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The Freezing Point of Water in Puddled and Unpuddled Soils at Different Soil Moisture Tension Values

Robert B. Campbell

THE FREEZING POINT OF WATER IN PUDDLED AND UNPUDDLED SOILS AT DIFFERENT SOIL MOISTURE TENSION VALUES

by

Robert B. Campbell

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INTRODUCTION

A technique that will adequately describe the physical condition of water in the soil has long been desired by scientists. The method should include the effect of soluble materials on the osmotic pressure of the soil solution, and also the effect of surface force action between the soil and soil water.

Parker (8) demonstrated that the freezing point was reduced in the presence of finely divided material. This suggested the possibility of using the cryoscopic procedure to measure the physical condition of water in soil. More recently, the introduction of Thermistors for accurate temperature measurement have made it desirable to investigate in greater detail the freezing point of water in soil.

The experimental work reported here deals with the freezing point of water in soil and its relation to soil moisture tension as determined on three soils in a puddled and unpuddled condition. Several freezing treatments were included in this study to investigate improvements in the freezing technique. The treatments were arranged in a standard split plot experimental design. Eighteen hundred freezing measurements were made and analyzed statistically.

REVIEW OF LITERATURE

The cryoscopic method was used by Bouyoucos and McCool (4) and later by Hoagland (7) to determine the concentration of soluble salts in the soil solution. At a later date, Parker (8) demonstrated that finely divided material, in the absence of soluble salts, depressed the freezing point. Since then, a number of investigators have used the freezing method to determine the condition of soil water in the plant wilting range and at the moisture equivalent.

Parker (8) determined the freezing point of a group of ten soils leached free of soluble salts at the moisture equivalent. These freezing point depression values varied from 0.043 to 0.75 degrees centigrade. A conversion of freezing point depression to equivalent soil moisture stress yields a range of stress values from 0.50 to 0.92 atmospheres. Similar freezing measurements at the moisture equivalent on a group of seven soils were made by Schofield and Da Costa (15). They found pF to vary from 2.61 to 2.96 which gives a range of stress values of from 0.21 to 0.88 atmospheres. In these measurements the influence of soluble salts on the freezing point depression of the soil solution was not separated from soil moisture tension. Bodman and Day (2) calculated the osmotic potential at the moisture equivalent from the electrical conductivity of a 1:1 soil suspension on ten soils. These osmotic potential values averaged -0.84×10^6 ergs per gram. The corresponding average moisture potential for these soils was -1.20×10^6 ergs per gram. The difference between average osmotic potential and average moisture potential yields -0.354×10^6 ergs per gram. This difference converted to soil moisture tension is 0.349 atmospheres.

A number of investigators (3, 12, 14, 15, 17) have used freezing point to evaluate the physical condition of water in soil in the wilting range. Richards, Campbell, and Healton (13) have summarized the results of the above authors and have found the freezing point depression values to range from 0.59 to 3.56 degrees centigrade. This corresponds to a soil moisture tension range from 7.1 to 43 atmospheres. Some recent freezing point measurements in the wilting range were made by Blair, Richards, and Campbell (1). These measurements indicate that variability associated with replicates of the same soil sample was less than the variability between individual soils that represent a textural class range.

Schofield and Da Costa recognized that freezing dries the soil, and consequently pF values calculated from freezing point depression correspond to the moisture contents at the time the freezing point is read from the thermometer. Thus, to make a moisture content correction for undercooling, they calculated the amount of ice that formed during freezing and subtracted it from the initial moisture content. Bodman and Day (3) measured the observed freezing point on replicate samples of Yolo silt loam soil at various undercooling levels and from these freezing measurements plotted an underdooling-freezing point curve. The amount of ice formed as a result of undercooling during freezing was calculated in order to obtain a corrected freezing point-undercooling curve. An inspection of these curves show that at undercooling values greater than three degrees centigrade, the undercooling correction does not keep the corrected freezing point curve invariant with respect to undercooling. The failure of the corrected and uncorrected freezing point depression curves to correspond when interpolated to zero undercooling, indicates the inadequacy of this method for calculating the undercooling correction.

The foregoing type of undercooling correction is related to a moisture content change due to ice formed during freezing, but the correction does not account for the concentrating of soluble salt in the soil solution when freezing occurs. In some unpublished undercooling studies 1/, it was found, contrary to expectations, that soil in the 5 to 15 atmosphere soil moisture tension range gave a decrease in freezing-point depression rather than an increase with increasing undercooling. In these undercooling studies, many of the soils in the low soil moisture tension range gave little or no change in the observed freezing point depression with change in undercooling in an undercooled range from one half to three degrees centigrade. Consequently no undercooling correction has been applied for freezing point calculations made in this paper.

A sample calculation to indicate the magnitude of the undercooling correction may be made as follows: Take a soil sample in the wilting range that contains 100 grams of dry soil and 6 grams of water, and assume that the sample has been frozen with an undercooling of one degree centigrade. Also assume the specific heat of the soil to be .25 calories per gram. The grams of ice formed upon freezing is taken to

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1/ The undercooling studies connected with freezing point measurements in soil were done by the author at the U.S. Regional Salinity and Rubidoux Laboratories, Riverside, Calif.

be $\frac{(100 \times 0.25) \div 6}{80} \times 1$ which reduces the soil from 6 percent to 5.64 percent of water. A 0.1 percent change of water content in soil in the wilting range produced approximately a one atmosphere change in soil moisture stress, as obtained from data reported by Richards, Campbell, and Healton (13). An average soil moisture stress value calculated from observed freezing point depression data on 52 soils by Blair, Richards, and Campbell (1) is 18.5 atmospheres. Taking this value as the soil moisture stress corresponding to 5.64 percent, we calculate the moisture stress at 6 percent water by subtracting 3.6 atmospheres from 18.5 to give 14.9 atmospheres.

Bouyoucos and McCool (5) observed that the freezing point depression in soil decreased when a sample was frozen, thawed, and then refrozen. In a later investigation it was found that sands, burned silicic acid, and kaolin depressed the freezing point to lesser degree than clay soils upon repeated freezing. They reasoned that freezing causes coagulation of the hydrogels and hydrosols in the soil and that this coagulation is accompanied by a decrease in the moisture absorptive power of soils. Schofield and Da Costa (16) have indicated that the difference in freezing point depression between successive freezings was minimized by use of their freezing procedure "A". This procedure was used to reduce cooling due to the soil surroundings during the freezing process in soil. These authors further suggest that possibly upon freezing, ice crystals produce cavities in the soil which do not return to their original size upon thawing.

