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HARDPAN FORMATION
In Coarse and Medium-textured Soils
In the Lower Rio Grande Valley of Texas

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Summary

Research on hardpans by the Texas Agricultural Experiment Station has contributed to a better understanding of their make-up from the standpoint of the physical, chemical and mineralogical characteristics. Hardpans are a function of the interactions of many factors, such as, (1) rate of moisture loss, (2) temperature, (3) time or aging, (4) sodium concentration of water and soil, (5) sand, silt, clay, soil aggregate and organic matter content of the soil and (6) tillage.

Soil hardpans are found in virgin, as well as cultivated areas, because the rates of moisture loss and temperatures are apparently optimum for intensifying soil strength. Soil strength is negatively related to the rate of moisture loss. The greatest soil strength has been achieved at approximately 27° C. Rate of moisture loss and temperature in the top foot of soil are often optimum in the Lower Rio Grande Valley for increasing soil strength in the compacted layer. These factors, plus aging, probably are responsible for the presence of hardpans in virgin soils in the Valley and other areas having similar soils.

Factors such as the sodium content of both the soil and irrigation water, the low percentage of water-stable aggregates due to low contents of clay and organic matter, the high percentage of fine and very fine sand, and silt make the above processes which contribute to soil strength even more effective.

Research has established that coarse-textured soils are extremely susceptible to compaction when they are tilled at high moisture content. This is probably the most important factor influencing compaction in soils under cultivation, although plant roots may exert compactive forces under certain moisture conditions. Plant roots may contribute to compaction by exerting compactive forces during the process of penetrating the soil and by setting up tension forces during the absorption of water.

Hardpan conditions can be alleviated or minimized by (1) periodic subsoiling, (2) discrete use of intensive farming practices over extended periods of time (cotton-vegetable rotation), (3) use of good quality water except in emergencies, (4) tilling when soil moisture content is such that minimum compaction takes place, which would occur when the surface three to four inches is fairly dry and (5) use of green manure crops in the crop rotation.

Contents

HARDPAN FORMATION IN COARSE AND MEDIUM-TEXTURED SOILS IN THE LOWER RIO GRANDE VALLEY OF TEXAS

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COMPACTED OR INDURATED SOIL LAYERS of reduced permeability in the soil profile are commonly called hardpans. The influence of hardpans on plant growth is widely recognized and has been discussed by many investigators. The literature has been comprehensively reviewed by Lutz (12), Raney, *et al.* (15), and Winters and Simonson (17). Raney *et al.* (15) classified compacted zones into induced and genetic hardpans. Dense layers in soils which were produced by compactive forces such as tillage implements were referred to as induced hardpans; whereas genetic hardpans have been used to describe those dense layers which have been produced during the soil weathering processes.

The development and occurrence of hardpans in certain soils have been attributed to many different agents or factors. Some of them which have been considered as contributing to hardpan formation are (1) iron and aluminum oxides, (2) amount and type of clay, (3) dispersed organic matter, (4) soluble aluminum, (5) colloidal silica, (6) cultivation when the soil is at optimum moisture content for compaction and (7) close-packing of soil particles.

According to a report by the American Society of Agricultural Engineers in 1958, investigators in 21 states and several Canadian provinces were actively engaged in soil compaction research. This report is indicative of the widespread occurrence of soil compaction and of the significance attached to its effects on agricultural production.

Modern farming practices have resulted in the frequent use of heavy equipment which is conducive to soil compaction. Many of the above investigators were engaged in field studies aimed at finding ways to minimize the adverse effects of compaction due to tillage implements. This type of research is needed, but it usually does not contribute to a basic understanding of compacted layers. This is particularly true of compacted layers that resemble induced hardpans but occur under virgin conditions. A basic understanding of the factors contributing to hardpan formation is essential to the establishment of management practices which will alleviate or minimize the adverse affects of genetic or induced hardpans. Further basic understanding of these hardpans can also contribute to a better understanding of soil properties such as crusting and aggregation.

In 1955, research was initiated at the Weslaco station in cooperation with the Department of Soil and Crop Sciences, Texas A&M University, to obtain a better understanding of hardpans in coarse and medium-textured soils in the Lower Rio Grande Valley. This information would apply not only to the Lower Rio Grande Valley, but also to similar hardpans in Texas and the United States. This publication is a summary of research conducted during 1955-62.

The objectives of this publication are (1) to point out the prevalence of certain hardpans both locally and nationally and to emphasize their influence on plant growth, (2) to present a description of the physical, chemical and mineralogical properties of such hardpans, (3) to discuss some of the factors which influence or contribute to the formation of hardpans and (4) to suggest methods and management practices for alleviating the unfavorable soil conditions caused by soil hardpans.

DESCRIPTION OF HARDPANS

Intensively farmed, irrigated, coarse and medium-textured soils, such as the Willacy fine sandy loam, are particularly susceptible to hardpan formation. These soils develop hardpans under both cultivated and virgin conditions. It is likely, therefore, that factors other than compaction from tillage implements contribute to their formation. The hardpans develop in the first foot of the soil profile and are usually from 3 to 6 inches thick.

In the Lower Rio Grande Valley, hardpans occur on most of the coarse and medium-textured soils. The intensity and thickness of the hardpans will vary from location to location, and indications are that hardpans on the coarse-textured soils usually are of greater intensity than those on soils of medium texture. Possible explanations for this occurrence will be presented later in the manuscript.

Most of the investigations reported here were conducted on Willacy fine sandy loam and Willacy loam soils. However, related soil types such as Hidalgo fine sandy loam[1] and Hidalgo loam soils are known to have hardpans.

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[1] Subsoiling study (2) reported on page 9 was on a Hidalgo loam soil.

Similar hardpans have been reported by investigators throughout the United States. Locke *et al.* (11) described similar hardpans at Woodward, Oklahoma and Mandan, North Dakota. Taylor and Gardner (16) have reported the occurrence of similar hardpans on the Amarillo fine sandy loam soil in the Southern Great Plains of Texas. In early 1900, Hilgard (9) observed that a sandy loam soil in California would develop hardpans which were impervious to water and roots. He attributed the formation of these hardpans to close-packing of soil particles.

The close-packing of soil particles mentioned by Hilgard (9) was apparently similar to the hardpans that occur in the Lower Rio Grande Valley, with the exception that those described by Hilgard occurred at soil depths of 18 to 36 inches. It is apparent from a survey of the literature that similar hardpans, as described above and more completely defined in the next section, are fairly widespread. Their importance in soil and crop management has long been recognized and is not a problem of recent origin.

