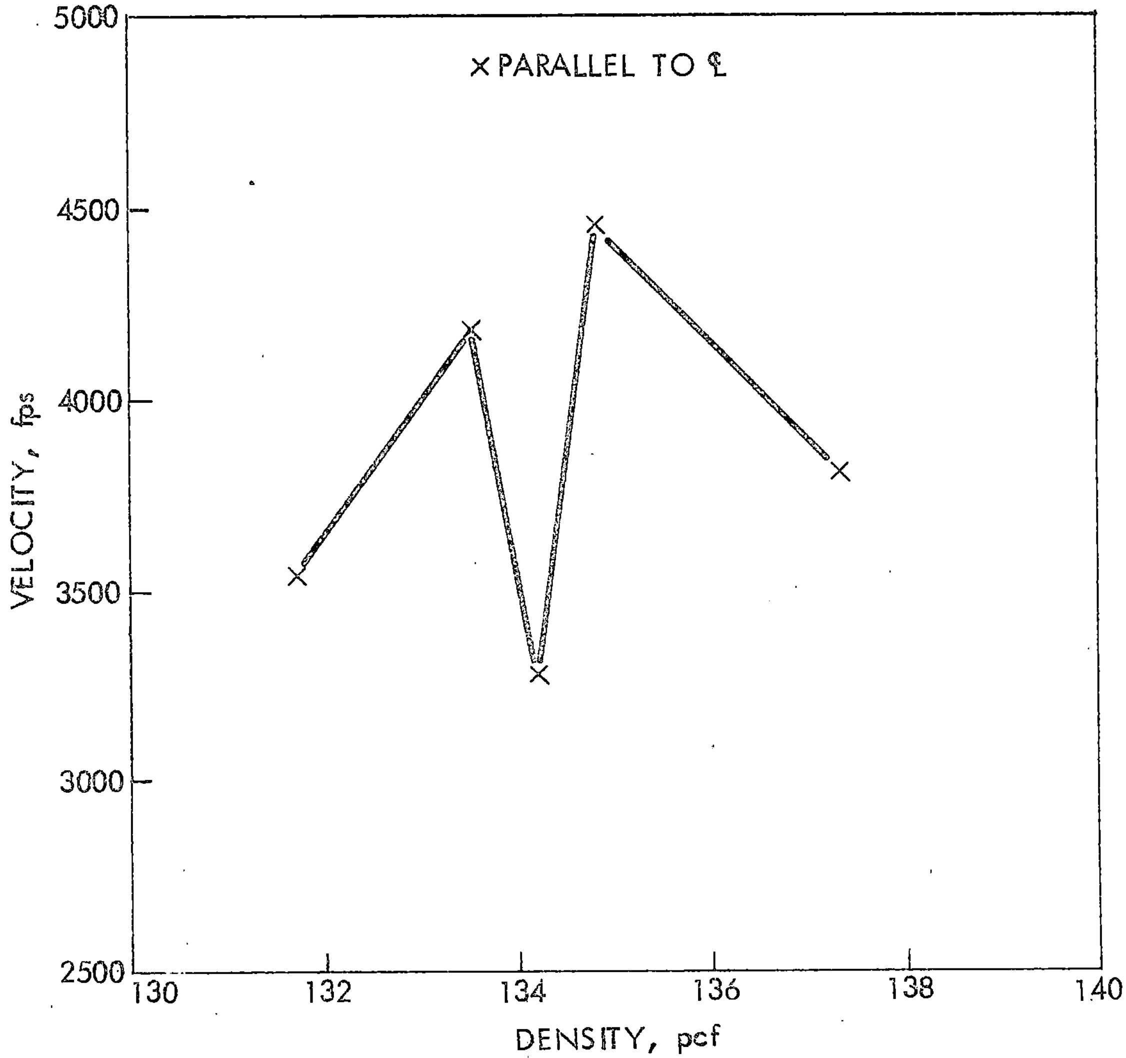


Fig. 41. Field test results, sample location number 22.

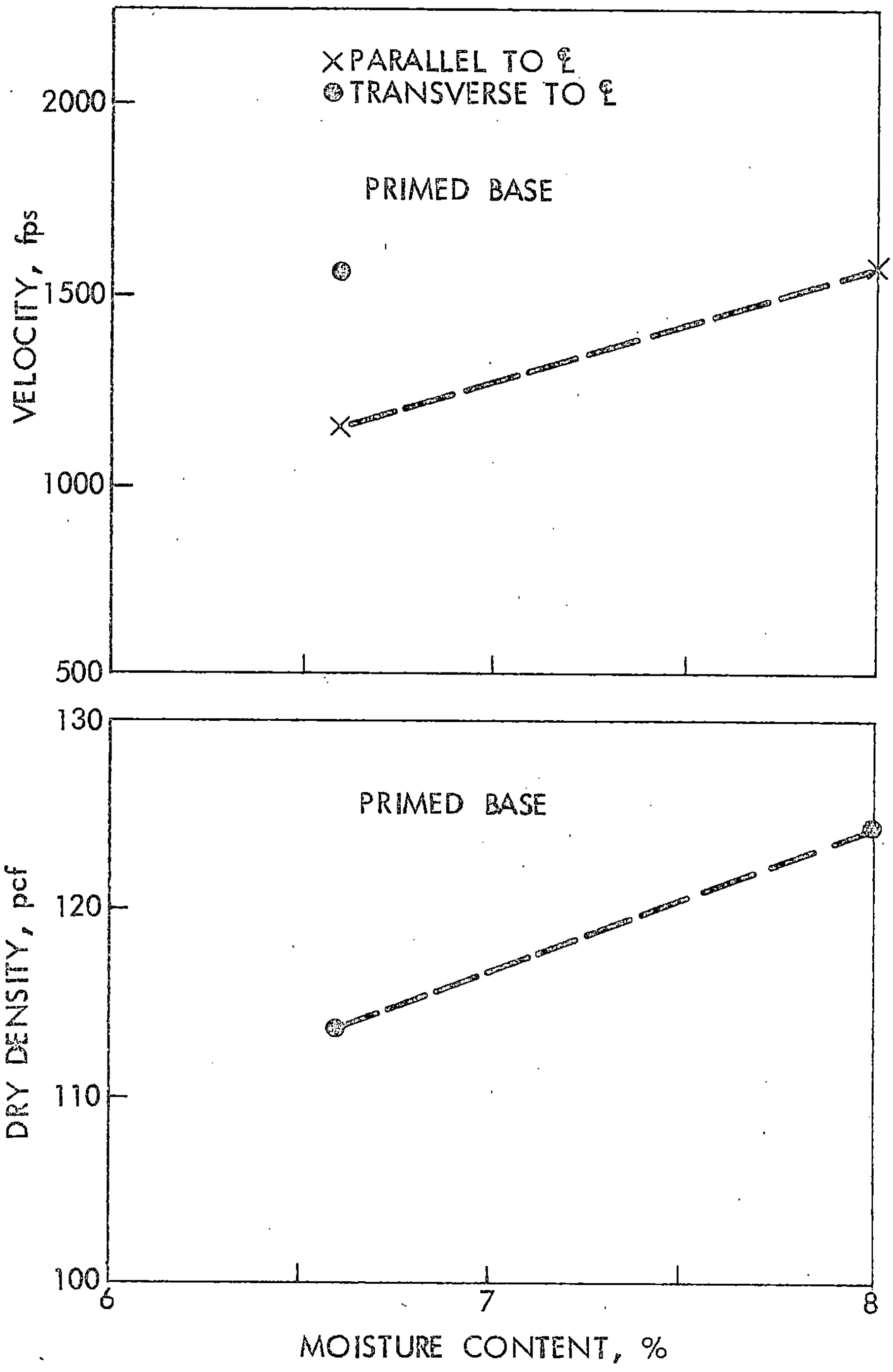


Fig. 42. Field test results, sample location number 23.

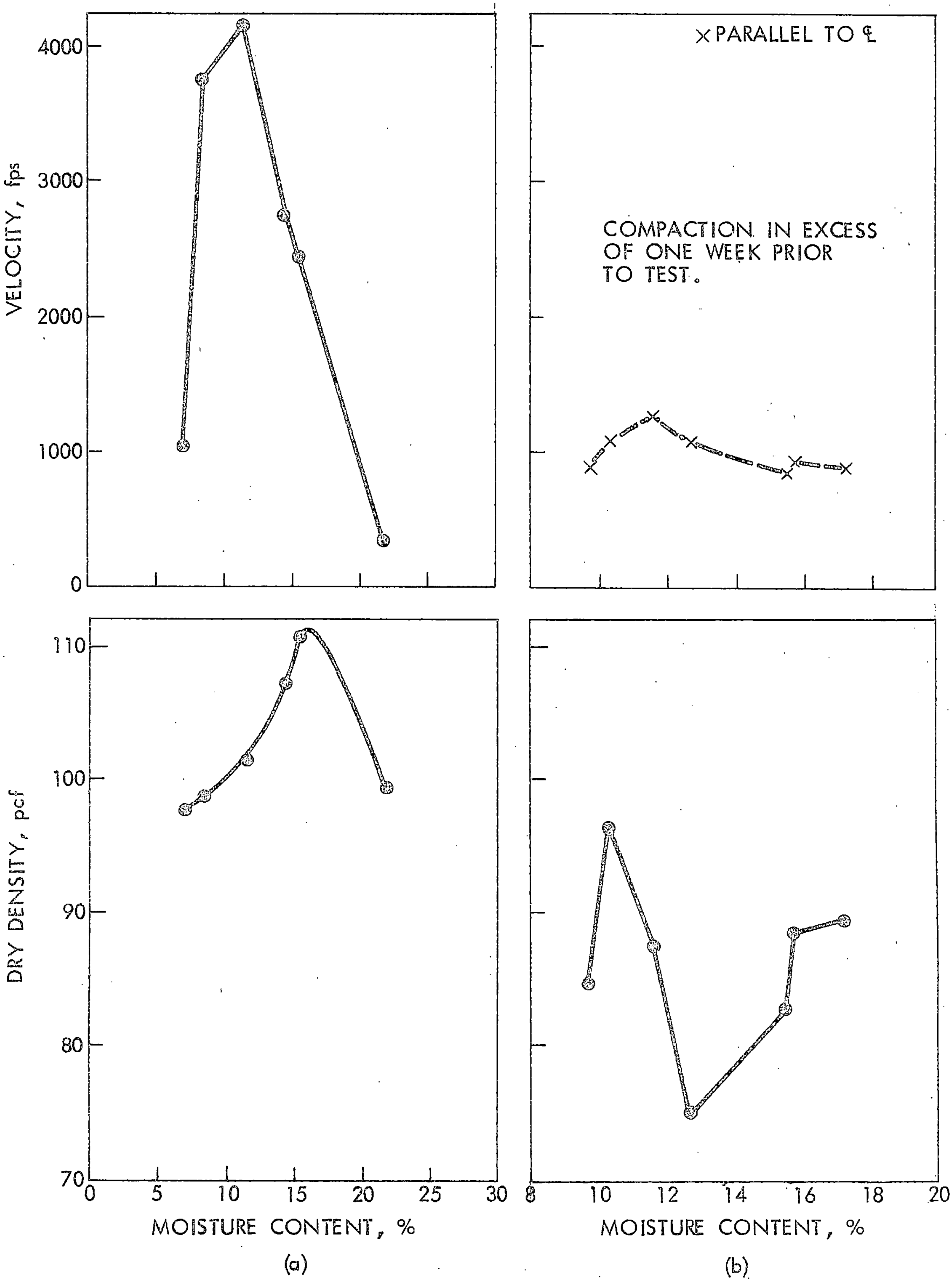


Fig. 43. Field test results, sample location number 24.