EXPERIMENTAL PROCEDURE

Three soil types, whose salinity and moisture characteristics are given in table 1, were selected to represent a textural range for mineral soils. The soils were air dried, passed through a 2 mm. round-hole sieve, and subdivided into pint jars. Thus, replicate samples were available for the study. One half of the soil samples were moistened to approximately field capacity and stirred with a rod to obtain a high degree of puddling. These soils were saturated with water and poured on porous membranes. The unpuddled soils were divided into brass rings on the porous membranes and were saturated by applying water to the upper soil surface. Ceramic plates (10) were used for the one third to one atmosphere pressure range with cellulose membranes (9) being used for pressures above one atmosphere. The puddled and unpuddled soils were brought to equilibrium at 1/3, 1, 5, and 15 atmospheres of pressure. The corresponding freezing points were then determined.

Hard rubber cylinders with plastic caps similar to those described by Richards and Campbell (12) were used as soil containers. Cores were cut from the layers of soil on the porous membranes and inserted into the cylinders. These core containers were dropped into 3/4 inch glass test tubes closed with a rubber stopper to prevent moisture loss. The same test tubes were inserted into an air jacket mounted in a freezing bath as described by Richards and Campbell (11).

Five successive freezings and thawings were made on fifteen replicate core samples for each soil at four tension levels in both a puddled and unpuddled condition. The cores were thawed in an ice bath

Table 1.—Some salinity and moisture characteristics of soils selected for study.

Soil Acc. No.	Soil type	$EC_e \times 10^3$ *	O.P. of sat. ext.	Sat'n	1/3 atm.	15 atm.
				%	%	%
3044	Pachappa fine sandy loam	1.20	.39	29	13.7	5.2
83	Ft. Collins loam	0.76	.24	42	21.1	9.9
377	Chino clay loam	0.98	.31	62	37.9	17.2

* Electrical conductivity of the saturation extract expressed in millimhos per centimeter.

between freezings to minimize the movement of moisture within the soil.

Fifteen cores representing each soil at four tension levels were randomized into three groups of five cores each. These cores were subjected to a "normal freeze", a "deep freeze", and an "adiabatic freeze". In the "normal freeze" process, the cores were undercooled to 1.0 to 1.5 degrees centigrade below the expected freezing point. Freezing was initiated and the temperature maxima observed during freezing were recorded and are referred to as the observed freezing points, T_o. The samples given the "deep freeze" treatment were frozen initially by the "normal freeze" procedure and immediately transferred to a deep freeze unit at minus 20 degrees centigrade. After three hours the samples were transferred from the deep freeze unit to a bath at zero degrees centigrade for thawing. All subsequent freezings of these soil cores were completed by the normal freezing procedure. For the "adiabatic freeze" the temperature difference between the sample and its surroundings was kept small to minimize heat loss from the sample during freezing. To accomplish this, the core was undercooled approximately one degree centigrade, freezing was initiated, and the sample then transferred to a bath previously adjusted to the expected freezing point.

The soils were selected for the experiment on the basis of their low salt content in order to reduce the effect of soluble salts on the freezing point. The magnitude of this effect is indicated in the osmotic pressure data listed in table 1. The osmotic pressure of the soil solution was calculated from the electrical conductivity of the extract obtained from the saturated soil paste. The extraction of water from the soil on the porous membrane was initiated when the soil moisture content approximated its saturation percentage. For the osmotic pressure calculation at any tension level it has been assumed that the concentration of the solution in the soil did not change during the moisture extraction process. In other words, at any time during the moisture extraction the salt content of the solution in the soil is assumed to be equal to the salt concentration in the extract.

EXPERIMENTAL RESULTS

Soil moisture tension is plotted against soil moisture content in figure 1. The observed freezing point depression values are plotted in figure 2 against the corresponding moisture percentages at each soil moisture level as given in the first figure. The curves in both figures are hyperbolic in form. To convert freezing point depression values to soil moisture tension, the osmotic pressure, OP, of the soil solution was subtracted from the quantity 12.05 x ΔT_o. Soil moisture tension data obtained on the porous membrane apparatus are also plotted in figure 3.

The relation between soil moisture tension and the observed freezing point depression are plotted in figures 4 and 5. In figure 4, the curve for puddled soil is shown adjacent to the corresponding curve for the unpuddled soil. In figure 5, the puddled soils are separated from the unpuddled soil treatments to show differences between the individual soils under test. The freezing point depression values for unpuddled soil were statistically higher than values which were obtained in puddled soil at any soil moisture tension level. Chino clay loam gave smaller freezing-point values than either Pachappa fine sandy loam or Ft. Collins loam at corresponding soil moisture tension levels.

Average observed freezing-point depression values for soil frozen adiabatically, i.e., cores frozen in a bath adjusted to the expected freezing point, were not statistically different from values obtained in soil cores frozen by the normal freezing method. To obtain this