Soil hardpans may significantly affect the growth of plants and the production of crops. Reduced permeability of the soil to air, water and plant root activity may result in a significant reduction in crop yield, making the problem one of economic importance to the farmer.

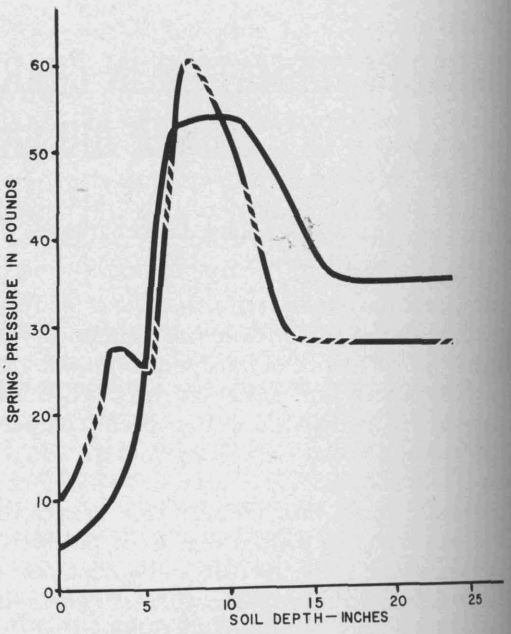

Figure 1. *Typical field hardpan in Willacy fine sandy loam as characterized by two penetrometer curves (7). The two curves show some of the variability in the intensity and thickness of the hardpan.*

PHYSICAL, CHEMICAL AND MINERALOGICAL DESCRIPTION OF HARDPAN AND ASSOCIATED SOIL LAYERS

A summary of the physical and chemical properties of Willacy fine sandy loam from five locations is indicated in Tables 1 and 2 (13, 14). The hardpan layer can be identified by lower water permeability as indicated by hydraulic conductivity data, although the bulk density values were not greatly different from the layers below the hardpan. The existence of the hardpan is easily distinguishable by penetrometer analyses as indicated in Figure 1 (7).

The coarse-textured Willacy fine sandy loam soil is characterized further by a low percentage of clay and high percentage of fine and very fine sand (13). According to Milford (14), the content of cementing agents essential for aggregate formation is low as indicated by low percentages of clay, organic matter, and extractable SiO_2, Fe_2O_3 and Al_2O_3, Table 2. Water-stable aggregates were found to be almost

TABLE 1. PHYSICAL PROPERTIES OF THE WILLACY FINE SANDY LOAM SOIL (13).

Samples[1]	Depth of sample, inches	Bulk density, g./cm.	Hydraulic conductivity, inches/hr.	Particle size distribution, percent			Sand separates, percent[2]				Clay separates percent[2]	
				Sand 2-0.05mm.	Silt $50\text{-}2\mu$	Clay $<2\mu$	0.5mm.	0.5-0.25mm.	0.25-0.10mm.	0.10-0.05mm.	$2\text{-}0.2\mu$	$<0.2\mu$
1-T	1-4	1.34	2.7	71.4	17.7	10.9	0.2	1.6	57.7	11.9	50	50
1-H	16-12	1.38	0.8	68.9	18.4	12.7	0.2	1.7	55.4	11.6	51	49
1-U	13-19	1.40	4.9	65.9	18.9	15.2	0.2	1.7	53.4	10.6	57	43
2-T	1-4	1.36	2.0	77.7	14.5	7.8	0.2	1.9	62.1	13.5	47	53
2-H	5½-10	1.60	1.1	71.2	16.8	12.0	0.2	1.3	55.9	13.8	46	54
2-U	12-16	1.60	1.4	70.4	15.3	14.3	0.2	1.4	56.3	12.5	46	54
3-T	1-4	1.44	0.8	80.0	11.6	8.4	0.2	1.8	66.7	11.3	46	54
3-H	7-12	1.56	0.3	73.9	12.7	13.4	0.2	1.5	62.1	10.0	44	56
3-U	14-19	1.39	5.2	68.0	14.7	17.3	0.2	1.2	55.5	11.1	45	55
4-T	1-4	1.41	7.5	84.6	8.8	6.6	0.1	0.4	75.6	8.5	53	47
4-H	5-9	1.53	1.5	82.8	8.5	8.7	0.1	0.4	73.7	8.6	51	49
4-U	9-14	1.51	2.9	78.8	9.1	12.1	0.1	0.3	69.4	9.0	48	52
5-T	1-3½	1.44	4.5	64.3	21.3	14.4	0.1	0.4	49.9	13.9	57	43
5-H	3½-7½	1.62	1.9	65.5	18.4	16.1	0.1	0.4	50.6	14.4	58	42
5-U	8-12	1.55	3.7	61.2	18.4	20.4	0.1	0.4	47.5	13.2	49	51

[1] Samples 1, 2 and 3 are from cultivated sites, while 4 and 5 are from virgin sites. The Letter T denotes the surface sample; the letter H, the hardpan sample; and the letter U, the sample subjacent to the hardpan.

[2] Sand separates are reported as percentage of the soil, while clay separates are reported as percentage of the clay fraction.

negligible and often less than 2 percent (6). Such physical properties indicate that this soil is essentially single-grained in structure. The low content of stable aggregates makes the soil extremely susceptible to close-packing but not susceptible to the development of planes of weakness in the profile such as occur in the finer-textured soils. The amount of cementing agents and aggregation have been found to be greater in the medium than in the coarse-textured soils. This might help to explain the greater soil strength of hardpans in coarse than in medium-textured soils.

The exchangeable sodium percentages reported by Milford (14) (Table 2) are rather low except in the case of site 3. However, Gerard *et al.* (6) have reported higher concentrations of exchangeable sodium in similar soils, Table 3. This factor would make the soils more susceptible to hardpan formation. The sodium ion disperses the soil particles and, therefore, makes the soil more susceptible to compaction.

Milford *et al.* (13) reported quartz to be the major component of the sand and silt fractions of the Willacy fine sandy loam, although feldspars and micas were present. They also found the clay fraction to be composed predominantly of illite and a poorly crystallized, weathered product of illite with small amounts of kaolinite and quartz.

Studies by Milford *et al.* (13) indicated no differences in the physical, chemical and mineralogical properties between the hardpan and adjacent layers. However, hydraulic conductivity data of undisturbed cores of these layers indicated the existence of a hardpan. Penetrometer analyses of these soils (7) also indicated the presence of a hardpan.