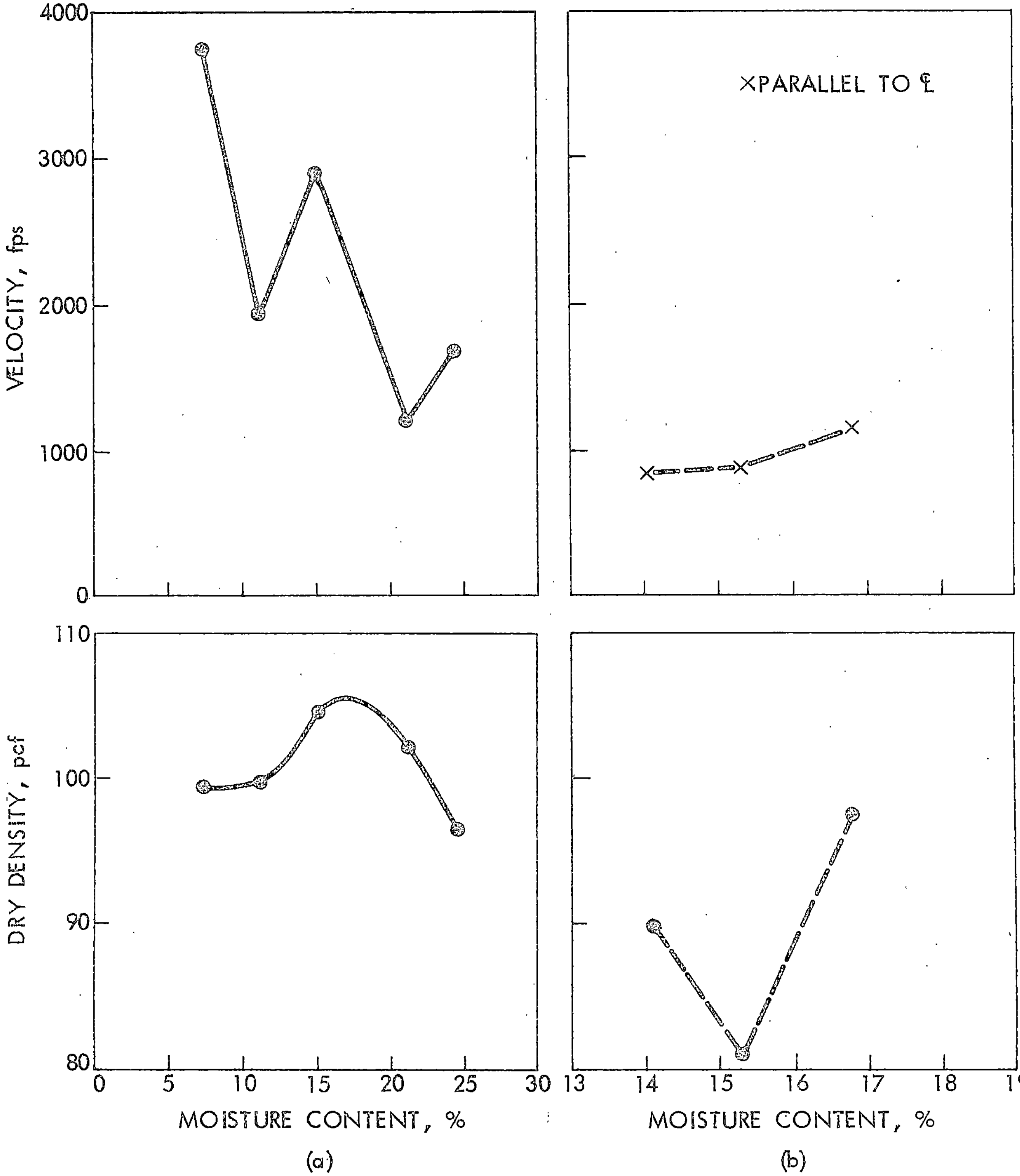


Fig. 44. Field test results, sample location number 25.

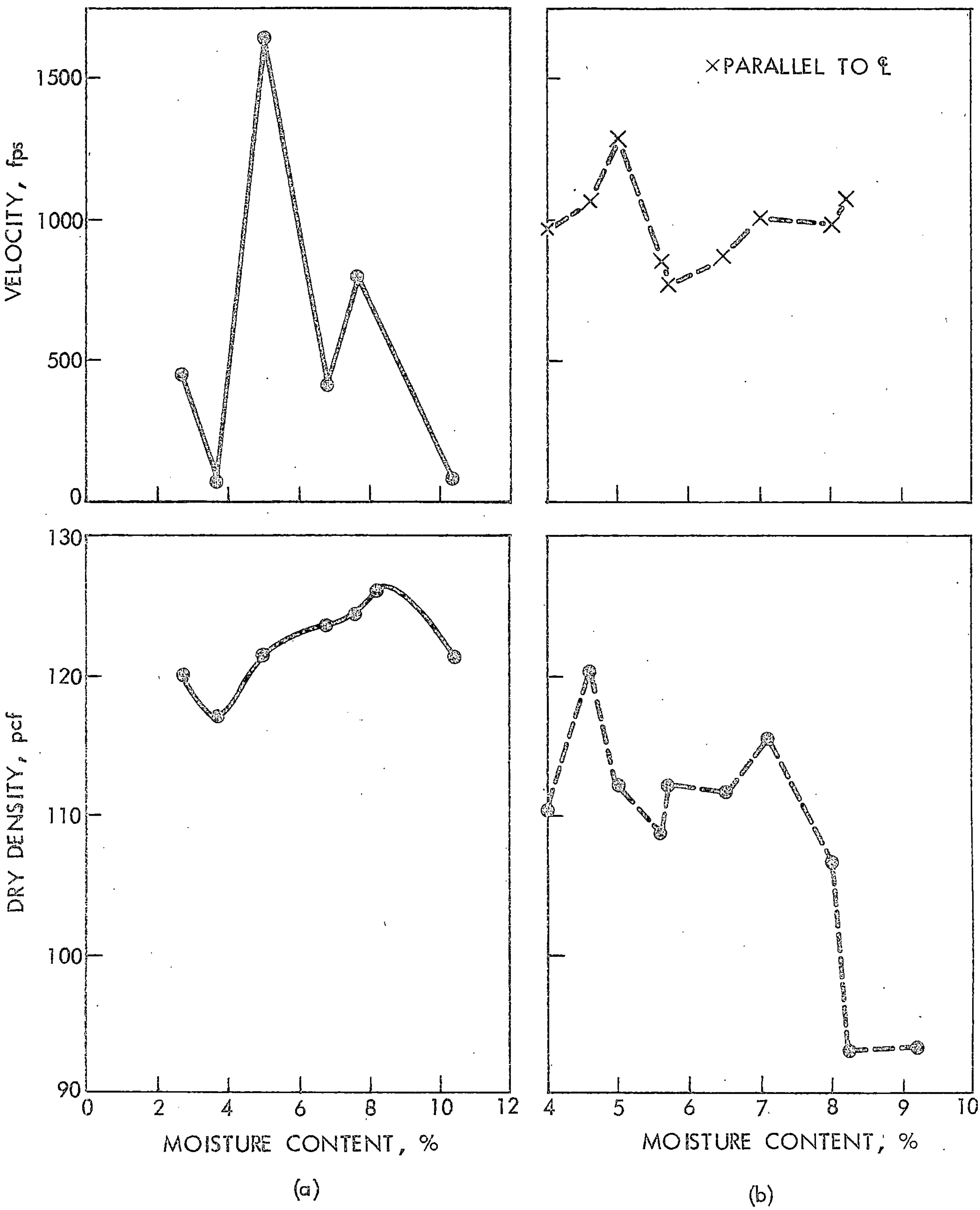


Fig. 45. Field test results, sample location number 26.

Figures 24a, 26a, 29a, 37a and 38a indicate the variations of moisture vs. velocity during the field lab moisture-density test due to having pins or no pins in contact with the pickup unit for each specimen tested. Figure 24a indicates only negligible variation in velocity due to lack of pins, while the remaining figures show sizeable variations in velocity. As can be seen in the following table there was no apparent relationship of velocity variations due to classification of the material. Neither was there any apparent relationship due to moisture content or density.

Location no.	Classification	Velocity variations
3	A-7-6(13)	negligible
5	A-6(2)	> pins
8	A-6(7)	> no pins
16	A-2(4)	> no pins
18	A-7-6(4)	> pins

Many of the specimens either failed or were extremely unstable and difficult to handle when conducting the seismic portion of the moisture-density tests. This is noted in Figs. 27a, 30a, 32a, 36a, and 37a and occurred predominantly with the more coarse grained materials. Wrapping specimens in Saran Wrap, molding in a rubber membrane, or encasement in slotted lengths of thin plastic tubing did not control the instability of the materials under hammer blows.*

*Flathead pins were inserted through the Saran Wrap and membranes, or were exposed along the slot of the plastic tubing.

After the "standard" moisture-density-velocity test at two of the locations, each specimen was arbitrarily laid on its side and velocities were determined in a horizontal rather than vertical direction. Figures 25a and 39a show an extreme lowering of velocities due to this deviation in procedure. Since the travel path through the specimen is unchanged, it would appear that laying the specimens on their sides allowed opening of compaction planes. Nevertheless with the specimens on their sides, Fig. 40a shows an excellent correlation between the moisture-density and moisture-velocity curves.

At one site velocity was related to number of passes of compaction equipment, Fig. 40. The in-place moisture content-density determination was made following the fifth pass. Note that the velocities reduced with increasing number of passes. No formal conclusion can be reached on the basis of only one "growth" test. However, it is necessary to relate the in-place velocities to Eq. (1), Part 1 of this report, where it was shown that the velocity of a longitudinal (compression) wave is inversely proportional to density; i.e., if number of passes of compaction equipment are assumed to increase density, then compression velocities should be reduced. Alternately the velocity may have been progressively reduced by formation of shear planes during compaction.

Two seismic lines were usually used for each point, one parallel to the centerline of the roadway, and the second transverse thereto, intersecting at about the one-third point of the roadway. The volumeter hole was dug near the intersection of the lines following the seismic tests. This orientation of seismic line with respect to the centerline of the roadway must not be misconstrued as differentiating between longitudinal (compression) or transverse (shear) waves since the pickup unit was oriented longitudinally to each seismic line.

The orientation of seismic lines is indicated in Figs. 23 through 45. It is evident that orientation had a definite effect on measured velocities at identical in-place moisture contents and/or densities. It may be hypothesized that the variation in velocities is due to particle orientation or shear planes created by the action of various compaction equipment used during construction. However, neither orientation gave consistently higher or lower velocities in similar materials at similar densities and moisture contents. This is particularly true of those materials showing the shotgun pattern of in-place velocities versus moisture content or density.

When determining velocities with a seismic timer, the slope of a time versus distance curve is the velocity of the first arrival wave. Occasionally, two or more slopes are evident on the plot, indicating that the wave has refracted through an equivalent number of layers, possibly of varying degrees of densification. When such a plot occurs, it is possible to determine the thickness of the first layer by the following equation:[14]

$$D_1 = \frac{X_1}{2}\sqrt{\frac{V_2 - V_1}{V_2 + V_1}}$$

where

D_1 = thickness of layer in ft

V_1 = velocity in the first layer in fps

V_2 = velocity in the second layer in fps

X_1 = distance, in ft, from the origin to the intersection of V_1 and V_2 on the time-distance plot.

The approximate thickness of successively deeper layers may be computed by similar equations.

During the field tests only a small number of both the field lab and in-place velocities plotted anything approaching a straight line, and no quantitative evidence was found for two or more velocities on the time-distance plots. The time-distance data were therefore analyzed by a continuous linear regression program utilizing a computer and automatic plotter. Printed on the plot was the mean of each set of time data, versus distance. The purpose of the plot was two-fold:

1. Provide the linear regression line.
2. Analyze the mean values of each plotted point of time versus distance data for discontinuities from the linear regression line indicative of two or more velocities.

Neither of the above objectives was achieved. Mean data points were still randomly patterned on both sides of the regression line as typically illustrated in Fig. 46.* Consequently, the computed velocities from the linear regression plot were used in Figs. 23 through 45, and Table 4.

It is pertinent to note that the shapes of the moisture-density and moisture-velocity curves, Figs. 23 through 45, are quite dissimilar. Whereas the moisture-density curves peak out in typical fashion convex to the abscissa, the moisture-velocity curves vary from concave to convex to the abscissa to a continuous slope. These inconsistencies may be due to slight variations of density and/or moisture content in a Proctor specimen. Though careful preparation of each compacted layer may be accomplished, some

*From sample number 23, parallel to centerline, velocity 1155 fps, dry density 113.6 pcf, moisture content 6.6%.