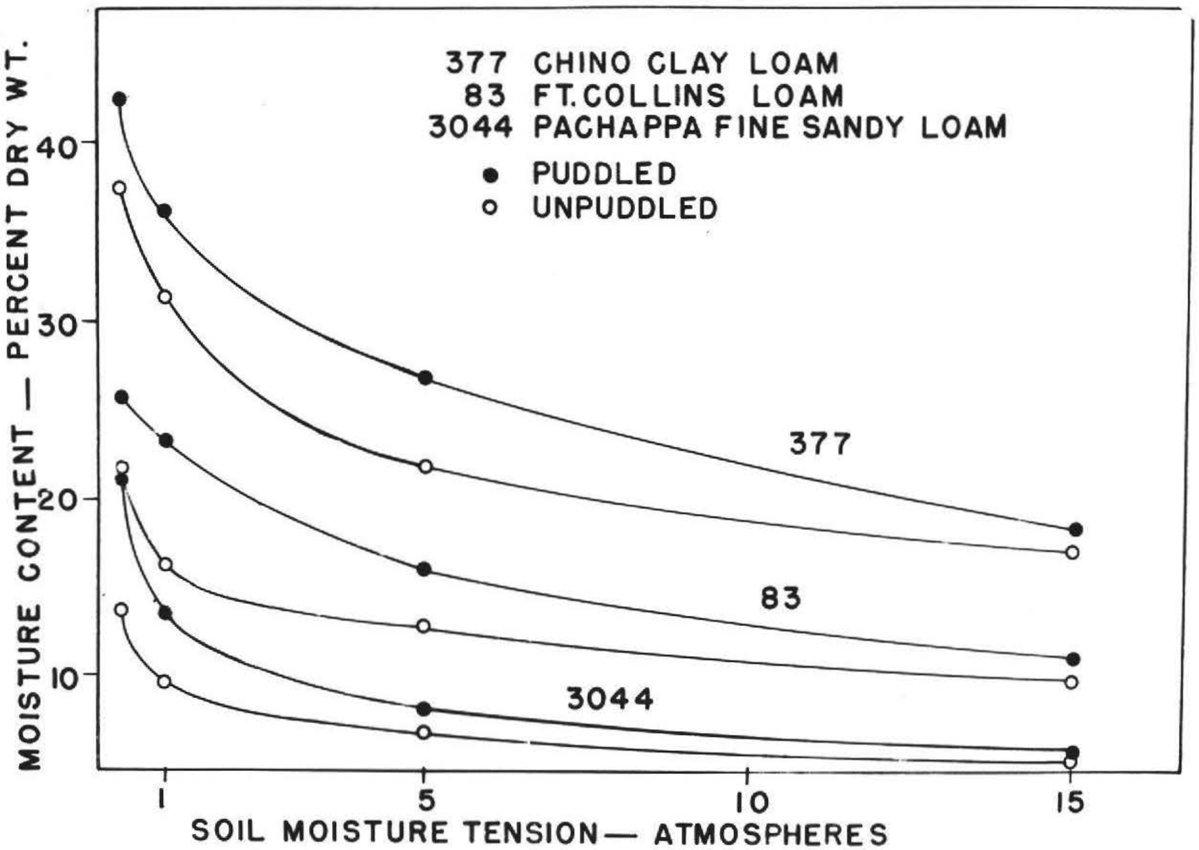

Figure 1. Soil moisture tension curves for three soils in a puddled and unpuddled condition.

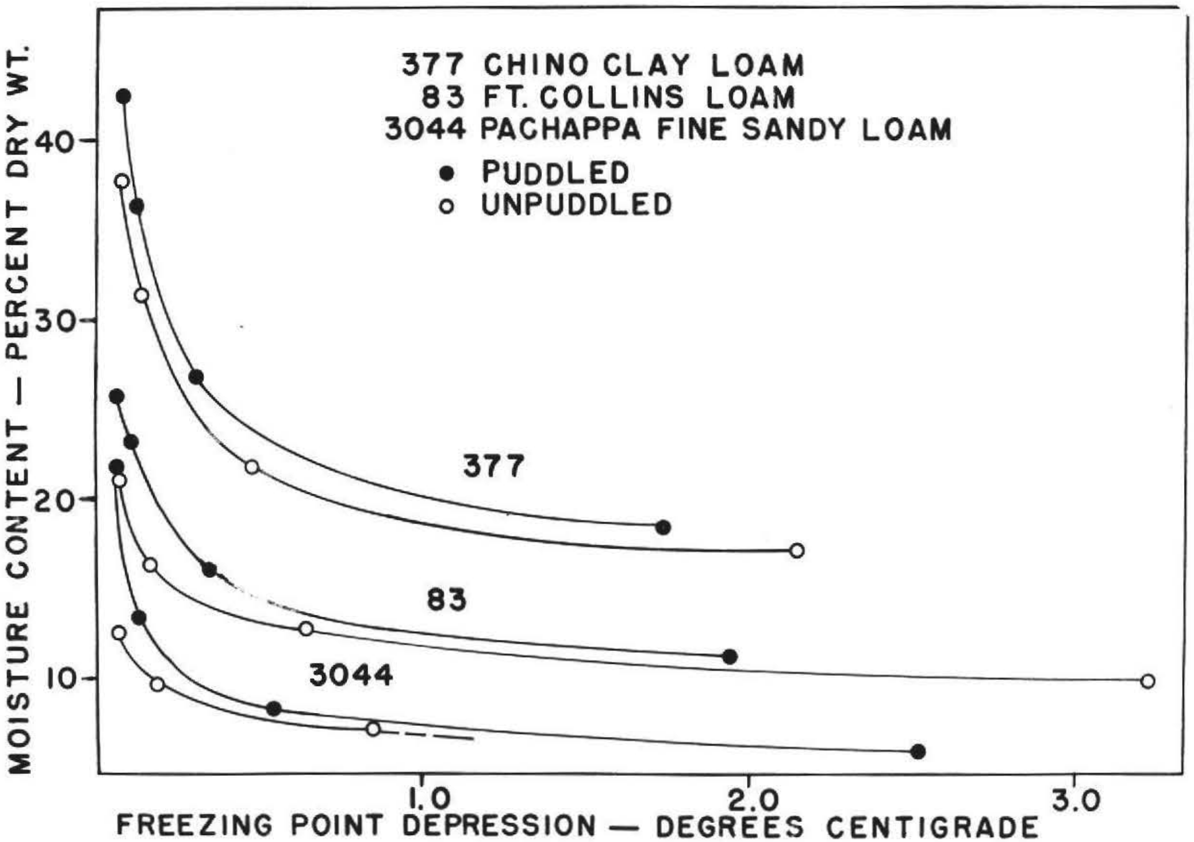

Figure 2. Relation of freezing point depression to moisture content for three soils in a puddled and unpuddled condition.