Penetrometer analyses have indicated that soil hardness in the hardpan was a function of moisture content. Taylor and Gardner (16) also have pointed out this fact by stating that plant root development is dependent not only upon the occurrence of a soil hardpan, but also on the moisture content of the compacted layer.

TABLE 3. EXCHANGEABLE SODIUM PERCENTAGES OF WILLACY FINE SANDY LOAM IN 1957 AND 1958 AS INFLUENCED BY SOIL AND WATER TREATMENTS (6)

Soil treatments		Year — 1957		Year — 1958	
		Depth		Depth	
		0-6	6-12	0-6	6-12
No treatment	Canal[1]	13.7	5.4	4.0	5.8
	Well[2]	25.5	16.9	10.7	14.1
Krilium	Canal	13.2	7.4	3.7	5.0
	Well	25.5	21.3	11.1	12.8
Gypsum	Canal	15.6	6.8	3.5	4.8
	Well	20.5	20.1	9.1	12.9
Sulfur	Canal	10.1	4.0	3.4	4.3
	Well	18.3	11.0	10.2	12.7

[1] Canal water (good quality water) contained about 800 ppm total salt. The cation concentration was about 50 percent sodium and 50 percent calcium plus magnesium.

[2] Well water (poor quality water) contained about 2,400 ppm total salts. The cation concentration was about 75 percent sodium and 25 percent calcium plus magnesium.

INVESTIGATIONS OF FACTORS WHICH INFLUENCE HARDPAN FORMATION

Research concerning hardpans and their formation was initiated at the Lower Rio Grande Valley Experiment Station and has been directed toward obtaining data that would lead to a better understanding of the interrelated factors contributing to the formation of such hard layers in the soil. It was generally agreed that soils in which the hardpans occurred were susceptible to compaction by tillage implements, but the presence of such compacted layers under virgin conditions has indicated that factors other than forces exerted by tillage implements were instrumental in their formation. Studies were initiated and research techniques were developed to evaluate the influence of such factors as moisture level treatments, rate of moisture loss, temperature, relative

TABLE 2. CHEMICAL PROPERTIES OF THE WILLACY FINE SANDY LOAM SOIL (13, 14)

Sample	pH 1:1 soil paste		Organic matter, percent	Cation exchange capacities, me/100g.			Exchangeable cation percentages				Base saturation, percent	SiO_2, percent	F_2O_3, Percent	$A1_2O_3$, percent
	1 hr.	5 hr.		Soil	$2\text{-}0.2\mu$	$<0.2\mu$	Ca	Mg	K	Na				
1-T	7.6	7.6	1.3	11.1	46	83	70	19	10.2	1.8	101	0.18	0.29	0.34
1-H	7.7	7.8	0.9	12.7	47	89	66	16	7.0	1.5	91	0.14	0.28	0.35
1-U	7.9	8.0	0.8	14.7	52	93	64	16	5.9	2.8	89	0.13	0.32	0.40
2-T	7.3	7.4	1.1	8.7	41	78	65	16	9.9	2.1	93	0.13	0.25	0.31
2-H	7.5	7.6	0.9	11.8	44	98	61	17	6.8	2.3	87	0.12	0.30	0.36
2-U	7.7	7.8	0.7	13.4	50	90	60	16	4.9	4.4	85	0.09	0.35	0.50
3-T	7.3	7.3	1.0	8.9	44	88	59	17	8.2	3.7	88	0.10	0.28	0.16
3-H	7.9	7.8	0.9	14.3	47	94	51	15	7.4	8.6	82	0.12	0.28	0.15
3-U	8.0	8.2	0.8	15.5	54	87	55	16	7.4	13.4	92	0.13	0.36	0.10
4-T	6.5	6.6	0.6	6.2	37	76	53	14	6.3	1.4	75	0.12	0.22	0.11
4-H	6.3	6.4	0.7	7.4	37	81	51	16	6.3	1.2	75	0.11	0.22	0.35
4-U	6.4	6.5	0.6	10.3	41	85	50	16	5.6	1.1	73	0.10	0.23	0.36
5-T	7.2	7.3	1.6	13.6	45	77	58	15	10.0	3.7	87	0.20	0.31	0.32
5-H	7.3	7.4	1.5	14.7	47	80	63	13	10.0	1.6	88	0.18	0.32	0.32
5-U	7.3	7.4	1.2	16.7	45	86	66	15	7.5	1.7	90	0.16	0.41	0.51

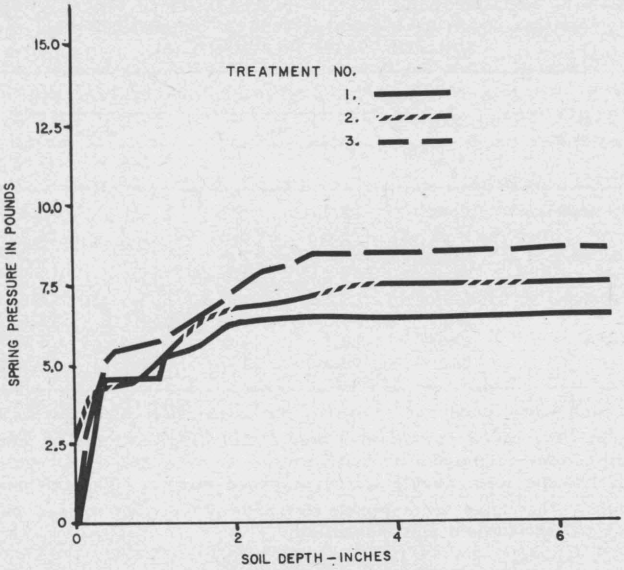

Figure 2. The influence of treatments 1, 2 and 3 on soil compaction at various depths as evaluated with a self-recording soil penetrometer (7). Description of soil moisture treatments are indicated in Table 4.

humidity, and wetting and drying cycles on soil compaction or strength. The compactibility of the problem soils at different soil moisture contents has been studied. The influence of different proportions of sand and silt-clay fractions in the soils as related to hardpan formation has also been evaluated.

In 1959, a laboratory investigation was initiated to evaluate the influence of certain factors on close-packing of soil particles in the Willacy fine sandy loam soil. Columns 3¾ inches in diameter and 12 inches high were filled with air-dry soil to a depth of 9 inches. These columns were divided into six duplicated treatments as described in Table 4. After saturation the columns were weighed and placed in a force-draft oven at 50° C. Each column was weighed daily until the moisture losses indicated that it was time to saturate it again. Each treatment received the number of irrigations listed in Table 4. After the indicated number of irrigations, the soil columns were evaluated as to soil consistency or compaction with a soil penetrometer.