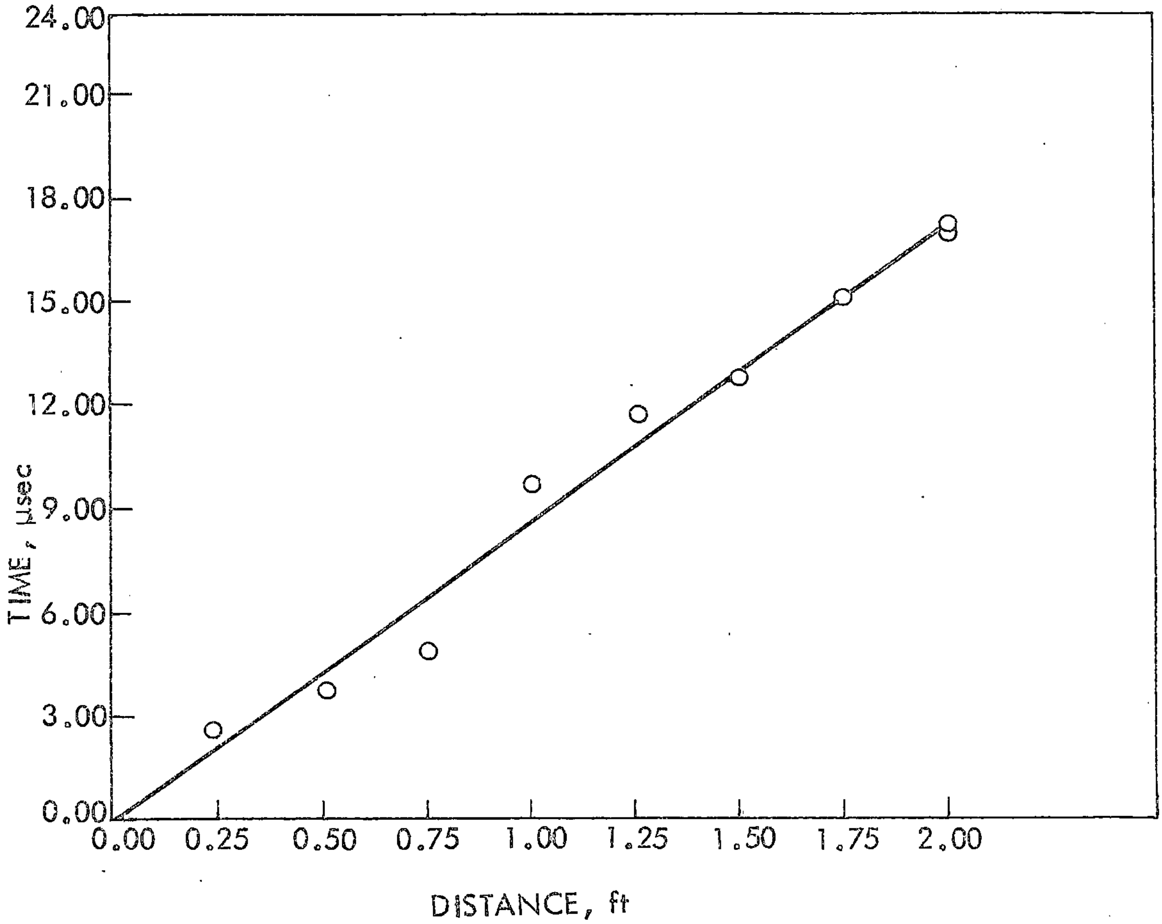


Fig. 46. In-place time versus distance data, plus linear regression plot for sample location number 23.

Table 4. Summary of field test results.

Sample no.	AASHO classification	Field Lab Tests: Maximum dry density (pcf)	Field Lab Tests: Dry density at maximum velocity (pcf)	Field Lab Tests: Optimum moisture content (%)	Field Lab Tests: Moisture content at maximum velocity (%)	Field Lab Tests: Maximum velocity (fps)	Field Lab Tests: Velocity at maximum dry density and optimum moisture content (fps)	In-Place Tests: Maximum velocity (fps)	In-Place Tests: Moisture content at maximum velocity (%)	In-Place Tests: Dry density at maximum velocity (pcf)	In-Place Tests: Maximum velocity at optimum moisture content (fps)	In-Place Tests: Dry density at optimum moisture content (pcf)
2	A-4(2)	120.0	120.0	13.0	13.0	1520	1520	1890[a]	10.7	105.5	1180[a]	106.0
3	A-7-6(13)	98.1	97.2	23.0	25.2	1550	1210	1090[b]	22.4	84.6	~ 1050[a]	~ 93.0
4	A-4(1)	122.2	118.5	12.5	9.0	2510	1050	2220[a]	4.4	132.3	N.D.[c]	N.D.[c]
5	A-6(2)	122.7	122.7	11.5	11.5	2240	2240	1420[b]	8.8	121.4	N.D.[c]	N.D.[c]
6	A-1-a	151.4	151.4	5.2	5.2	960[d]	960[d]	2880[b]	2.8	133.3	900[b]	138.3
7	A-4(1)	123.0	119.5	9.5	5.5	1330	370	1560[b]	11.0	124.7	1000	~ 90.0
8	A-6(7)	114.0	109.8	14.0	10.6	2160	1230	1350[a]	20.7	82.8	1230[b]	98.9
9	A-2-6(1)	124.2	123.6	10.1	11.2	2910	2050	1570[a]	7.6	121.0	N.D.[c]	N.D.[c]
10	–	N.D.[c]	N.D.[c]	N.D.[c]	N.D.[c]	N.D.[c]	N.D.[c]	5580[b]	8.6[e]	143.5	N.D.[c]	N.D.[c]
11	A-1-a	131.2	N.D.[c]	6.4	N.D.[c]	N.D.[c]	N.D.[c]	1450[a]	5.2	131.0	910[a]	129.3
12	A-6(2)	N.D.[c]	N.D.[c]	N.D.[c]	N.D.[c]	N.D.[c]	N.D.[c]	2500[a]	8.5	121.0	N.D.[c]	N.D.[c]
13	A-2-6(0)	N.D.[c]	N.D.[c]	N.D.[c]	N.D.[c]	N.D.[c]	N.D.[c]	– [f]	– [f]	– [f]	N.D.[c]	N.D.[c]
14	–	N.D.[c]	N.D.[c]	N.D.[c]	N.D.[c]	N.D.[c]	N.D.[c]	– [f]	– [f]	– [f]	N.D.[c]	N.D.[c]
15	A-6(4)	115.5	N.D.[c]	12.7	N.D.[c]	N.D.[c]	N.D.[c]	2540[b]	9.7	114.3	N.D.[c]	N.D.[c]
16	A-2-4	127.4	124.4	8.6	6.0	1580	1200	2830[b]	7.5	137.6	~ 1700[b]	~ 121.0
18	A-7-6(4)	117.5	114.0	13.0	9.4	2800	2410	1500[b]	8.5	121.5	N.D.[c]	N.D.[c]
20	A-7-6(7)	115.8	108.3	12.5	9.8	4400	4000	1450[a]	11.8	111.2	N.D.[c]	N.D.[c]
21	A-2-6(0)	122.6	121.6	11.0	9.8	1000	980	1440[a]	9.2	120.5	N.D.[c]	N.D.[c]
22	–	N.D.[c]	N.D.[c]	N.D.[c]	N.D.[c]	N.D.[c]	N.D.[c]	4450[b]	N.D.[c]	134.8	N.D.[c]	N.D.[c]
23	–	N.D.[c]	N.D.[c]	N.D.[c]	N.D.[c]	N.D.[c]	N.D.[c]	1580[b]	8.0	124.0	N.D.[c]	N.D.[c]
24	A-6(9)	111.0	101.5	16.0	11.4	4170	2300	1250[b]	11.6	87.3	920[b]	88.5
25	A-6(9)	105.7	99.5	17.0	7.3	3770	2400	1150[b]	16.8	97.5	N.D.[c]	N.D.[c]
26	A-1-b	126.5	121.5	8.5	5.0	1650	575	1290[b]	5.0	112.0	~ 1100[b]	93.0

(a) Velocity measured transverse to centerline.
(b) Velocity measured parallel to centerline.
(c) Not determinable — see appropriate figure.
(d) Specimens very unstable, nearly impossible to handle.
(e) Percent air voids — not moisture content.
(f) See appropriate figure. Tests widely scattered, with no correlation.

variation in density and/or moisture content may exist and would be detected in a series of needle pickup points along the side of a specimen as used in this study. The critical nature of the density-velocity relationship is further reflected in Figs. 34, 35 and 37, where slight changes of moisture and/or density are reflected by large changes in velocity.

A curt and cursory examination of the data in Figs. 23 through 45 (and Table 4) shows little relationship between the field velocities and densities in the right-hand graphs compared to the laboratory data of the left-hand graphs. Note that the right-hand graphs include variable compactive efforts and should not be expected to give smooth curves.

In Figs. 23, 24, 27, 43, 44, and 45, all field densities were below points on the laboratory moisture-density curve, indicating insufficient compactive effort, but in all except the last two, the field velocities were high enough to indicate adequate compaction.

In other figures, points may be individually checked and give erroneous findings. For example, the second field point in Fig. 26, with a moisture content of 8.8%, has a density equal to that obtained with standard compactive effort at this moisture content, but the velocity is too low by several hundred fps. Figure 28 shows two field densities, one slightly above the maximum dry density and the other far below, and at nearly the same moisture content, whereas both field velocities are well above the laboratory velocities obtained at these moisture contents. Other examples of inconsistencies may be cited, as well as some results which are consistent. For example, in Fig. 29 all field densities are low, as are all field velocities. In Fig. 37 most field densities are high, as are most field velocities. Nevertheless the inconsistencies indicate that the results are erratic, and the method as used is highly unreliable. In Figs. 25, 31, 32, 33, 34, 35, 36, 41, and 42, data were insufficient for comparison, either because laboratory tests were not performed or did not include a wide enough variation in moisture content.

CONCLUSIONS FROM FIELD INVESTIGATION

The above procedures for determining seismic velocity are unsuitable as a rapid means of determination of in-place density. Problems include the following:

1. While the method for in-place seismic tests is reasonably rapid, that used for field lab control curves is extremely time-consuming and requires considerable patience and dexterity on the part of one or more technicians. In addition, results of seismic tests from either proctor specimens or in-place materials are highly dependent on measurement of travel distance of wave between energy source and pickup. Variations in reported results may in part be due to extremely small errors of distance measurement.
2. The Model 217 Micro-Seismic timer gives good reproducibility of measured times so long as the pickup unit is very carefully adjusted for proper contact with a pin or nail head embedded in the material to be tested. Being a phonograph needle, the pickup unit is thus sensitive to contact pressure. Too much pressure dampens the sensitivity while too small a pressure does not fully utilize the sensitivity; i.e., quality of wave reproduction is

varied. The variation in reported velocities during the field tests is probably in part due to improper contact pressure. Where no pins were used on the field lab specimens, the problem of needle contact pressure may have been further compounded due to possible contact with a single loosely held surface grain.

3. A specimen fails when it is attempted to produce shock waves by hammering on a ball embedded in a molded and extruded specimen of coarse grained low plasticity materials. Failure also occurred when hammering on finer grained material specimens that were on the extreme dry or wet side of optimum moisture content.

4. Orientation of the in-place seismic line with respect to the roadway centerline produced definite variations in measured velocities at identical moisture contents and densities and may have been due to particle orientation or non-homogeneities of the materials during compaction.

In summary, it may be said that neither the laboratory nor the field procedure for determination of seismic velocities was satisfactory under conditions of tests normally encountered by field inspectors. A decision was made to spend the remaining time in the project trying to devise and perfect a different laboratory procedure.

ADDITIONAL LABORATORY TESTS

The preceding tests were dependent on a pickup unit (transducer) utilizing an extremely fine pointed needle, and thus covering a nearly infinitesimally small contact area. It was hypothesized that if the transducer contact area could be increased to at least several square inches without loss of close reproducibility of seismic times, many of the irregularities in velocities possibly due to insertion of pins, variations in moisture-density, and/or loose surface particles could be eliminated. Geophones would increase contact area but required insertion of a larger point, which would cause disruption of a material, particularly in a Proctor specimen.