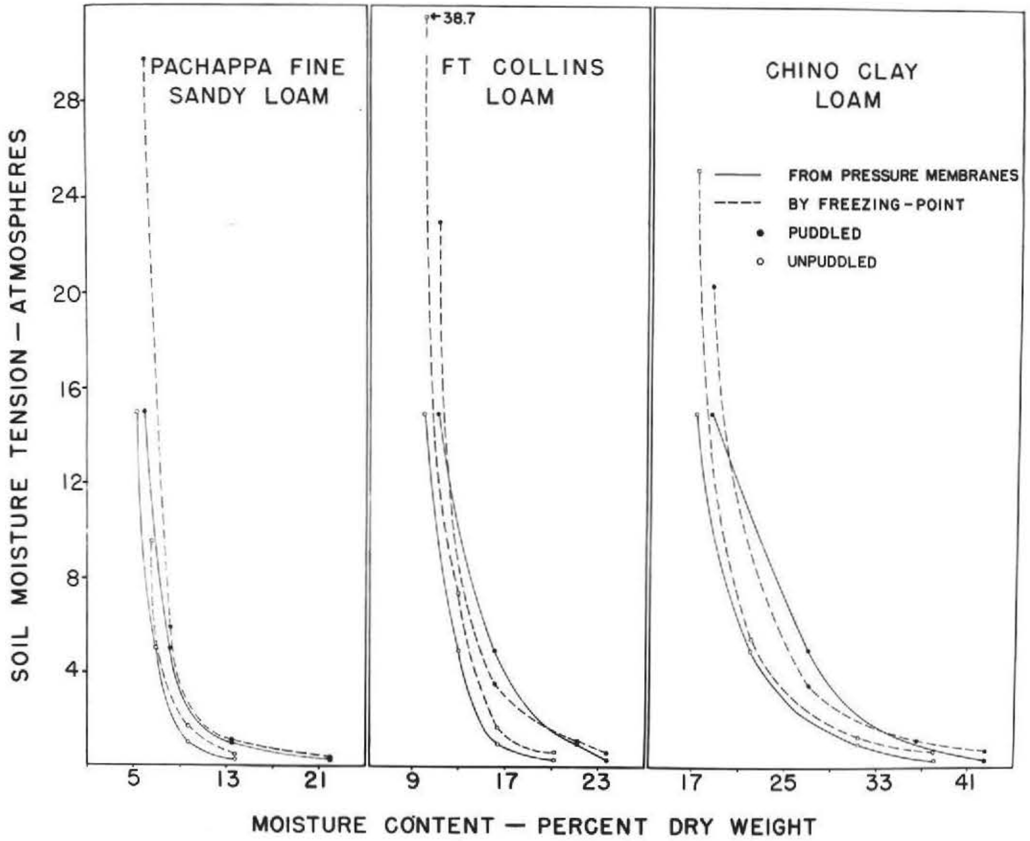

Figure 3. Soil moisture tension (SMT) curves obtained from pressure membranes and freezing point data. The dotted curves were obtained from freezing point values, ΔT_o, as follows: SMT = 12.05 ΔT_o − OP, where OP is the osmotic pressure of the soil solution.

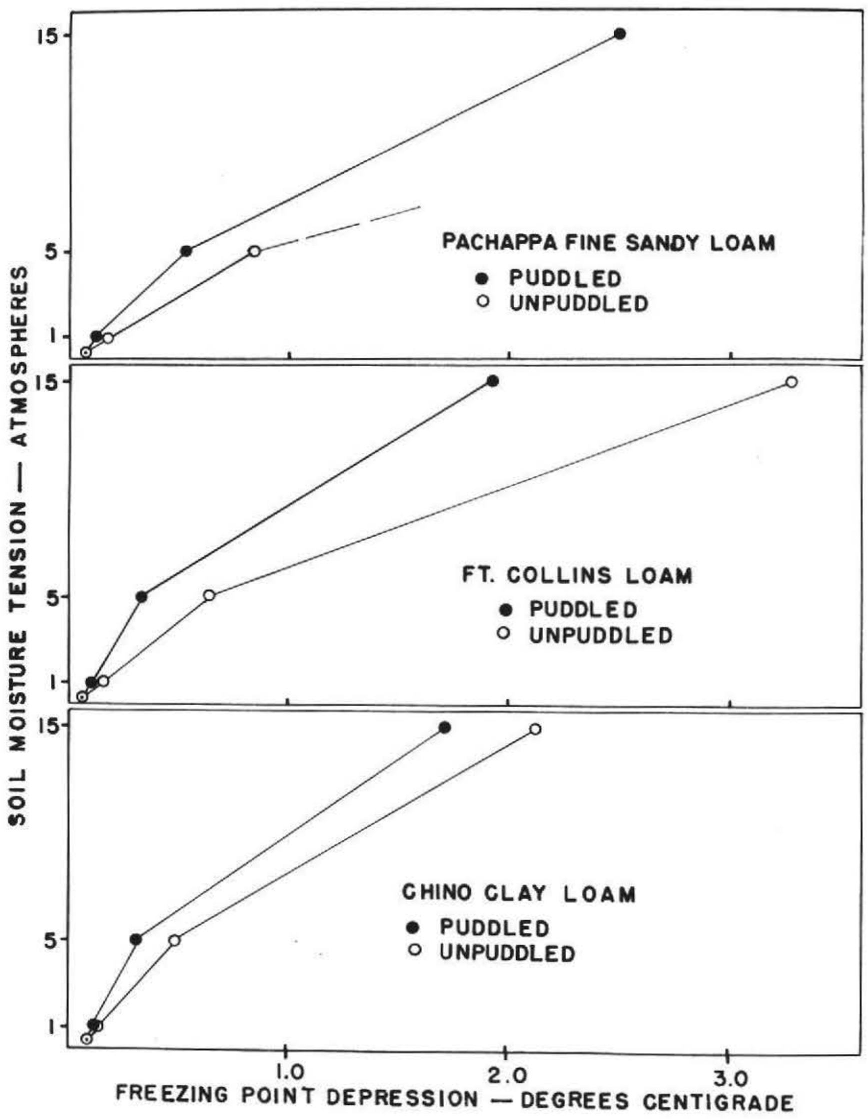

Figure 4. Relation of soil moisture tension to freezing point depression. The puddled soil curves are adjacent to the corresponding unpuddled soil curves for each soil.