TABLE 4. DESCRIPTION OF DIFFERENT SOIL MOISTURE TREATMENTS AND NUMBER OF IRRIGATIONS PRIOR TO ANALYSES WITH SOIL PENETROMETER. COLUMNS WERE DRIED THE INDICATED WETTING AND DRYING CYCLES IN A FORCE-DRAFT OVEN AT 50° C. (7)[1]

		Number of irrigations[1]
1.	Subirrigated when the average soil moisture was 12.2 per cent (≅ 1/3 atm. percentage)	25
2.	Subirrigated when the average soil moisture was 10.6 percent (≅ 3/4 atm. percentage)	23
3.	Subirrigated when the average soil moisture was 9.0 percent (≅ 2 atm. percentage)	17
4.	Subirrigated when the average soil moisture was 9.0 percent (≅ 2 atm. percentage) The soil surface was mulched with a spatula to a depth of 2 inches when the moisture content of the soil in the columns was approximately 13 percent.	18
5.	Surface irrigated (500 cc. of water) when the average soil moisture was 9.0 percent (≅ 2 atm. percentage). The surface was mulched with a spatula to a depth of 2 inches when the moisture content of the soil was approximately 13 percent.	17
6.	Subirrigated when the average soil moisture was approximately 1.0 percent or air-dry.	9

[1] Number of irrigations could be called wetting and drying cycles.

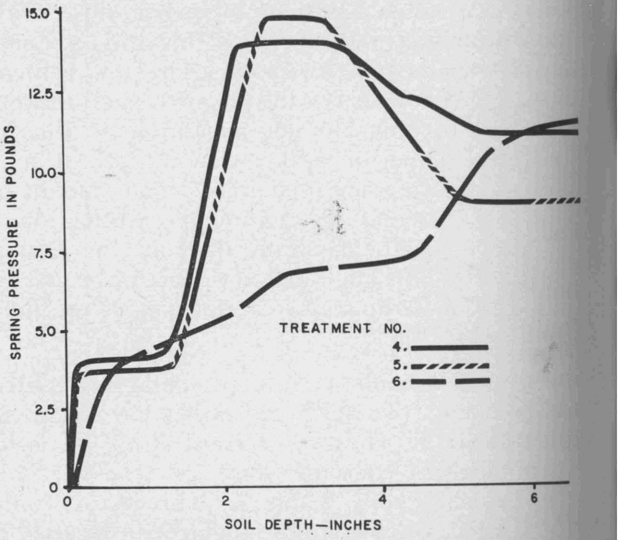

Figure 3. The influence of treatments 4, 5 and 6 on soil compaction at various depths as evaluated with a self-recording soil penetrometer (7). Description of soil moisture treatments are indicated in Table 4.

During this investigation, Gerard *et al.* (7) were able to develop hardpans under laboratory conditions and thus achieve a better understanding of the factors affecting their formation. Hardpans produced in the laboratory were not of the intensity found in the field but were characteristically similar to them.

Results of penetrometer analyses as shown in Figures 2 and 3, demonstrate that treatments 4, 5 and 6 produced greater soil strength than treatments 1, 2 and 3. The mulching operation may have caused differences in soil strength in the case of 4 and 5, but this does not explain the greater soil strength with depth under treatment 6, Figure 3. The investigators (7) have postulated that a slow rate of moisture loss contributed to differential soil strength as shown by the penetrometer measurements under treatment 6 and possibly treatments 4 and 5.

As a result of the initial findings, further research was undertaken to determine if a relationship existed between the rate of moisture loss and soil strength or compaction. Results of this investigation definitely showed a negative correlation between the rate of moisture loss and soil strength, Figure 4 and Table 5. Briquets, which were imbedded in air-dry soil to cause slow drying, were 25 to 30 percent stronger than surface-dried briquets. Lemos and Lutz (10) have reported that the rate of drying on briquet strength was important. Gill (8) postulated also that the action of the soil moisture films during drying was an extremely important factor in effecting the intensity of soil strength of a clay.

As indicated in Figure 4, maximum soil strength was achieved at 27° C. Briquets dried at 32° C. were slightly weaker than briquets dried at 27° C; briquets dried at 21° C. and 75 percent relative humidity were markedly lower in strength than briquets dried at 27° C. and 32° C. and 75 percent relative humidity. This might suggest that climatic conditions in the Lower Rio Grande Valley are often optimum for the development of hardpans. Results above may help explain the greater soil strength found by Locke *et al.* (11) in Oklahoma than in North Dakota.

In 1960, a laboratory experiment was conducted to evaluate the influence of moisture level, compactive force and drying cycles on soil compaction. Eighteen 2-gallon pots were filled to a depth of approximately 9 inches. The experiment consisted of nine soil moisture and compactive force treatments which are described in Table 6. The amount of force applied, mulching and irrigations were conducted according to the treatment schedule. Pots were placed in a constant temperature room at 32° C. and 25 percent relative humidity and were weighed at least every 2 days in order to determine the time for applying the scheduled treatment.

The research, to date, has established that temperature greatly influences soil strength.[2] The degree of packing or soil hardness attained at 32° C. was approximately twice the degree of hardness attained at 50° C. (4), Figures 2 and 5. It was also postulated from these data that soil hardness or strength was proportional to the degree of packing of soil particles and/or inversely proportional to the development of minute planes of weakness in the soil mass. In a previous paper the authors (7) have pointed out that penetrometer analyses are generally considered indices of soil consistency, compaction or close packing of soil particles. However, the penetrometer measurement may be an indication of relative numbers of planes of weakness occurring within the soil mass. These two conditions would not be synonymous necessarily since a close-packed soil could either have few or numerous planes of weakness.