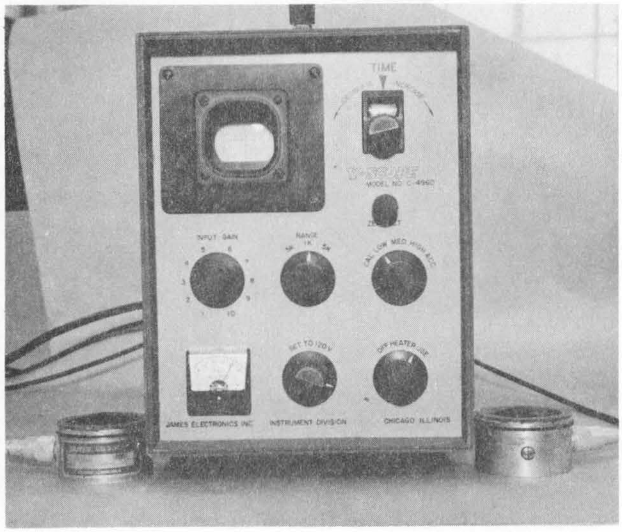
In addition, a method was needed which was less time consuming, required less precision and dexterity on the part of a technician, eliminated the need for hammering on a specimen, would work regardless of contact pressure of pickup to specimen and would measure velocity over full length of specimen, for average velocity, not velocity dependent on interior specimen irregularities.

In their study of pulse velocities in compacted soils, Sheeran, Baker, and Krizek[15] showed that the curves of peak velocities and dry densities were approximately parallel and were within ± 0.5% moisture content of each other, using a V-Scope.* In addition, the V-Scope source and receiver transducers each had a contact area of several square inches.

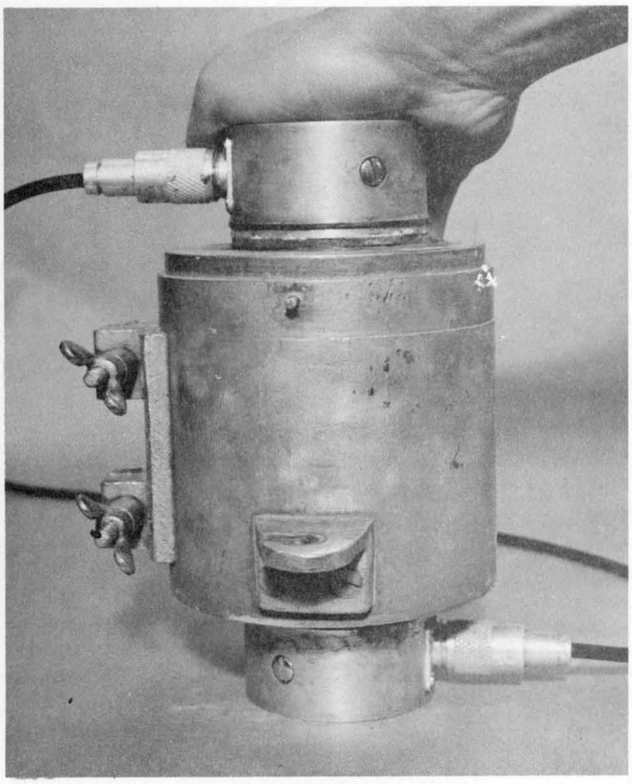
A V-Scope was rented for one month to conduct a limited velocity-moisture-density laboratory study on the bulk of the materials obtained from the field tests noted in the previous section of this report.

The V-Scope, Fig. 47a, combines an oscilloscope, pulse generator, source and receiver transducers in one unit. The transducers are Rochelle

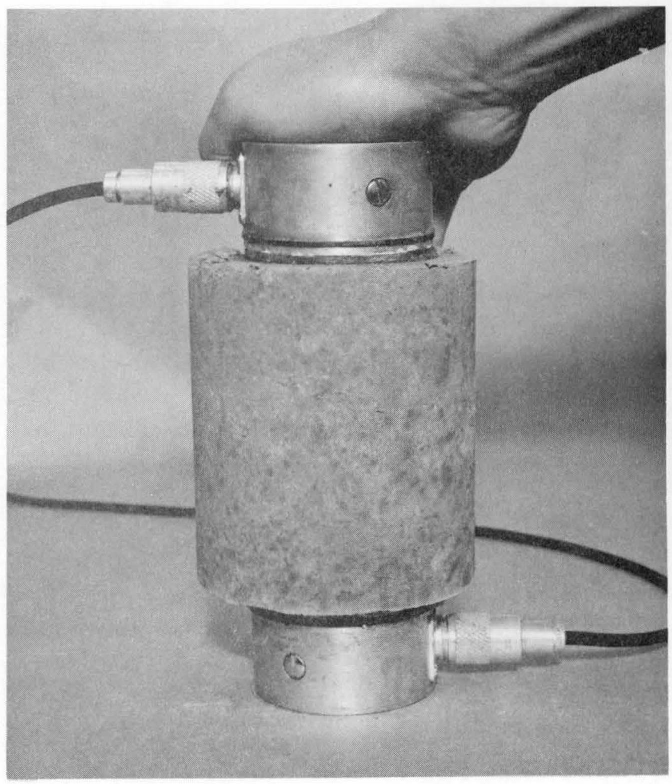
*James Electronics, Inc., 4050 North Rockwell St., Chicago, Illinois 60618.



A.



B.



C.

Fig. 47

A. James Electronics, Inc., V-Scope with source and receiver transducers.

B. Transducers mounted on in-mold specimen.

C. Transducers mounted on extruded specimen.

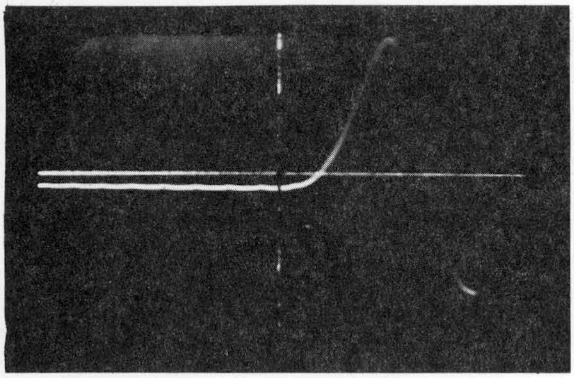
salt crystals in an aluminum enclosure, and capped under an oil filled rubber membrane which protrudes about 1/8 in. from the case.** Sweep of the oscilloscope is matched to the sonic frequency emitted from the source transducer, and a stationary trace is displayed on the oscilloscope. A short calibration process cancels all time delays associated with the instrument, cables and transducers. The time control on the face of the V-Scope is turned until the point at which the trace leaves the horizontal is directly lined up with a vertical reference line as shown in Fig. 48. The time, in microseconds, is then read directly from a counter. Distance divided by time is the velocity in fps.

Since the distance used in the laboratory study was constant (length of a Proctor specimen) a chart was made of time in micro-seconds, versus velocity in fps. Velocities were then read from the average of three or more time readings. The total time to determine velocity over a Proctor specimen was five minutes or less, and eliminated the need for plotting time versus distance, or reducing data with a computer.

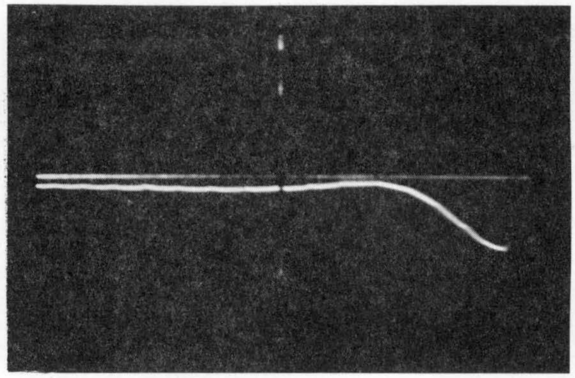
Two series of velocity tests were conducted on each Proctor specimen; i.e., prior to and following removal from the steel mold. Figure 47b and 47c photographically illustrate the two test series, with the source transducer lightly hand held on top of the specimens. The in-mold tests were a means of overcoming the instability of some extended specimens.

Results of the V-Scope velocity-moisture-density tests are shown in Figs. 49 through 59 and summarized in Table 5.

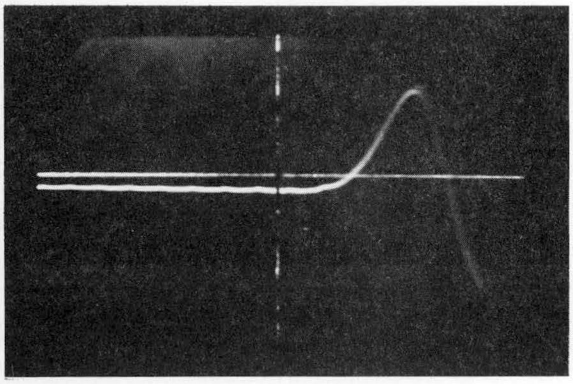
**The membrane protrudes from the case under pressure so that during the test the specimen is not in contact with the case.



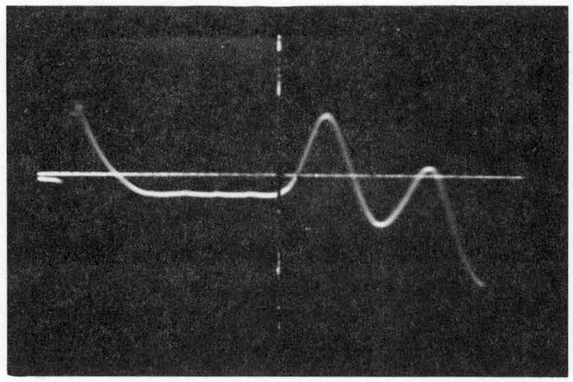
A.



C.



B.



D.

Fig. 48. Typical V-Scope traces.

A. Specimen number 2, sample number 20, in mold, dry density 107.3 pcf, moisture content 10.2%, velocity 2650 fps.

B. Specimen number 2, sample number 20, extruded. Time control at same point as in "a" above to show shift of signal and lowering of amplitude caused by removal of specimen from mold. After time control was properly adjusted, velocity was determined as 2490 fps at 107.3 pcf dry density and 10.2% moisture.

C. Specimen number 6, sample number 18, extruded, very wet, well above optimum moisture content. Velocity 1920 fps, at 100.3 pcf dry density, 22.5% moisture.

D. Core specimen of asphalt cement treated base material removed from location of sample number 10 during field tests (Figure 31), velocity 8482 fps. Illustrates potential use of V-Scope on cores or Marshall test specimen. Peak at left of photo is reference marker utilized in instrument zeroing and calibration--not noted on other photos since the higher the velocity the closer the reference marker is to the trace to be read.

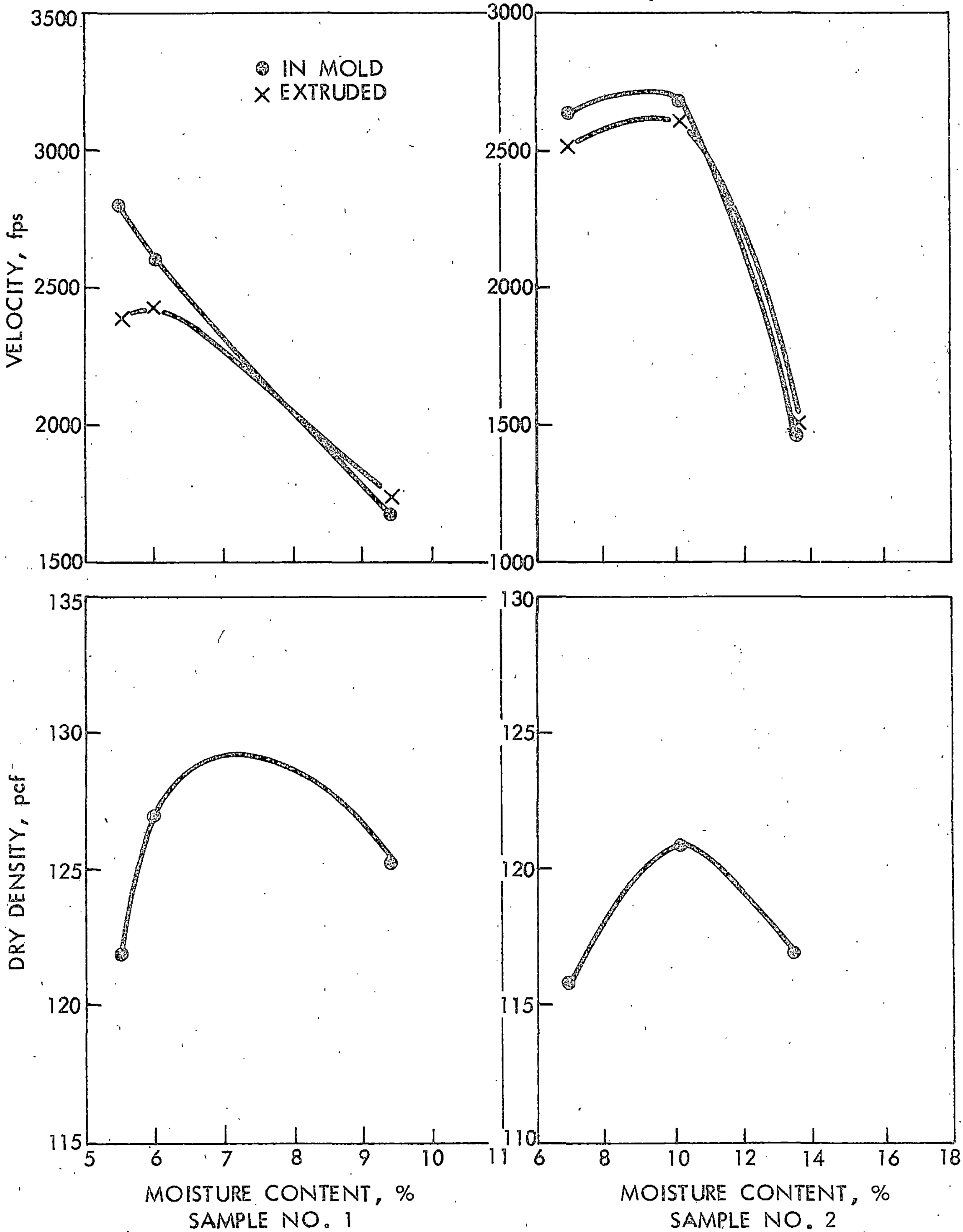


Fig. 49. Laboratory moisture-density-V-Scope velocity results, sample numbers 1 and 2.