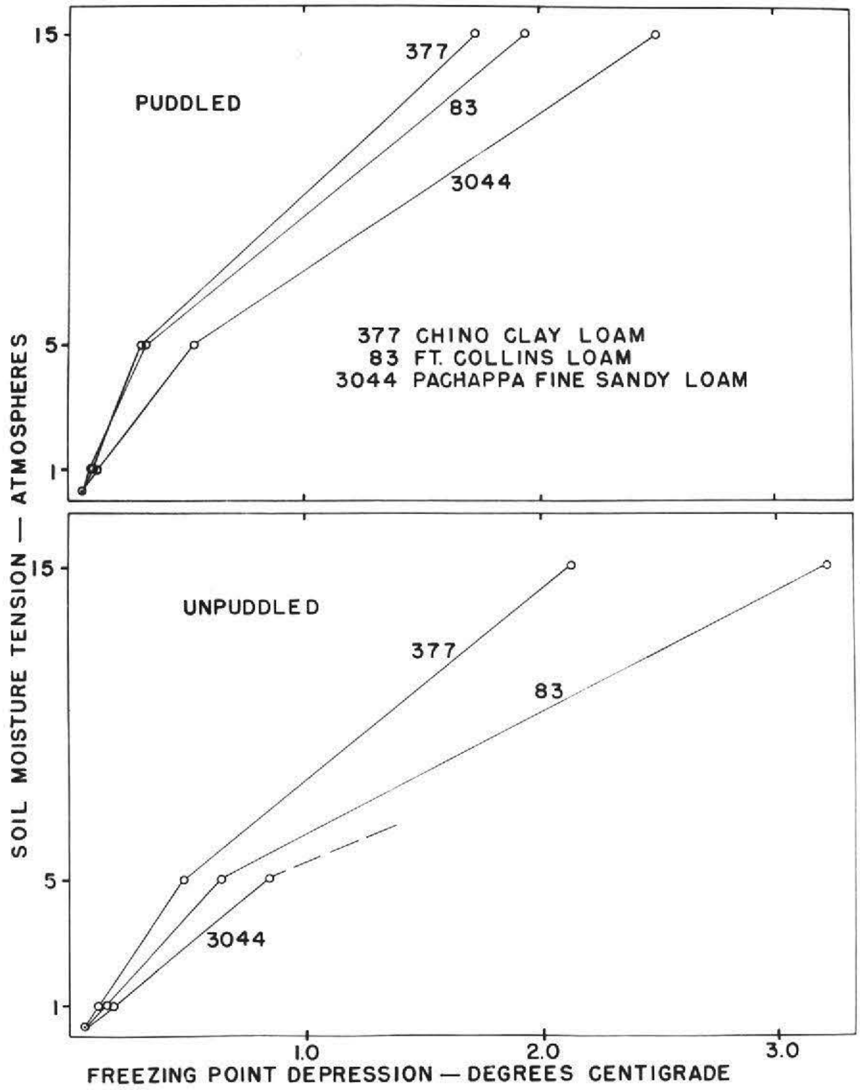

Figure 5. Relation of soil moisture tension to freezing point depression for three soils at two puddling levels.

result, the thermal time constant of the Thermistor 2/, in water, was about 2 to 4 seconds, which gives an indication of the low thermal capacity of the temperature-sensitive element used to measure the freezing point of soil. Usually the time required to obtain a measurable temperature of the core surroundings was 1 to 2 minutes. This time depends mainly upon the thickness and type of insulation about the soil core and the thermal diffusivity of the soil.

The effect of alternate freezing and thawing on the freezing point depression, FPD, is seen in figures 6 and 7. Larger decreases in the FPD were observed between the first and second successive freezing than between any other pair of successive freezing values. These results are in agreement with data reported by Bouyoucos and McCool (5), Schofield and Da Costa (16), and Buehrer and Rose (6). The soils given the "deep freeze" treatment gave larger decreases in the FPD than soils frozen by the normal freezing procedure between the first and second freezing. Thereafter, these soils gave FPD decreases that were nearly uniform for the remaining three freezings. One half of the successive freezing curves terminate with a gradual decrease in freezing point depression, whereas the remaining half terminate with no change or only a slight increase in the FPD as a result of repeated freezings. The decreases in the FPD at the high soil moisture tension levels were greater than at low tension levels.

2/ The Thermistor used was a Western Electric Type 14B. The Thermistor resistance minima observed during freezing were recorded and converted to temperatures from a previously determined calibration curve.