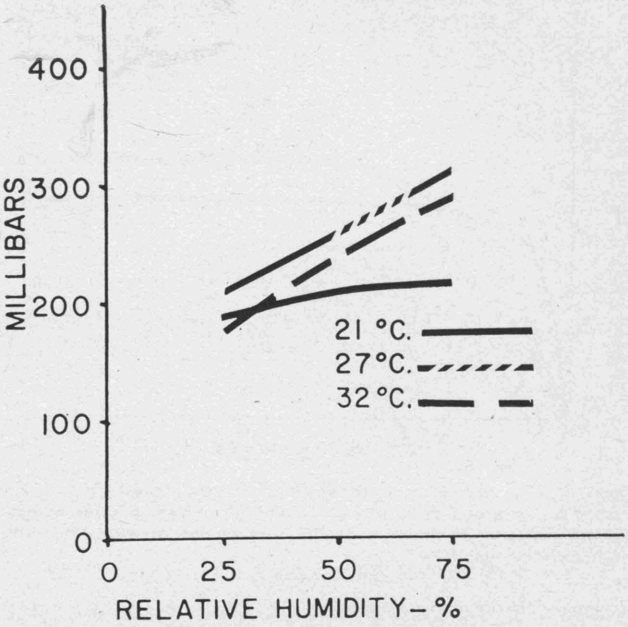

Figure 4. The influence of temperature and relative humidity on briquet strength expressed in millibars (4).

Further evidence concerning the influence of moisture loss rates on soil strength is apparent from a comparison of Figures 5, 6 and 7, (treatments 1, 4 and 7).

The increase in soil strength shown in these figures with successive wetting and drying cycles would indicate relatively rapid rate of particle rearrangement. This also would suggest that the beneficial effect of subsoiling in irrigated soils of the Valley may be short lived.

Other data (7) indicate that these soils are extremely susceptible to compaction by tillage imple-

TABLE 5. THE RELATIONSHIP BETWEEN BREAKING STRENGTH OF BRIQUETS (MILLIBARS) AND RATE OF MOISTURE LOSS (G./HR.) (4)

Drying temperature		Equation	R_3
°F	°C		
70	21	$y_1 = -40.2\ x_2 + 234.3$	−0.765
80	27	$y = -82.8\ x + 345.1$	−0.998
90	32	$y = -49.1\ x + 331.5$	−0.996

y = modulus of rupture in millibars.
x = rate of moisture loss in g./hr.
Correlation coefficient.

TABLE 6. DESCRIPTION OF SOIL MOISTURE AND COMPACTIVE FORCE TREATMENTS. TREATMENTS WERE DRIED AT 32° C. AND 25 PERCENT RELATIVE HUMIDITY (4)[1]

Treatment number[2]	Force applied lb./sq. in.[3]	Percent moisture at time of compaction and mulching[4]	Percent moisture when irrigated
1	0	12.5	9.5
2	5	12.5	9.5
3	10	12.5	9.5
4	0	9.5	6.5
5	5	9.5	6.5
6	10	9.5	6.5
7	0	5.0	2.5
8	5	5.0	2.5
9	10	5.0	2.5

[1] Penetrometer analyses of treatments 1, 3, 4 and 7 will be presented as Figures 5, 6, 7 and 8; penetrometer analyses of treatments 2, 5, 6, 8 and 9 will not be presented in this manuscript but are presented in (4).
[2] Each treatment was duplicated.
[3] The force was applied by using a hydraulic jack and platform scale.
[4] 12.5 percent ≅ ½ atmosphere percentage; 9.5 percent ≅ 7 atmosphere percentage; 6.5 percent 15 atmosphere percentage.

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[2] Soil strength refers to the ability of the soil to resist force or penetration.

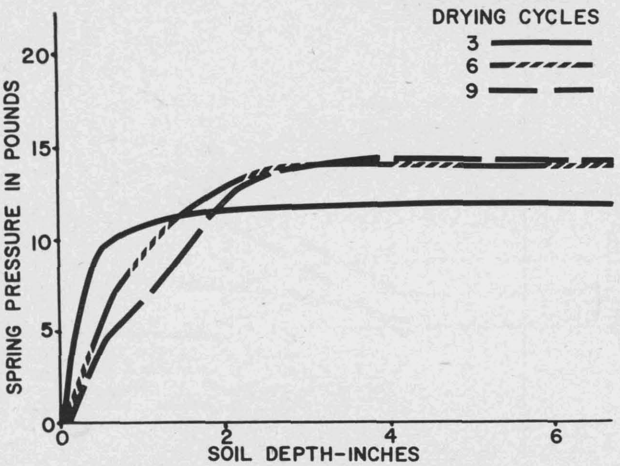

Figure 5. The influence of treatment 1 (0 force, mulching at 12.5 percent moisture and dried at 32° C. and 25 percent relative humidity) and numbers of drying cycles on compaction as evaluated with a soil penetrometer (4).

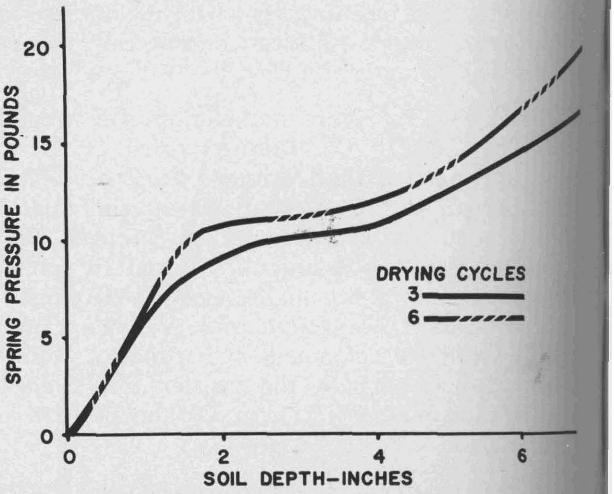

Figure 7. The influence of treatment 7 (0 force, mulching at 5.0 percent moisture and dried at 32° C. and 75 percent relative humidity) and numbers of drying cycles on compaction as evaluated with a soil penetrometer (4).

ments. The coarse-textured soils are often cultivated after surface drying when subsurface moisture is optimum for compaction. Evidence of the susceptibility of these soils to compaction is indicated in Table 7 and Figure 8.

Cultivation of these soils when subsurface moisture is at a high level is probably conducive to compaction because of the compactive force of the tillage implements and the behavior of the soil moisture films within the compacted layer. Compaction due to tillage implements often improves the capillary conductivity of soils and, therefore, increases the probability of replacing the water films which are evaporated from the dense layer. Evaporation of the water films from the compacted layer usually occurs by vapor movement through the cultivated or mulched surface soil. The evaporation of the water films and subsequent capillary conductivity results in the action of repeated cohesive forces on the soil particles in the affected zone. The cohesive forces exerted by the moisture films are apparently a function of both the rate of evaporation and of temperature. During the evaporative process, repeated cohesive action of the moisture films on the soil particles is conducive to further strengthening of the already compacted layer.