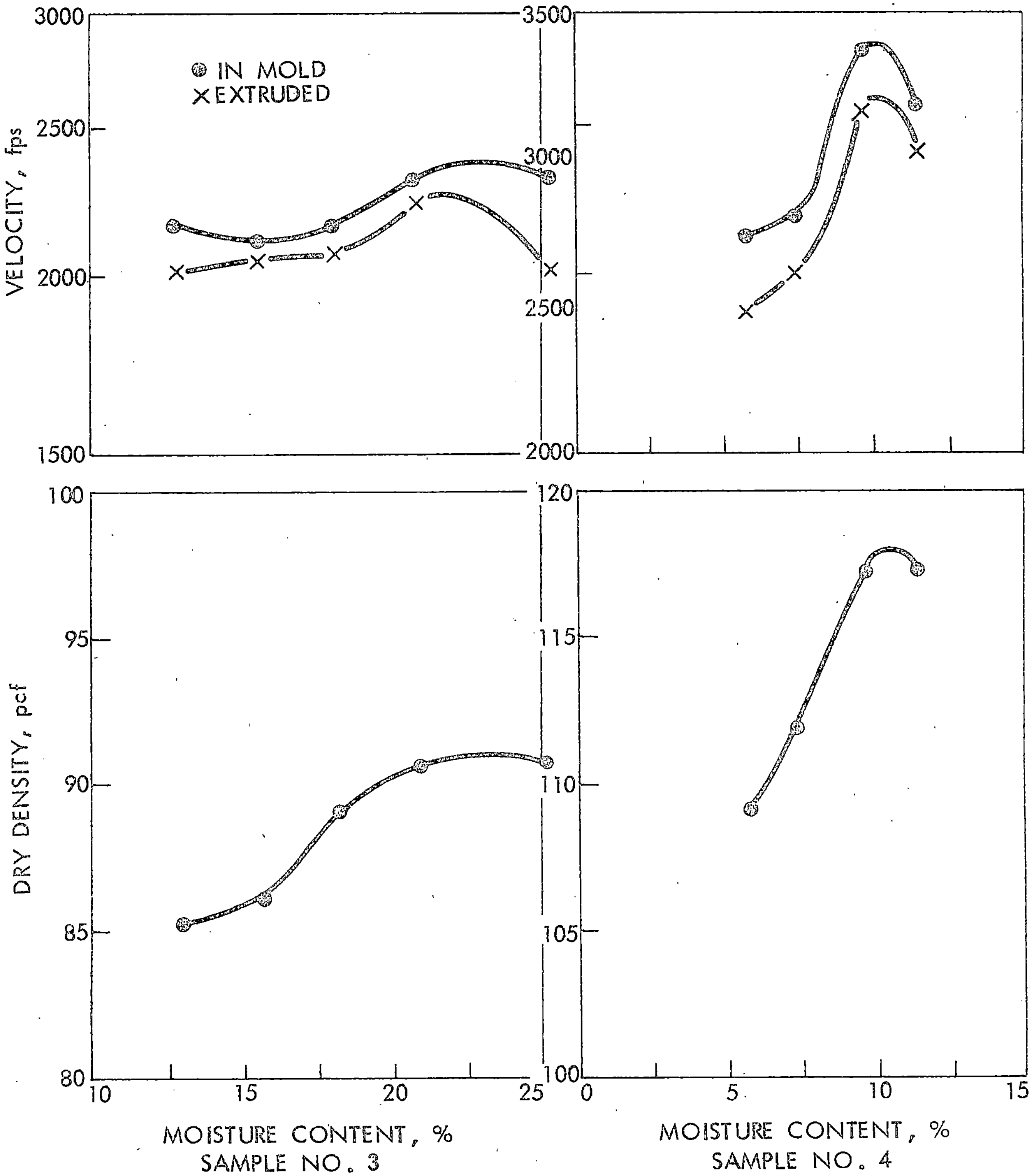


Fig. 50. Laboratory moisture-density-V-Scope velocity results, sample numbers 3 and 4.

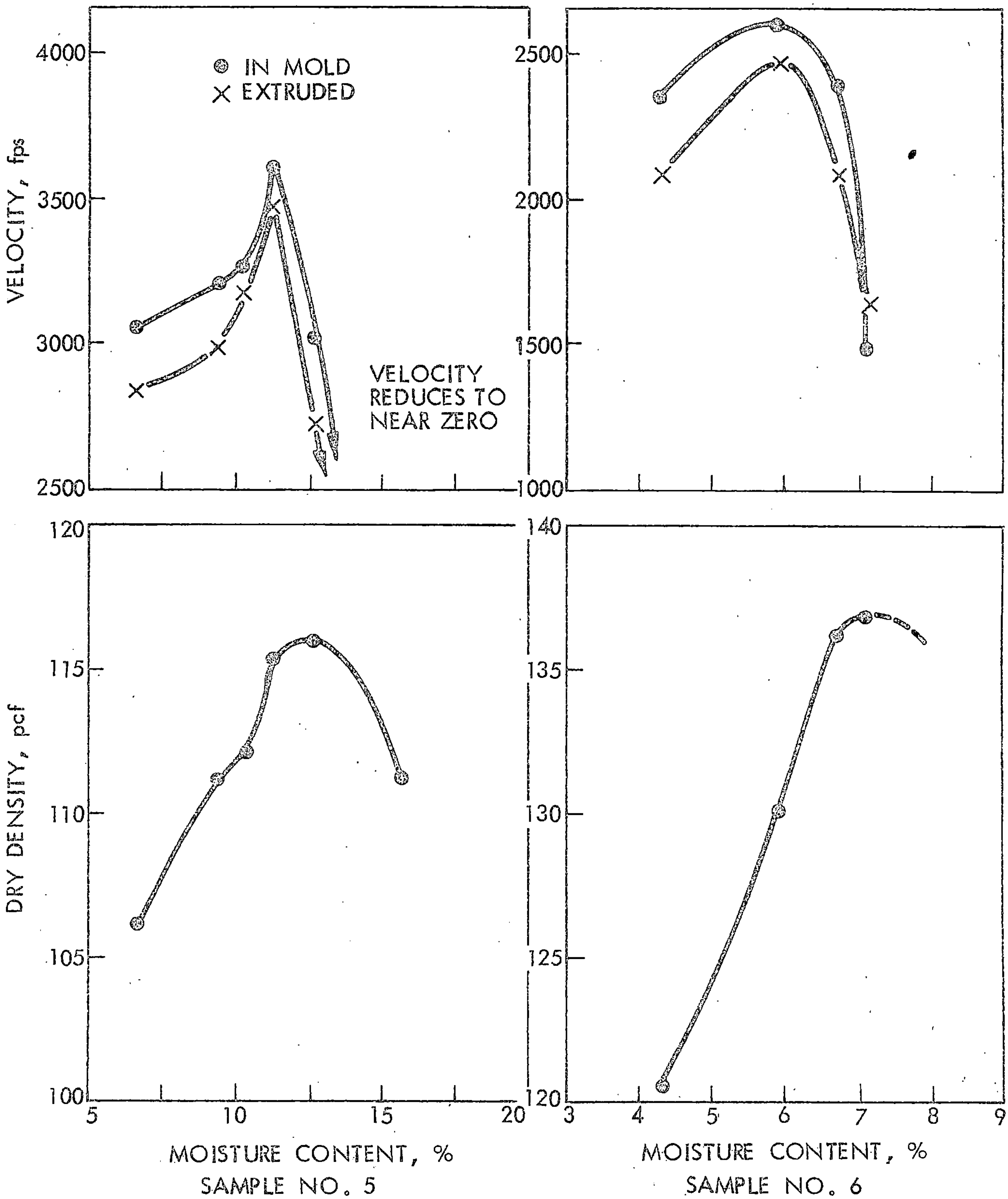


Fig. 51. Laboratory moisture-density-V-Scope velocity results, sample numbers 5 and 6.

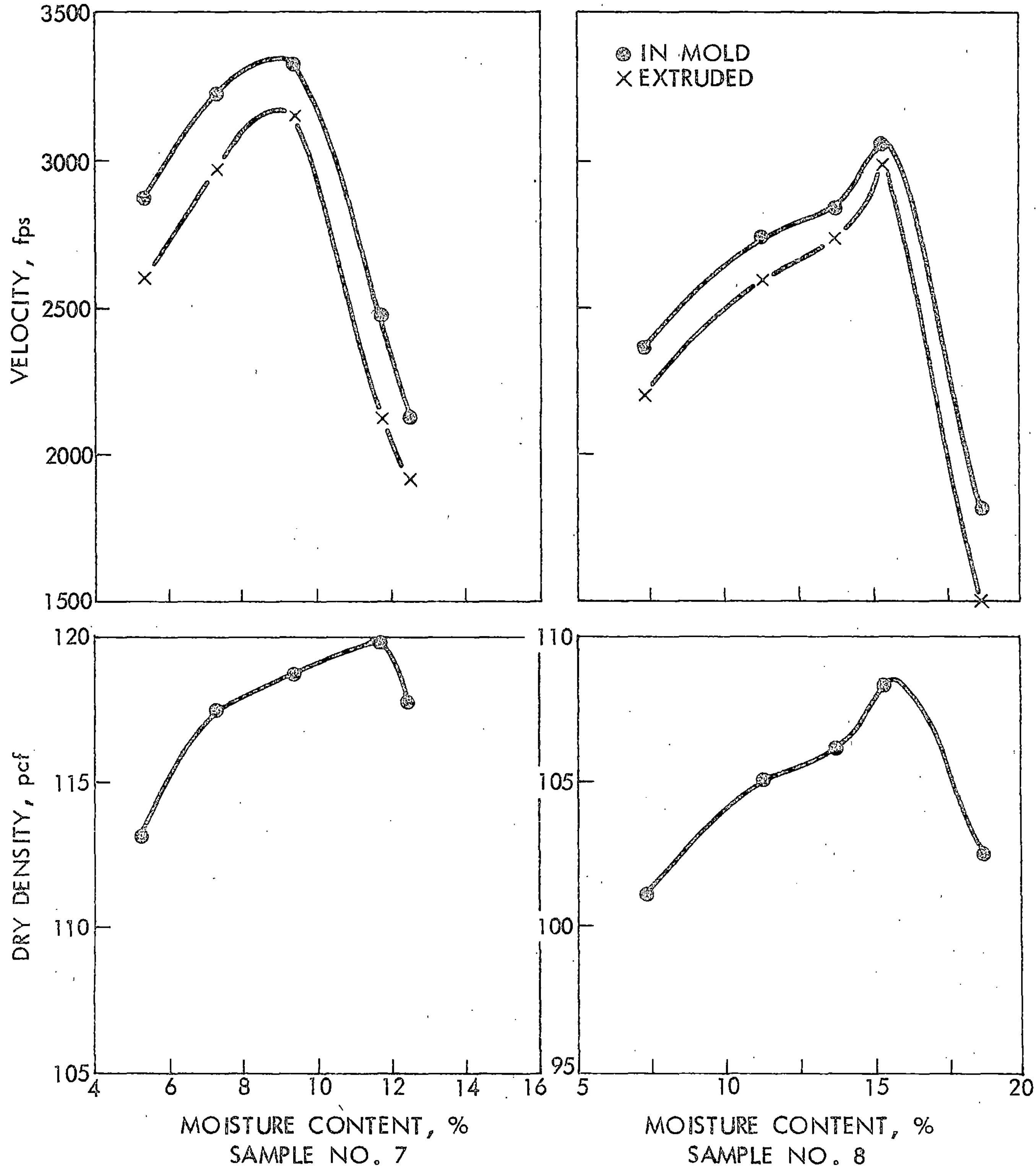


Fig. 52. Laboratory moisture-density-V-Scope velocity results, sample numbers 7 and 8.