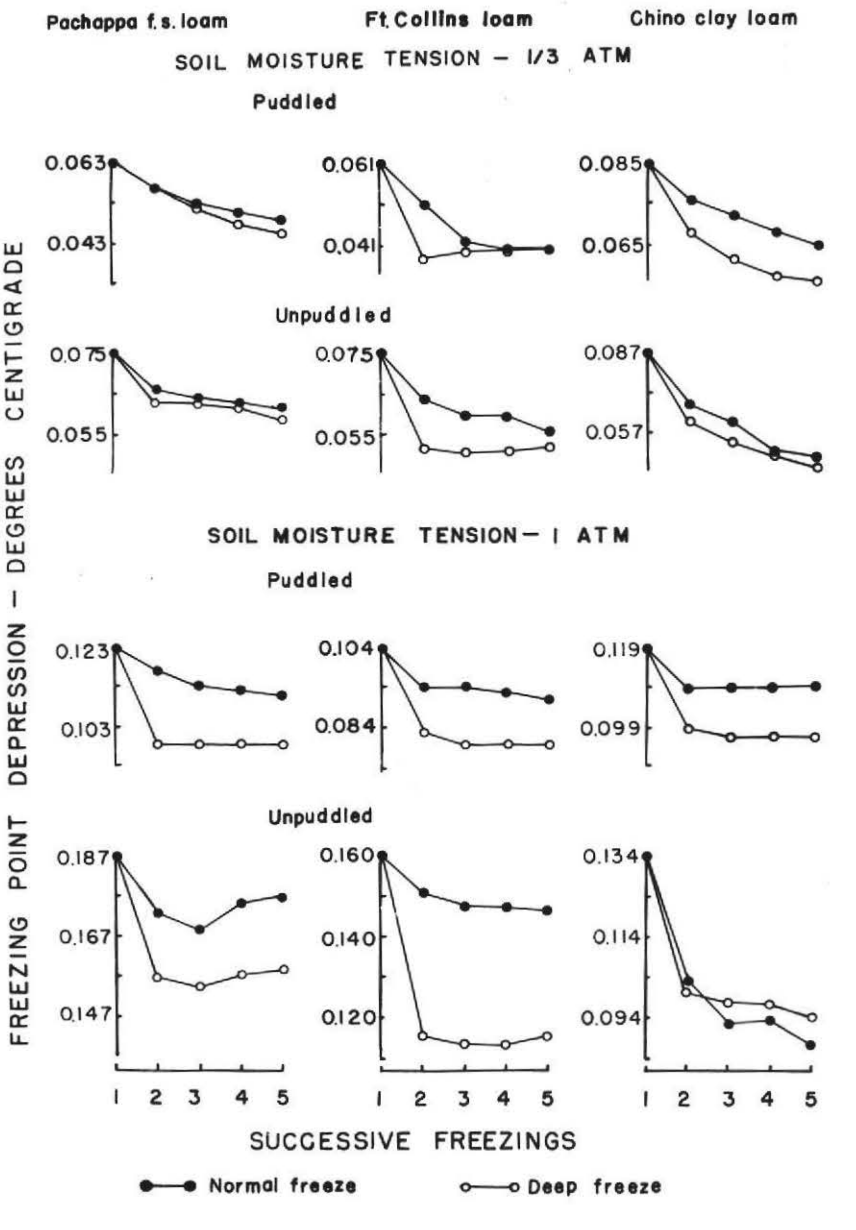

Figure 6. Effect of alternate freezing and thawing on the freezing point depression of soil at 1/3 and 1 atmosphere of soil moisture tension.

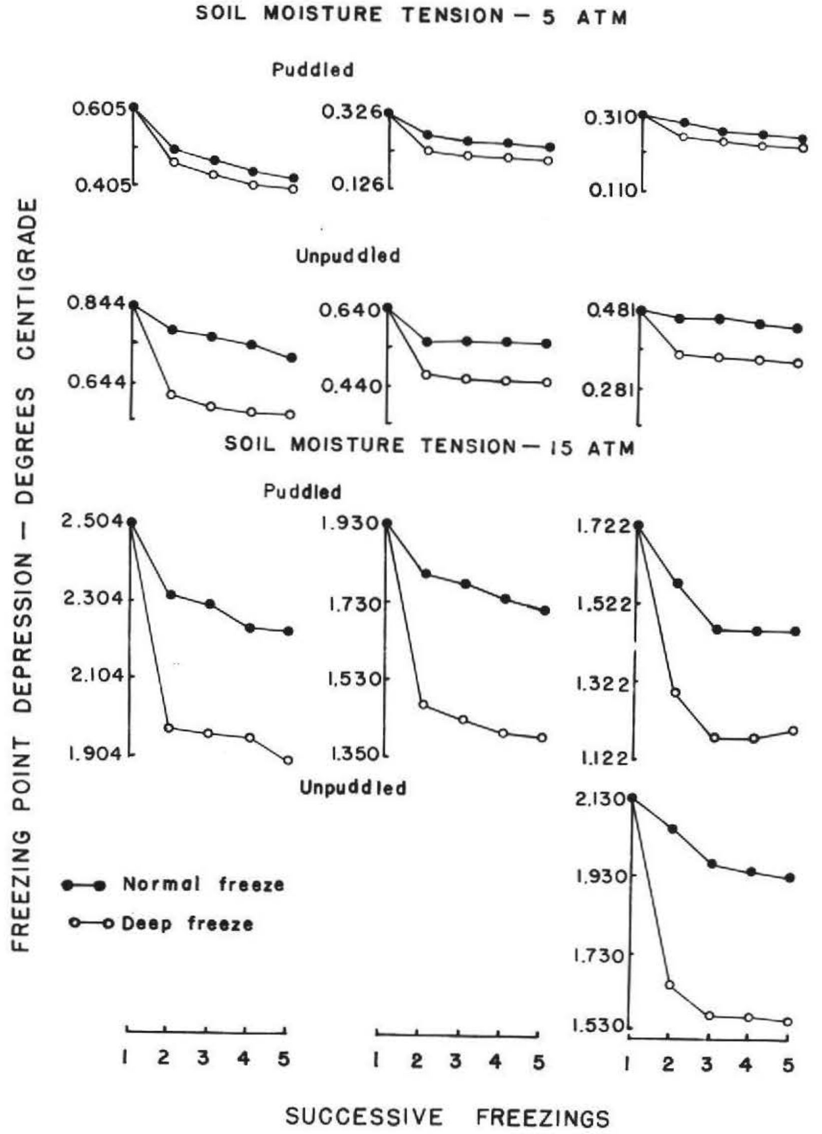

Figure 7. Effect of alternate freezing and thawing on the freezing point depression of soil at 5 and 15 atmospheres of soil moisture tension.

The freezing point depression values and the standard error in degrees centigrade for puddled and unpuddled Chino clay loam, Ft. Collins loam, and Pachappa sandy loam at several soil moisture tension levels are given in table 2. The average standard error for the soils tested over the moisture tension range considered here varies between 0.005 and 0.090 degrees centigrade. The coefficients of variability for soils in the 1/3 to 15 atmosphere pressure range vary from 30.9 to 14.4 percent.

Table 2.--The standard error, SE, of the freezing measurements at several soil moisture tension levels

Soil type		Soil Moisture Tension							
		1/3 atm.		1 atm.		5 atm.		15 atm.	
		P*	Unp.**	P	Unp.	P	Unp.	P	Unp.
		°C	°C	°C	°C	°C	°C	°C	°C
Pachappa fine sandy loam	FPD	0.063	0.075	0.124	0.180	0.527	0.844	2.504	
	SE	0.002	0.003	0.006	0.014	0.053	0.058	0.133	--
Ft. Collins loam	FPD	0.062	0.075	0.104	0.164	0.326	0.640	1.930	
	SE	0.006	0.007	0.003	0.007	0.025	0.029	0.044	--
Chino clay loam	FPD	0.085	0.087	0.119	0.134	0.310	0.481	1.722	2.130
	SE	0.007	0.009	0.004	0.005	0.007	0.007	0.066	0.092
Avg. Std. Error		0.005	0.006	0.004	0.008	0.028	0.031	0.081	0.092
Avg. Std. Dev.		0.019	0.024	0.017	0.032	0.109	0.120	0.314	0.357
Avg. FPD*** °C		0.070	0.079	0.116	0.159	0.414	0.653	2.052	2.117
Coefficient of variability		26.7	30.9	14.4	20.1	26.6	18.4	15.3	16.8

* Puddled soil

** Unpuddled soil

*** FPD = Freezing point depression

DISCUSSION

The differences between the calculated soil moisture tension curves and the actual soil moisture tension curves probably arise from assumptions connected with the osmotic pressure calculation and also from the fact that no undercooling correction was made on the observed freezing point depression. Errors from both of these sources tend to increase at low moisture, high tension levels.