There is indirect evidence that considerable force is probably exerted by plant roots. The force of plant roots and their effect on soil compaction have not been comprehensively evaluated. The influence of plant roots on soil structure has generally been considered completely beneficial because the roots return organic matter to the soil and cause lines of weakness in the soil mass. In spite of such beneficial effects of plant roots, it is important to recognize that plant roots can and probably do exert excessively high compactive forces which are probably functions of both soil moisture content and type of plant. Furthermore, stresses developed by plant roots during the absorption of water may contribute significantly to soil compaction. More research is needed to evaluate these effects.

Bauer (1) has submitted different soil mixtures of sand and silt-clay fractions of Willacy fine sandy

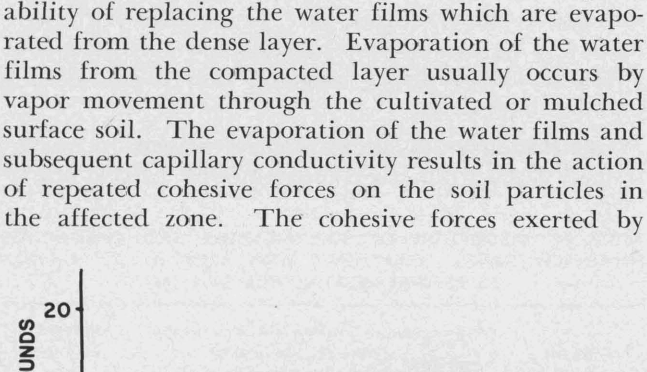

Figure 6. The influence of treatment 4 (0 force, mulching at 9.5 percent moisture and dried at 32° C. and 25 percent relative humidity) and numbers of drying cycles on compaction as evaluated with a soil penetrometer (4).

TABLE 7. THE INFLUENCE OF SOIL MOISTURE ON THE COMPACTIBILITY OF WILLACY FINE SANDY LOAM (7)

Soil moisture percentage	Bulk density g./cc
3.8	1.76
6.5	1.88
8.6	1.99
10.6	2.09
12.4	2.08
14.3	1.99
16.0	1.93

A Standard Proctor Apparatus was used to apply the compaction force. The compaction force was a 5-pound hammer and a 12-inch fall, 3 layers—25 blows per layer. Compaction force = 6.63 foot-pounds per cubic inch.

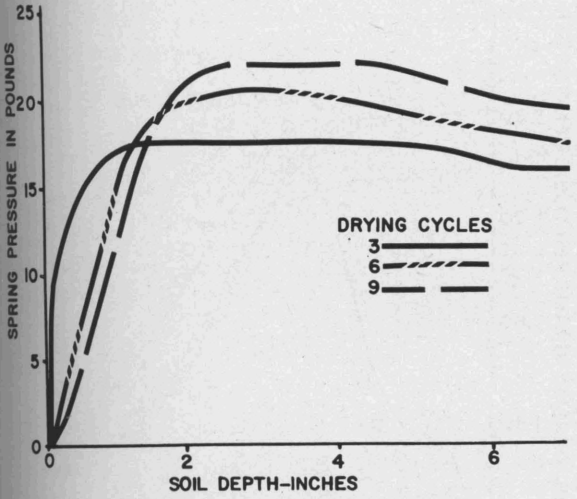

Figure 8. The influence of treatment 3 (10 lb./in.^{2} of force, mulching at 12.5 percent moisture and dried at 32° C. and 25 percent relative humidity) and number of drying cycles on compaction as evaluated with a soil penetrometer (4).

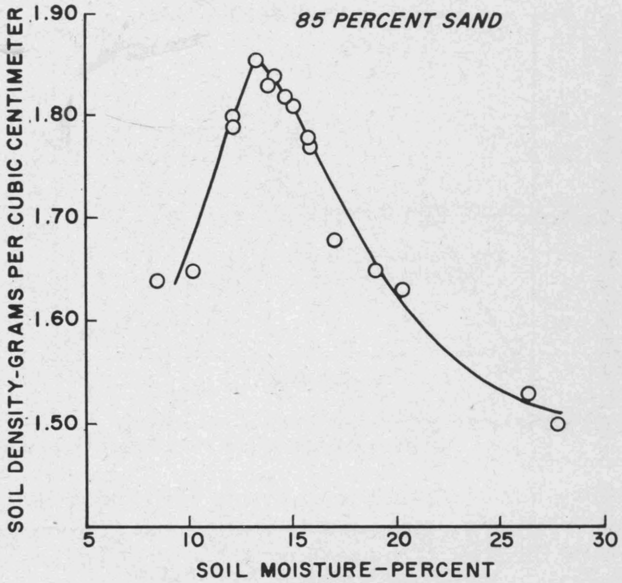

Figure 10. Compactibility of 85 percent sand and 15 percent silt and clay at different moisture contents (Mixture II) (1).

loam to different soil moisture treatments. He reported that the wetting and drying of the different soil mixtures did not yield any evidence which would indicate the formation of compacted layers. The research data suggest the need for further investigation and modification of these treatments before final interpretation of the role of particle size and moisture level treatment and their interaction on soil strength can be made. Compactive curves of these mixtures are indicated in Figures 9, 10, 11 and 12. The curves show that maximum compaction for mixtures II and III was approximately 13.5 percent moisture and for mixture IV was 15.0 percent moisture.

SUGGESTED MANAGEMENT PRACTICES TO ALLEVIATE HARDPAN CONDITIONS

The practice most generally recommended for alleviating the undesirable effects of hardpan as outlined in this publication, is subsoiling. Burleson *et al.* (2) have reported substantial increases in cotton yield