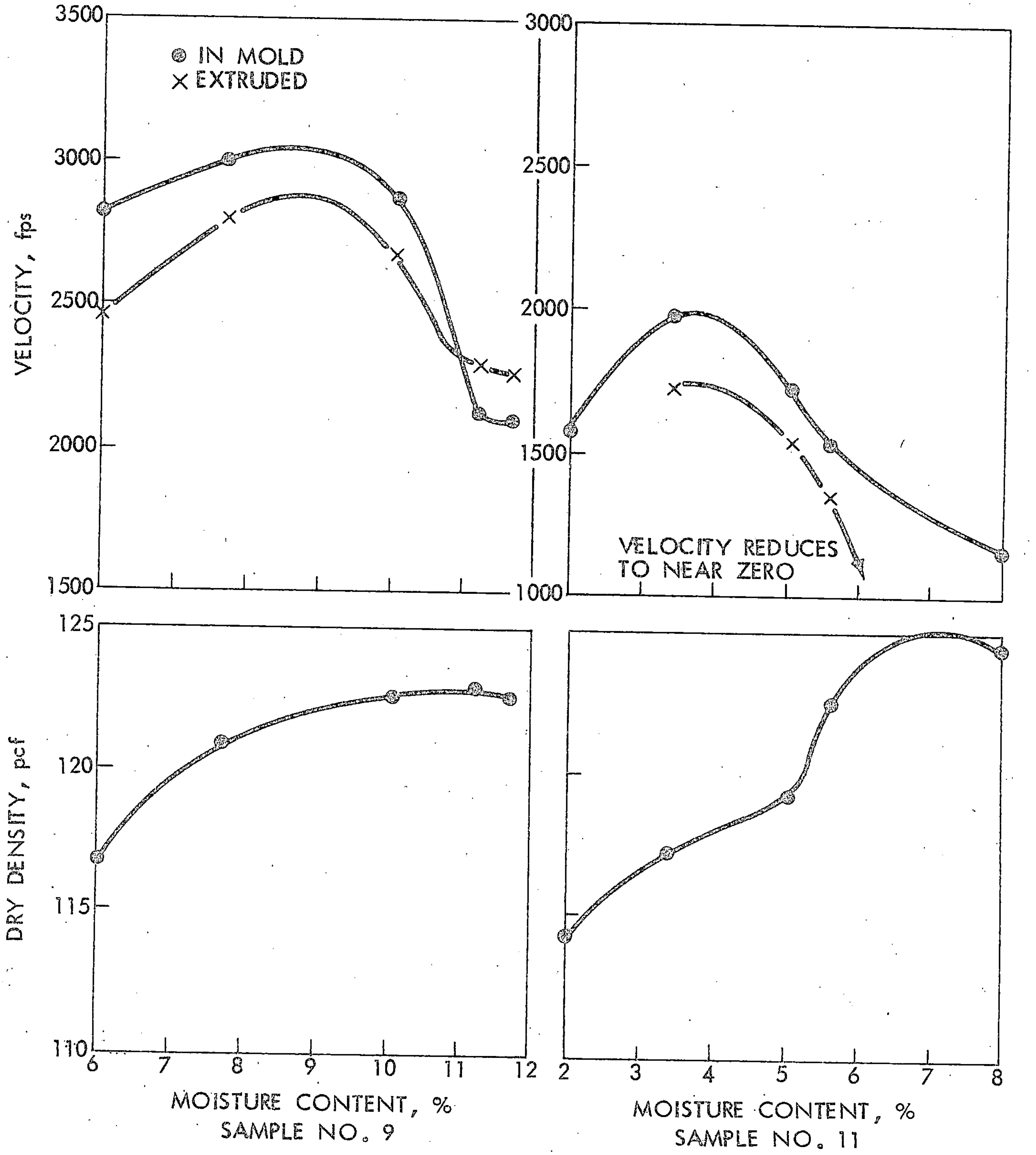


Fig. 53. Laboratory moisture-density-V-Scope velocity results, sample numbers 9 and 11.

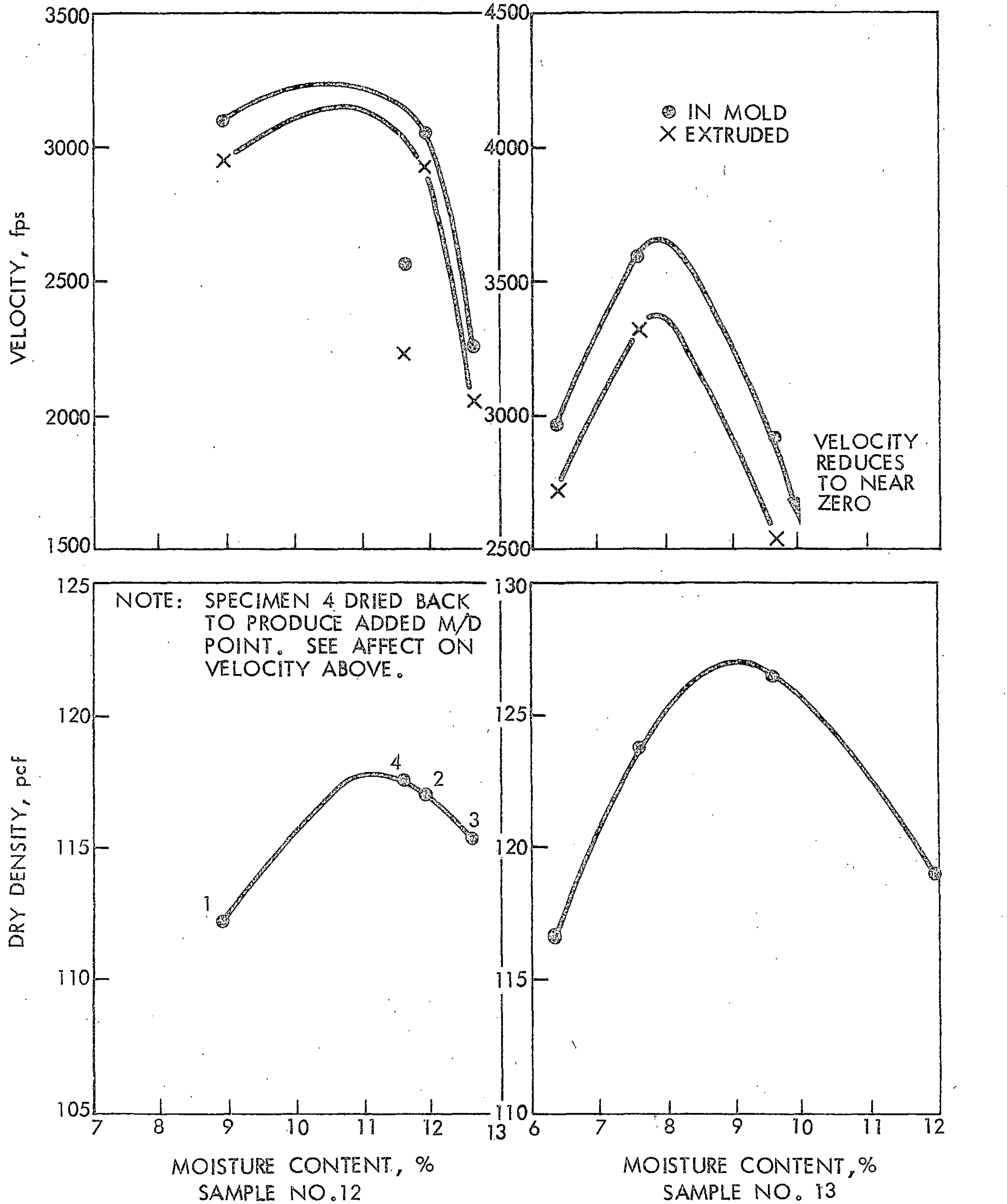


Fig. 54. Laboratory moisture-density-V-Scope velocity results, sample numbers 12 and 13.

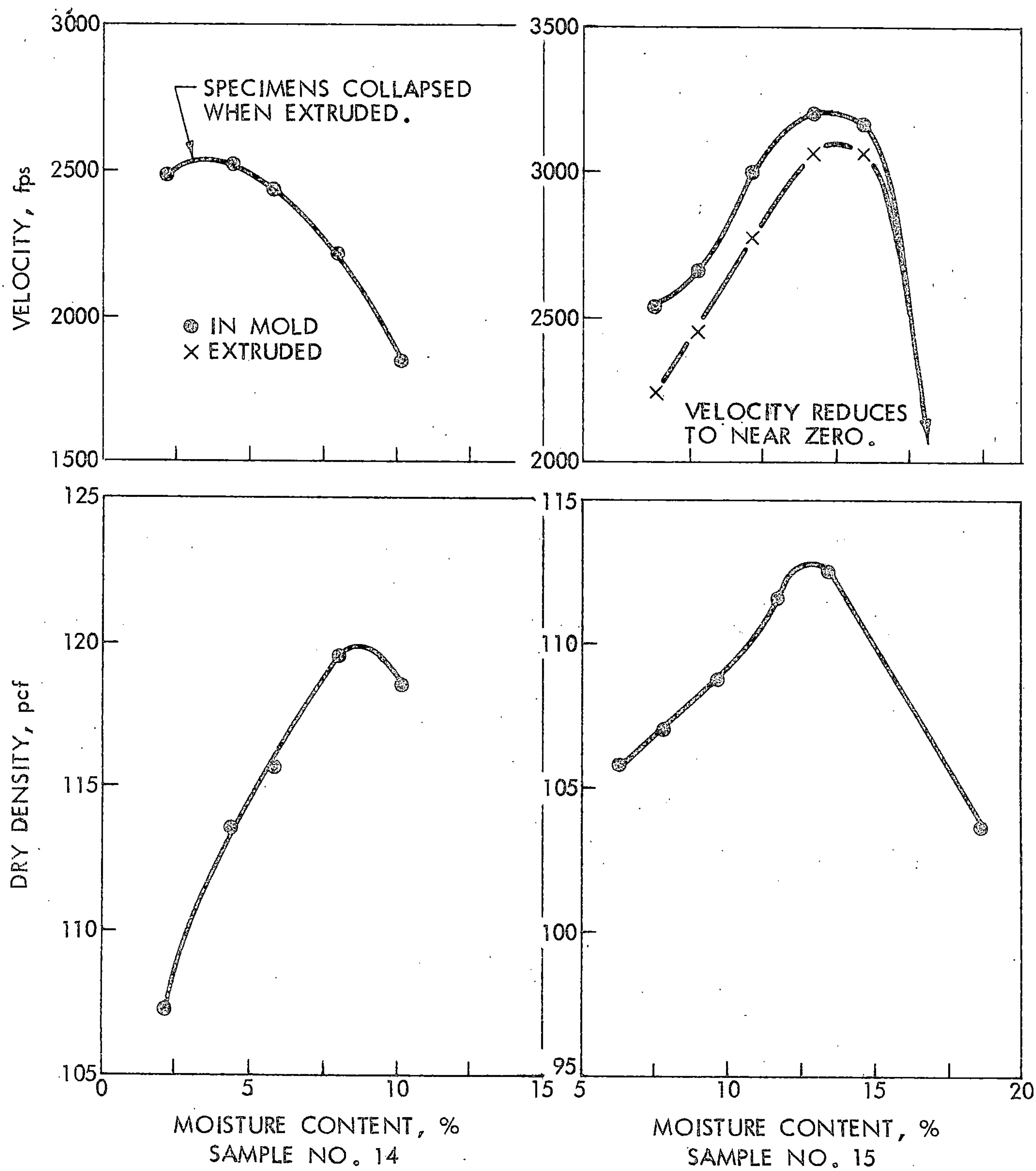


Fig. 55. Laboratory moisture-density-V-Scope velocity results, sample numbers 14 and 15.