For the experimental technique used, the average observed freezing point values for soil cores frozen by the normal freezing method at the undercooled temperature were essentially the same as for cores frozen adiabatically in a bath adjusted to the expected freezing point. Precautions associated with the adiabatic freezing technique are made unnecessary by surrounding the soil sample with adequate thermal insulation and by reducing the heat capacity and the thermal lag of the temperature-sensitive element used in the freezing measurement.

In the successive freezing study it was observed that larger decreases occur between the first and second freezings than between any two later freezings. This decrease in the freezing point depression may be due to a decrease in the "mechanical resistance" of soil to ice crystal formation. In other words, during later freezings, ice may re-form in cavities that were produced during the earlier freezings. Also there is the possibility that there may occur a change of soil structure which causes some water to be held less securely by the soil after freezing and thawing. Both of these effects may cause the observed change in freezing point depression with successive freezing.

SUMMARY

Pachappa fine sandy loam, Fort Collins loam, and Chino clay loam soils contained higher percentages of water (oven dry basis) at the same soil moisture tension level in a puddled condition than in an unpuddled condition within the soil moisture tension range up to fifteen atmospheres. These same soils gave freezing point depression values which were larger in the case of a puddled sample than for an unpuddled sample at the same moisture content.

It was found that the average observed freezing point depression values for soil cores frozen by the usual freezing procedure at the undercooled temperature were the same as for cores frozen adiabatically in a bath adjusted to the expected freezing point.

A relationship between soil moisture tension and freezing point depression, ΔT_o is presented. To obtain soil moisture tension values from freezing point depression, the osmotic pressure of the soil solution was subtracted from the quantity $12.05 \times \Delta T_o$.

Larger decreases in the freezing point depression were observed to occur between the first and second freezing than between any two later freezings in all the soils under test.

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APPENDIX

Tables of Freezing Points and the Corresponding Statistical Analysis.

To simplify the presentation of the freezing point data and the statistical analysis of these measurements the following group of symbols were adopted.

Soil Types	Soil Number
Pachappa fine sandy loam	3044
Fort Collins loam	83
Chino clay loam	377

Soil treatment abbreviations:

Freezing type	FT
Normal freeze	NF
Adiabatic freeze	AF
Deep freeze	DF
Successive freezing	SF
Soils (texture)	S
Puddled soil	P
Unpuddled soil	NP

Miscellaneous abbreviations:

Soil moisture tension (atmospheres) . .	SMT
Freezing point depression (degrees centigrade)	FPD
Freezing point resistance (ohms) . . .	FPR
Significance at 5% probability level . .	*
Significance at 1% probability level . .	**

Table 3. Freezing point resistance data for Pachappa fine sandy loam soil # 3044, at the 1/3 atmosphere soil moisture tension level.

Treatments			Successive Freezing				
S	FT	SMT	1	2	3	4	5
P	NF	1/3	6607.1	6605.2	6604.9	6604.6	6603.1
P	AF	1/3	6609.3	6607.3	6605.1	6604.0	6603.0
P	DF	1/3	6608.1	6606.2	6604.6	6603.4	6602.7
Average FPR			6608.2				
Average FPD			0.063	.759			
NP	NF	1/3	6612.6	6609.9	6609.5	6609.3	6608.9
NP	AF	1/3	6612.4	6608.3	6607.7	6607.7	6607.3
NP	DF	1/3	6612.5	6607.9	6608.0	6608.1	6607.1
Average FPR			6612.5				
Average FPD			0.075 x12.05 = .904				

Table 4. Freezing point resistance data for Pachappa fine sandy loam soil #3044 at the 1 atmosphere soil moisture tension level.

Treatments			Successive Freezing				
S	FT	SMT	1	2	3	4	5
P	NF	1	6626.5	6625.3	6623.0	6623.6	6622.7
P	AF	1	6626.6	6623.6	6623.1	6622.1	6622.6
P	DF	1	6627.9	6620.0	6619.9	6620.1	6620.1
Average FPR			6627.0				
Average FPD			0.124	1.49			
NP	NF	1	6641.7	6636.6	6636.1	6636.8	6636.1
NP	AF	1	6644.8	6640.7	6638.3	6641.1	6641.2
NP	DF	1	6643.0	6634.0	6633.2	6634.1	6634.4
Average FPR			6643.2				
Average FPD			0.180	2.169			

Table 5. Freezing point resistance data for Pachappa fine sandy loam soil #3044 at the 5 atmosphere soil moisture tension level.

Treatments			Successive Freezing				
S	FT	SMT	1	2	3	4	5
P	NF	5	6731.9	6702.2	6693.2	6685.0	6679.9
P	AF	5	6747.0	6710.6	6701.3	6694.5	6688.7
P	DF	5	6762.3	6716.1	6706.1	6700.8	6697.6
Average FPR			6747.1				
Average FPD			0.527	6.35			
NP	NF	5	6841.9	6827.8	6827.0	6817.7	6805.2
NP	AF	5	6840.9	6814.8	6806.9	6797.8	6788.5
NP	DF	5	6852.0	6776.3	6765.7	6761.3	6759.7
Average FPR			6844.9				
Average FPD			0.844	10.17			

Table 6. Freezing point resistance data for Pachappa fine sandy loam soil #3044 at the 15 atmosphere soil moisture tension level.