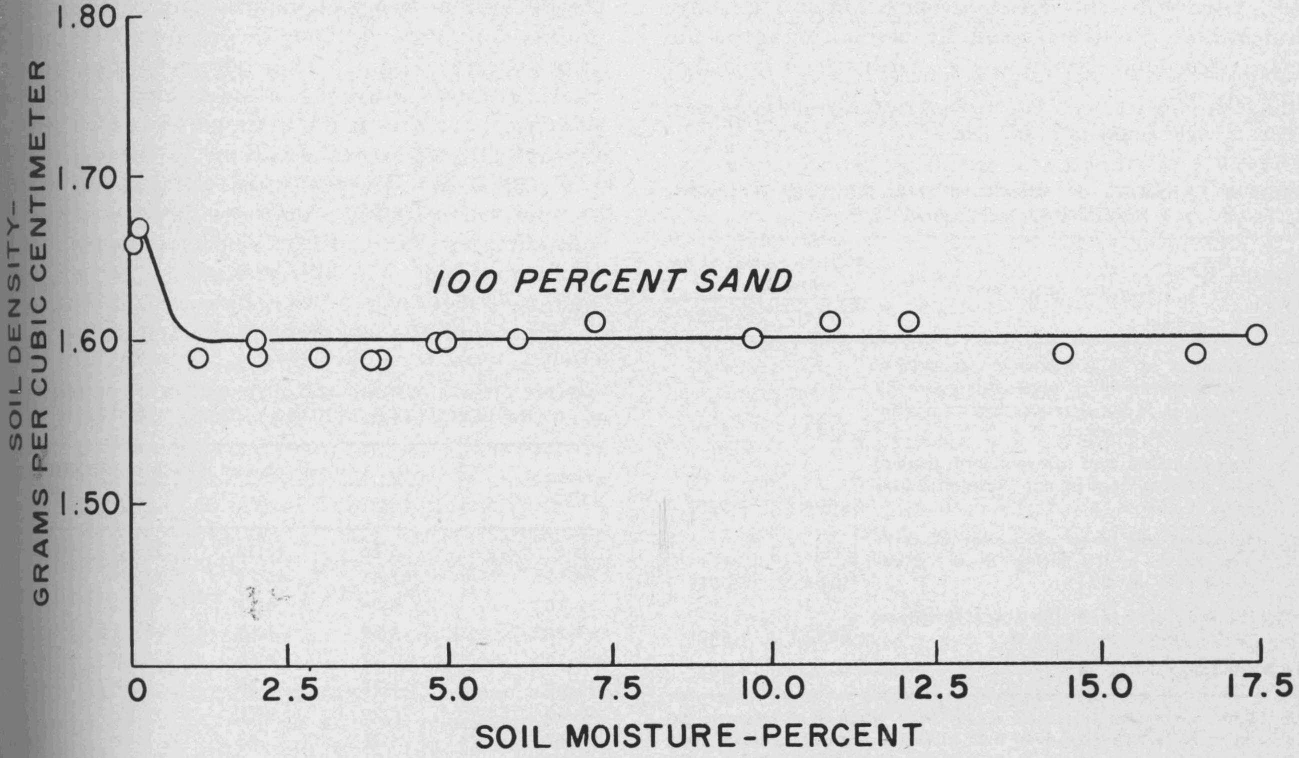

Figure 9. Compactibility of 100 percent sand at different moisture contents, (Mixture I) (1).

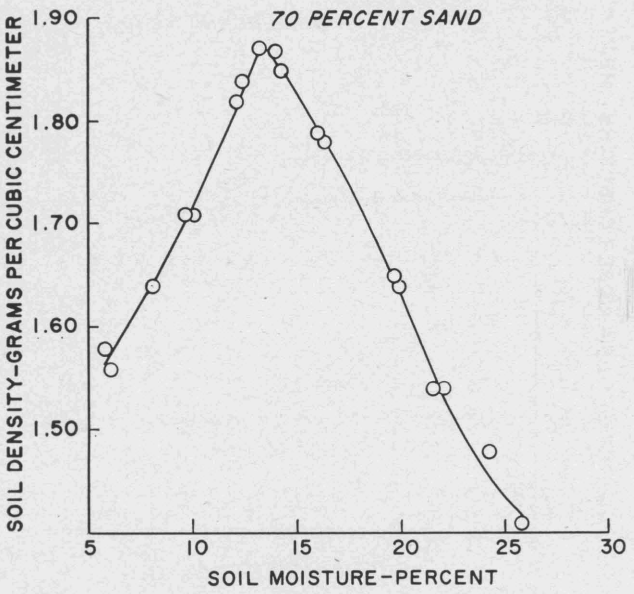

Figure 11. Compactibility of 70 percent sand and 30 percent silt and clay at different moisture contents (Mixture III) (1).

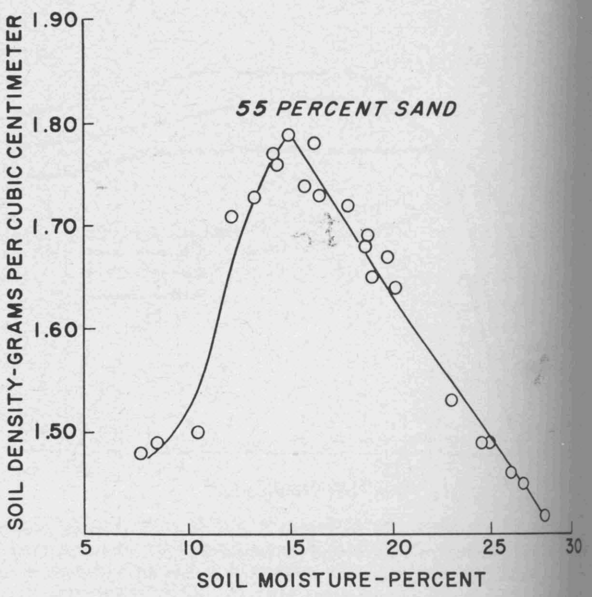

Figure 12. Compactibility of 55 percent sand and 45 percent silt and clay at different moisture contents (Mixture IV) (1)

from subsoiling. These data are shown in Table 8. Increased growth of cotton due to subsoiling was especially marked in 1956 but only minor differences in height were noted in 1957, Figure 13 (2). Root distribution as influenced by subsoiling are indicated in Table 9. The increase in the concentration of cotton roots in the 6 to 12-inch zone could have been a result of subsoiling.

A comparison of a hardpan condition before and after thorough cross-chiseling[3] is presented in Figure 14. Obviously, the chiseling operation was effective in breaking up the hardpan. The subsoiling operation often does not eliminate the hardpan entirely but does create some planes of weakness in the soil mass. Research is needed to evaluate further the effectivness of the different subsoiling procedures and their residual influence on crop growth and yield.

Gerard *et al.* (6) and others have reported a high correlation between exchangeable sodium and soil strength as evaluated by modulus of rupture analyses. The use of "poor" quality water (high sodium content) can definitely intensify soil strength and hardpan formation in these soils. In these investigations, the "poor" quality water contained about 2,400 parts per million of total salt and 75 percent of the soluble cations were sodium. The sodium ion disperses soil particles and intensifies close-packing. Studies at Weslaco have shown the existence of a high concentration of exchangeable sodium in the top foot of soil, Table 3. Dispersion of soil particles by the sodium ion probably accelerates the close-packing of soil particles due to tillage or cohesive action of soil moisture films. For this reason, the use of "poor" quality irrigation water may have a marked influence on the subsoiling requirement of these soils.