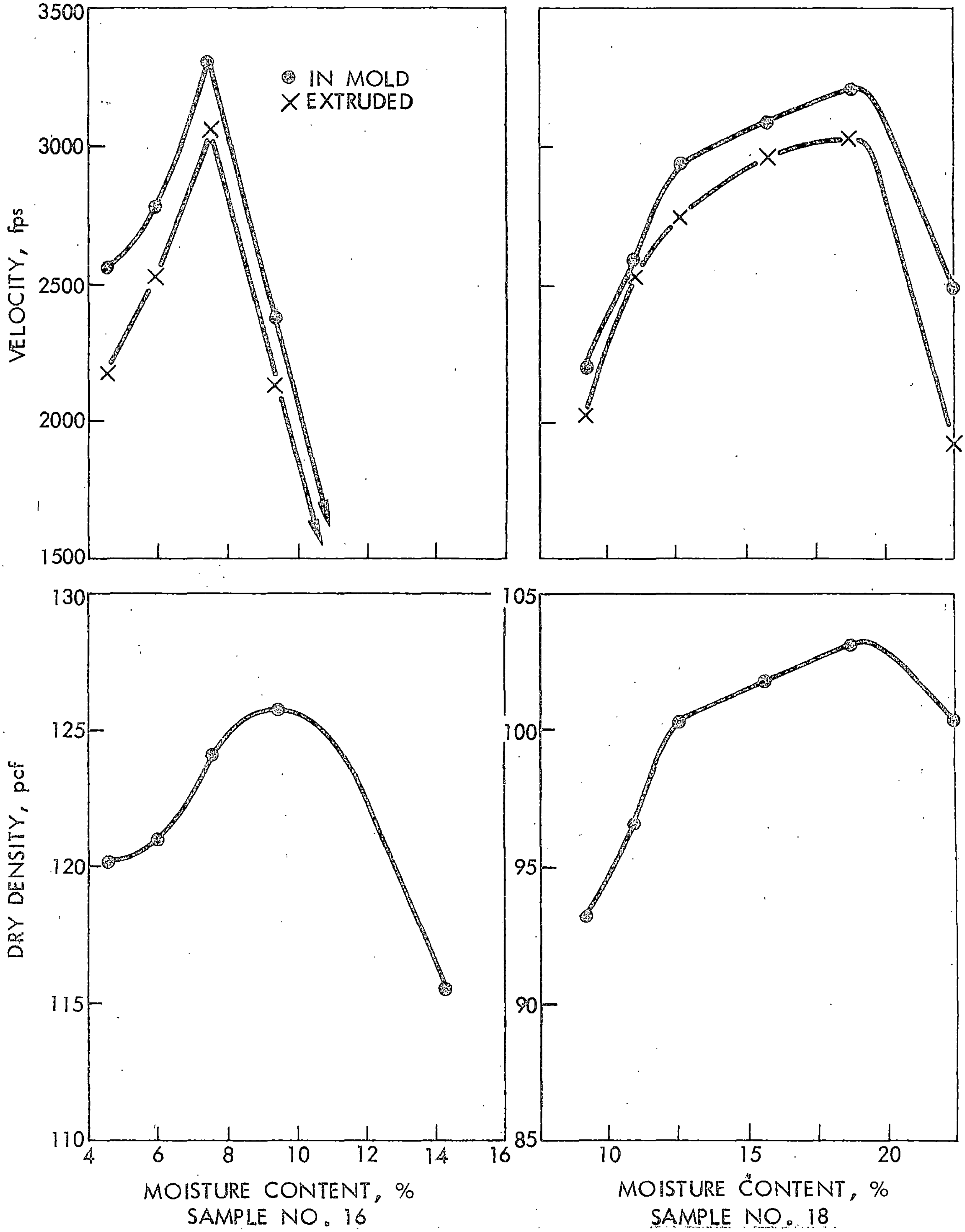


Fig. 56. Laboratory moisture-density-V-Scope velocity results, sample numbers 16 and 18.

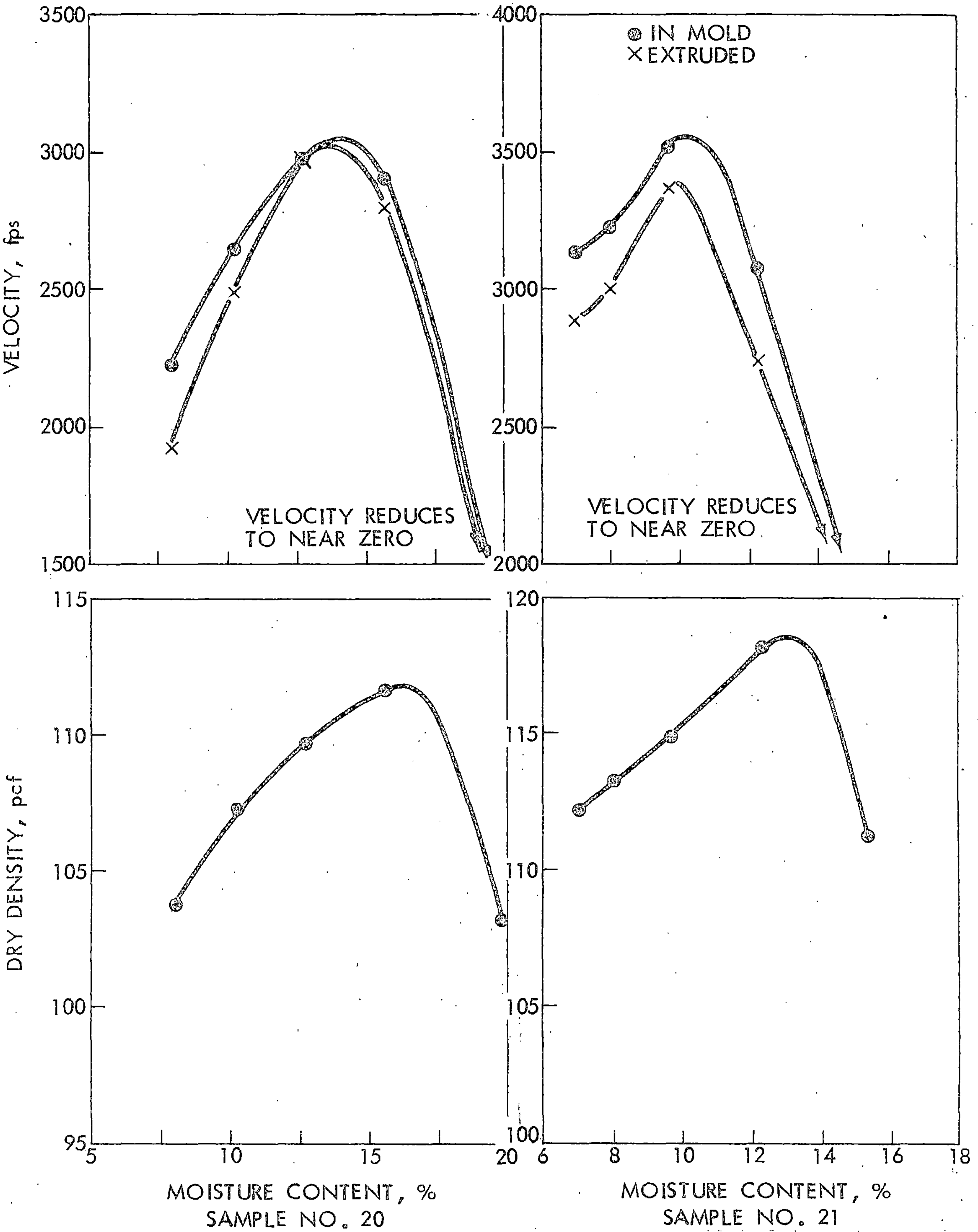


Fig. 57. Laboratory moisture-density-V-Scope velocity results, sample numbers 20 and 21.

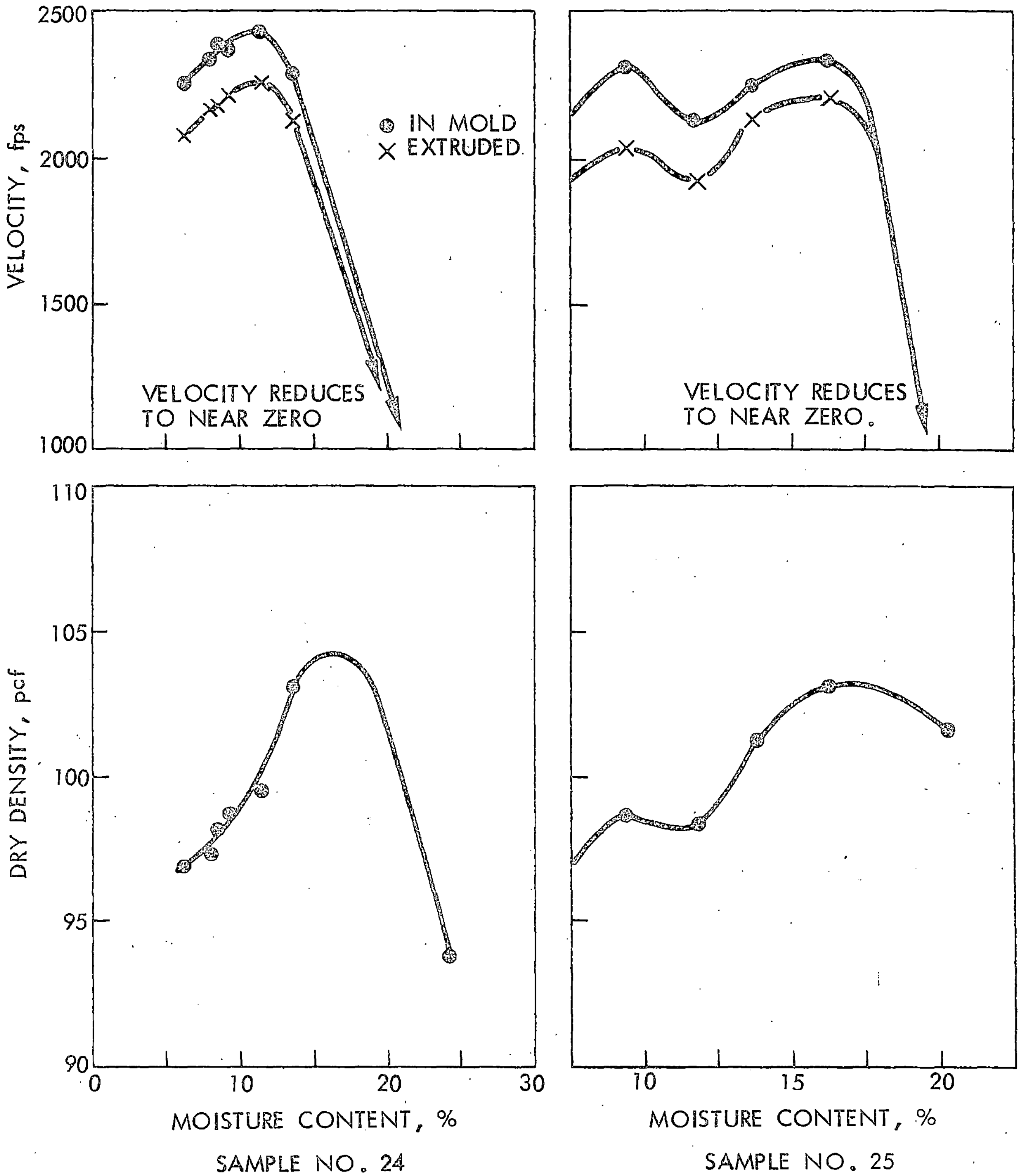


Fig. 58. Laboratory moisture-density-V-Scope velocity results, sample numbers 24 and 25.

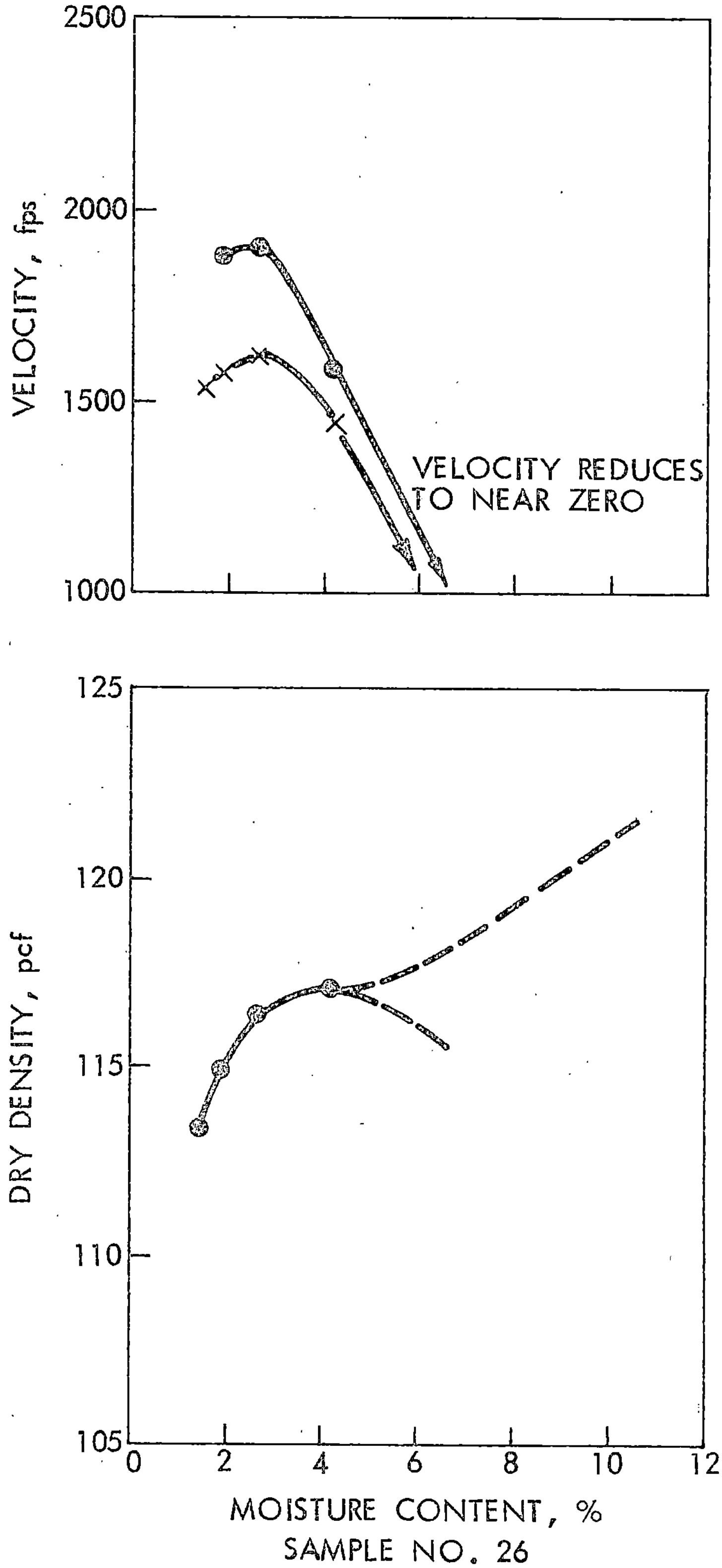


Fig. 59. Laboratory moisture-density-V-Scope velocity results, sample number 26.

Table 5. Summary of laboratory moisture-density-V-Scope velocity results.

Sample no.	AASHO classification	Maximum 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)	
			In mold	Extruded		In mold	Extruded	In mold	Extruded	In mold	Extruded
1	—	129.2	—	127.0	7.1	—	6.0	—	2420	2300	2250
2	A-4(2)	121.0	120.5	120.5	10.2	9.3	9.3	2700	2600	2670	2590
3	A-7-6(13)	91.0	91.0	90.8	23.0	23.0	21.8	2500	2380	2500	2350
4	A-4(1)	118.0	117.8	117.8	10.5	10.0	10.0	3400	3200	3380	3190
5	A-6-(2)	116.0	115.5	115.5	12.7	11.3	11.3	3610	3480	3020	2730
6	A-1-a	136.9	128.6	130.1	7.1	5.7	5.9	2600	2470	1490	1630
7	A-4(1)	119.8	118.4	118.4	11.7	8.7	8.7	3350	3170	2470	2120
8	A-6(7)	108.5	108.5	108.5	15.5	15.5	15.5	3060	2990	3060	2990
9	A-2-6(1)	122.9	121.8	121.8	11.2	8.7	8.7	3050	2880	2120	2300
11	A-1-a	125.0	117.7	117.7	7.0	3.8	3.8	2000	1750	1300	near 0
12	A-6(2)	117.7	116.7	117.2	11.1	10.4	10.6	3250	3150	3210	3130
13	A-2-6(0)	127.0	124.9	124.9	9.0	7.9	7.9	3650	3380	3230	2900
14	—	119.9	111.3	—	8.6	3.5	—	2540	—	2130	—
15	A-6(4)	112.8	112.0	112.7	12.7	12.0	12.5	3200	3100	3190	3100
16	A-2-4	125.7	124.0	124.0	9.4	7.6	7.6	3300	3050	2370	2130
18	A-7-6(4)	103.2	103.1	103.1	19.2	18.7	18.7	3200	3020	3190	3000
20	A-7-6(7)	111.7	110.7	110.5	16.3	14.2	13.6	3050	3010	2800	2680
21	A-2-6(0)	118.5	115.8	115.3	13.0	10.4	10.0	3550	3390	2760	2510
24	A-6(9)	104.2	99.6	100.0	13.0	10.5	10.7	2430	2250	1880	1760
25	A-6(9)	103.1	102.9	103.0	17.0	15.8	16.0	2330	2200	2290	2170
26	A-1-b	117.0	115.9	116.4	4.0	2.4	2.8	1910	1620	1640	1500

Shapes of the moisture-density and moisture-velocity curves were comparable for about two-thirds of the twenty-one materials tested. With the exception of sample number one in mold, moisture-velocity curves peaked at some maximum velocity. This is not fully consistent with the results of Sheeran, Baker and Krizek.[15]

As noted in Table 5, the moisture contents at maximum dry density were not within $\pm$ 0.5% of those for maximum velocity, as presented by Sheeran, et al.[15] Instead, moisture contents at a maximum velocity were from 0 to about 3% less than those at maximum dry density, with the exception of sample number 14 which was 5.1% less. These variations are more consistent with the results presented by Manke and Galloway,[8] who demonstrated that maximum velocities occurred on the dry side of optimum moisture content for a natural clay and silty clay. Results presented in Part 1 of this report also noted similar reduction in moisture content from maximum dry density to maximum velocity.

Moisture contents at maximum velocity in-mold varied from 1.4% greater to 0.5% less than those extruded, and were generally equal, one to the other. However, maximum velocities in-mold were from 40 to 290 fps higher than those extruded. Velocities at maximum dry density and optimum moisture content in-mold were from 180 fps less than, to 350 fps higher than, those extruded (disregarding sample number 11). Most of the variation in velocities in-mold to those extruded were probably due to

1. A shortened time of sonic wave movement by refraction through the steel mold.

2. A release of compactive energy following extrusion, decreasing the magnitude of particle to particle contact within the specimen.

In-mold velocities at optimum moisture content and maximum dry density were from 0 to 1110 fps less than in-mold maximum velocities, though over half were only 0 to 300 fps less. Disregarding sample number 11, extruded velocities at optimum moisture and maximum dry density were from 0 to 1050 fps less than in-mold maximum velocities, with slightly less than half only 0 to 300 fps less.

Though not conclusive, it is interesting to compare average in-mold and extruded velocities at optimum moisture content and maximum dry density with their respective broad AASHO classifications as noted in the following table.

AASHO classification	In-mold velocity(fps)	Extruded velocity(fps)
A-1	1477	1043
A-2	2620	2460
A-4	2840	2633
A-6 (without loess samples 24 and 35)	3120	2988
A-6 (with loess samples 24 and 25)	2775	2647
A-7	2830	2677

Disregarding the loess samples, numbers 24 and 25, there is an apparent peak-out of velocities in the A-6 group, possibly indicating the maximum potential of particle to particle contact of specimen grains. Including the loess samples, there is a striking similarity of average velocities from the A-2 through the A-7 classifications. The latter point tends to substantiate a portion of the theory presented in Part 1 of the report; i.e., seismic velocity is not a direct measure of soil density, and any correlation between density and velocity is empirical.

No in-place field tests were conducted with the V-Scope due to termination of project. However, Table 6 presents a comparison of selected V-Scope laboratory data with in-place field results using the Micro-Seismic Timer. The mutually common data point for comparison of results at each sample number was the optimum moisture content obtained during the V-Scope study. It is obvious from Table 6 that no correlation existed; the field velocities in every case being lower.

It is interesting to compare the magnitude of velocities obtained using the Micro-Seismic Timer and the V-Scope as noted in Tables 4, 5 and 6. In general, maximum velocities with the Timer are less than those with V-Scope, while maximum V-Scope velocities more closely follow the range of velocities of seismic waves in near surface soils presented by Leet[16] and summarized in the following table:

Generalized material	Velocity (fps)
Sand	650-6500
Loess	1000-2000
Alluvium	1600-6500
Loam	2600-5900
Clay	3300-9200

In a study of seismic refraction for subsurface investigations of rock, Staub[17] shows a relatively good correlation of results using a V-Scope on laboratory cores as compared to field measurements using a Aerospace Corporation GT-2A portable refraction unit over ¼ and ½ mile-long spreads.

It is also interesting to compare optimum moisture contents and maximum dry densities obtained during the V-Scope laboratory study and the Micro-Seismic field study for each of the various materials, Tables 4 and 5. The same mold, hammer and balances were used in each study but by different personnel. Conditions of test were different however: The V-Scope study was conducted under more nearly ideal laboratory conditions, including controlled temperature oven for moisture content determination, etc. Figures 49 through 59, and Table 5 indicate a much better control of moisture-density data.

Table 6. Comparison of V-Scope laboratory results with micro-seismic Timer field results.

Sample no.	AASHO classification	V-Scope (Laboratory) Maximum dry density (pcf)	Optimum moisture content (%)	Velocity at maximum dry density-optimum moisture content (fps) In mold	Extruded	Micro-Seismic Timer (Field) Maximum velocity at optimum moisture content (fps)	Dry density at optimum moisture content (pcf)
3	A-7-6(13)	91.0	23.0	2500	2350	1050[a]	93.0
8	A-6(7)	108.5	15.5	3060	2990	1250[a]	97.0
11	A-1-a	125.0	7.0	1300	near 0	930[b]	119.0
12	A-6(2)	117.7	11.1	3210	3130	1550[b]	115.7
13	A-2-6(0)	127.0	9.0	3230	2900	2150[b]	134.6
24	A-6(9)	104.2	13.0	1880	1760	1040[b]	76.0
25	A-6(9)	103.1	17.0	2290	2170	1070[b]	99.0
26	A-1-b	117.0	4.0	1640	1500	990[b]	110.0

(a) Velocity measured transverse to centerline.
(b) Velocity measured parallel to centerline.

CONCLUSIONS AND RECOMMENDATIONS

Following is a summary of conclusions and recommendations from laboratory tests utilizing the V-Scope for determination of first arrival seismic wave velocities.

1. The V-Scope appears to be more reliable and much less time consuming than a seismic timer for determination of velocities.
2. The equipment appears suitable for use with all types of materials compacted to a Proctor specimen size.
3. Shapes of moisture-density and moisture-velocity curves were comparable for about two-thirds of the materials tested. All but one of the remainder of the materials showed a peak point moisture-velocity curve.
4. Moisture contents at maximum velocity were equal to or less than moisture contents at maximum dry density which is consistent with previously reported data.
5. Velocities in-mold were generally higher than those obtained on extruded specimens of the same material. Field studies are needed to see which velocity is the most acceptable.
6. The V-Scope is adaptable to field use and can be fitted with other specific shapes or frequencies of transducers than those used in this laboratory study. Additional lab and field studies with this equipment are definitely recommended.

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