TABLE 8. SUMMARY OF SUBSOILING AND FERTILIZER PLACEMENT TREATMENTS IN 1956 AND 1957 (2)

Treatment	Description of treatment	Average pounds of lint cotton per acre	
		1956	1957
A[1]	Subsoiled to 18 inches and conventional method of fertilizer application with 60 pounds of N per acre applied as a sidedressing at squaring.	1156	689
B	Non-subsoiled and conventional method for fertilizer application. Sidedressed as in A.	1094	570
C	Subsoiled and deep placement of fertilizer at 6 to 18 inches deep. Sidedressed as in A.	1187	609
D	Non-subsoiled with deep placement as in C. Sidedressed as in A.	1087	538
L.S.D. (0.05)		N. S.	103

[1] In 1956, conventional method of fertilizer application refers to 60 pounds of N and 60 pounds of P_2O_5 placed in the soil approximately 3 inches below the seed zone before planting. The P_2O_5 was increased to 120 pounds in 1957.

TABLE 9. TOTAL WEIGHT AND DISTRIBUTION OF COTTON ROOTS AS INFLUENCED BY SUBSOILING AND DEEP FERTILIZATION (2)

Depth, inches	Percent of total weight by treatment			
	A	B	C	D
0-6	5.26	33.33	27.01	6.71
6-12	82.41	46.75	51.00	70.78
12-18	4.04	4.11	3.84	6.02
18-24	3.32	5.40	5.02	5.95
24-36	3.47	6.88	9.83	8.40
36-48	1.25	2.79	2.67	3.00
48-60	.24	.71	1.13	.10
60-72	.06	.03	.49	.04
Total weight (g.)	4.5	5.3	5.9	5.4

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[3] Cross-chiseling is a term used to described two chiseling operations at right angles to each other.

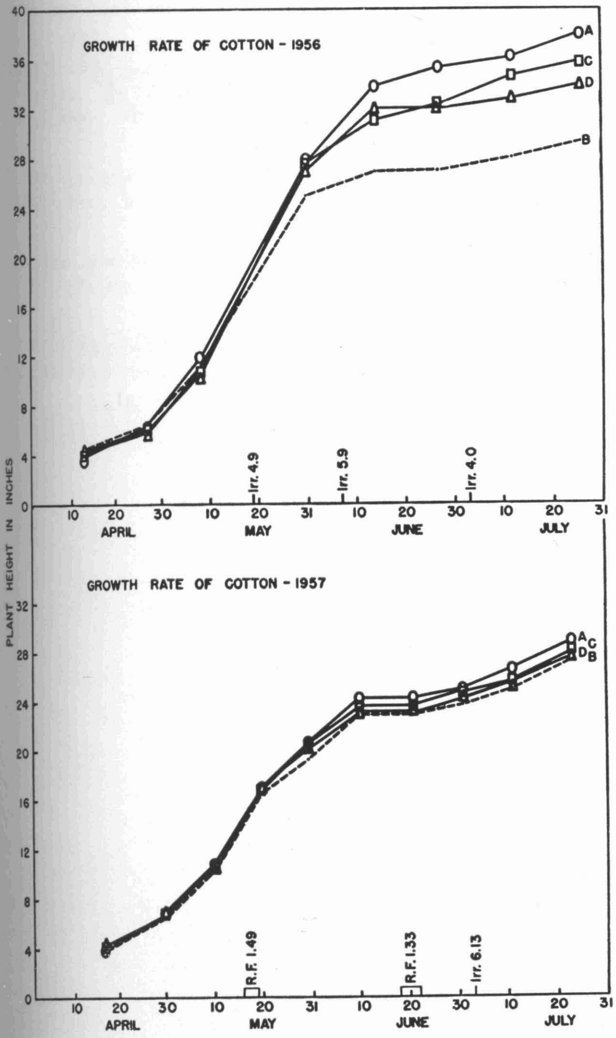

Figure 13. The effect of subsoiling and fertilizer placement on the growth of cotton (2). Treatments are described in Table 8.

Results from cropping system studies at Substation No. 15 (5) have demonstrated that rotations, which include vegetable production generally accelerate the formation and intensity of soil hardpans. Management practices in the production of vegetables almost always necessitates cultivation when subsurface moisture is optimum for compaction, as illustrated in Figures 10, 11 and 12. Vegetable production is often conducive to accumulations of exchangeable sodium in the soil because of greater frequency of irrigation during periods (especially in the fall) when the irrigation water supply is of poorer quality. Cropping systems consisting of cotton followed immediately by fall vegetables should not be used over an extended period of years because this particular practice causes marked deterioration in soil structure.

Soils which are allowed to approach air dryness to a depth of 12 inches or more will develop greater soil strength, which subsequently will impede air and water movement as well as root development. For this reason, subsoiling will probably be desirable following several seasons of drouth. Laboratory studies and field observations indicate that frequent subsoiling may be desirable on these soils, provided a well-balanced agronomic system is included in the overall program. Research is under way presently to determine how frequently subsoiling is needed on the soils which are highly susceptible to hardpan formation.

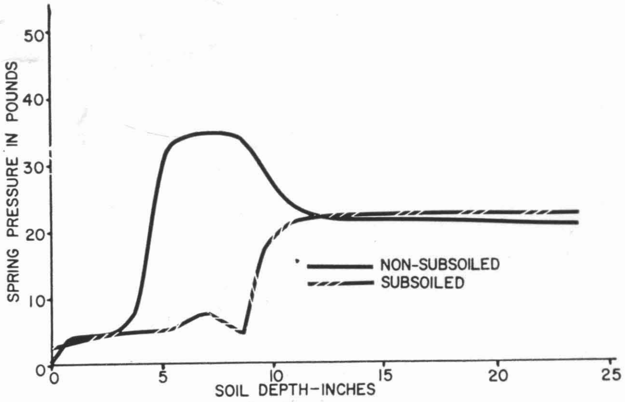

Figure 14. Penetrometer analyses showing the hardpan on Willacy fine sandy loam before and after cross-chiseling.

It is extremely important that such soils not be cultivated when too wet. The development of chemical weed control practices often could, or possibly will, eliminate the need for cultivation when subsurfacing moisture is optimum for compaction. Cooper (3) has pointed out that the best method of reducing soil compaction is to minimize the frequency of tillage and cultivate when the soils are as dry as practical.

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