Treatments			Successive Freezing				
S	FT	SMT	1	2	3	4	5
P	NF	15	7371	7316	7309	7290	7288
P	AF	15	7394	7306	7288	7281	7270
P	DF	15	7376	7222	7218	7216	7198
Average FPR			7380				
Average FPD			2.504	30.17			
NP	NF	15					
NP	AF	15	(Data incomplete)				
NP	DF	15					

Table 7. Freezing point resistance data for Ft. Collins loam soil #83 at the 1/3 atmosphere soil moisture tension level.

Treatments			Successive Freezing				
S	FT	SMT	1	2	3	4	5
P	NF	1/3	6609.2	6605.2	6602.0	6601.2	6601.3
P	AF	1/3	6607.6	6604.9	6602.4	6602.0	6601.9
P	DF	1/3	6606.8	6599.2	6599.8	6599.8	6599.8
Average FPR			6607.9				
Average FPD			0.063	.759			
NP	NF	1/3	6613.2	6607.6	6606.3	6606.0	6605.3
NP	AF	1/3	6611.5	6610.5	6608.0	6607.8	6606.0
NP	DF	1/3	6612.4	6604.8	6604.5	6604.4	6604.7
Average FPR			6612.4				
Average FPD			0.075	.904			

Table 8. Freezing point resistance data for Ft. Collins loam soil #83 at the 1 atmosphere soil moisture tension level.

Treatments			Successive Freezing				
S	FT	SMT	1	2	3	4	5
P	NF	1	6621.4	6617.7	6616.3	6616.2	6615.6
P	AF	1	6620.7	6617.7	6616.9	6616.6	6615.7
P	DF	1	6621.2	6613.2	6612.3	6612.4	6612.4
Average FPR			6621.1				
Average FPD			0.104	1.253			
NP	NF	1	6638.2	6636.5	6634.9	6634.7	6634.6
NP	AF	1	6636.6	6632.2	6631.6	6631.8	6631.2
NP	DF	1	6638.1	6623.6	6622.8	6622.7	6623.4
Average FPR			6637.6				
Average FPD			0.164	1.976			

Table 9. Freezing point resistance data for Ft. Collins loam soil #83 at the 5 atmosphere soil moisture tension level.

Treatments			Successive Freezing				
S	FT	SMT	1	2	3	4	5
P	NF	5	6687.3	6670.3	6667.1	6663.7	6663.4
P	AF	5	6687.0	6669.2	6664.5	6661.7	6659.0
P	DF	5	6687.0	6654.3	6650.7	6649.6	6647.5
Average FPR			6687.1				
Average FPD			0.326	3.93			
NP	NF	5	6793.6	6769.8	6771.2	6770.2	6770.0
NP	AF	5	6783.2	6757.0	6754.7	6753.4	6752.2
NP	DF	5	6768.1	6712.4	6707.9	6706.0	6705.3
Average FPR			6781.6				
Average FPD			0.640	7.712			

Table 10. Freezing point resistance data for Ft. Collins loam soil #83 at the 15 atmosphere soil moisture tension level.

Treatments			Successive Freezing				
S	FT	SMT	1	2	3	4	5
P	NF	15	7186	7142	7149	7139	7136
P	AF	15	7189	7151	7129	7119	7104
P	DF	15	7202	7056	7044	7035	7031
Average FPR			7192				
Average FPD			1.930	23.256			
NP	NF	15	7628	7530	7517	7523	7489
NP	NF	15	7621	7542	7546	7534	7511
NP	AF	15	(Data incomplete)				
NP	DF	15					
Average FPR			7628				
Average FPD			3.227	38.89			

Table 11. Freezing point resistance data for Chino clay loam soil #377 at the 1/3 atmosphere soil moisture tension level.

Treatments			Successive Freezing				
S	FT	SMT	1	2	3	4	5
P	NF	1/3	6612.8	6608.9	6608.3	6607.7	6606.5
P	AF	1/3	6613.7	6611.8	6610.0	6608.3	6607.8
P	DF	1/3	6617.5	6611.8	6609.6	6608.3	6607.8
Average FPR			6614.7				
Average FPD			0.085	1.024			
NP	NF	1/3	6615.9	6611.0	6609.7	6608.5	6608.2
NP	AF	1/3	6614.5	6610.7	6609.2	6606.3	6606.0
NP	DF	1/3	6615.8	6610.2	6608.4	6607.5	6606.5
Average FPR			6615.4				
Average FPD			0.087	1.048			

Table 12. Freezing point resistance data for Chino clay loam soil #377 at the 1 atmosphere soil moisture tension level.

Treatments			Successive Freezing				
S	FT	SMT	1	2	3	4	5
P	NF	1	6629.9	6619.2	6618.8	6618.7	6617.4
P	AF	1	6630.2	6619.2	6617.6	6617.5	6617.0
P	DF	1	6630.7	6620.5	6617.5	6617.9	6616.0
Average FPR			6630.3				
Average FPD			0.134	1.615			
NP	NF	1	6625.1	6622.0	6621.7	6621.5	6621.5
NP	AF	1	6623.6	6620.3	6621.0	6621.0	6620.9
NP	DF	1	6624.7	6618.1	6617.4	6617.6	6617.8
Average FPR			6624.5				
Average FPD			0.119	1.434			

Table 13. Freezing point resistance data for Chino clay loam soil #377 at the 5 atmosphere soil moisture tension level.

Treatments			Successive Freezing				
S	FT	SMT	1	2	3	4	5
P	NF	5	6683.3	6677.9	6670.6	6665.5	6664.4
P	AF	5	6680.9	6675.7	6671.1	6666.1	6664.6
P	DF	5	6681.5	6663.2	6659.8	6657.5	6657.0
Average FPR			6681.9				
Average FPD			0.310	3.736			
NP	NF	5	6732.7	6728.3	6728.9	6727.5	6724.8
NP	AF	5	6730.6	6722.6	6722.0	6718.1	6716.6
NP	DF	5	6733.4	6697.6	6693.0	6690.9	6691.3
Average FPR			6732.2				
Average FPD			0.481	5.796			

Table 14. Freezing point resistance data for Chino clay loam soil #377 at the 15 atmosphere soil moisture tension level.

Treatments			Successive Freezing				
S	FT	SMT	1	2	3	4	5
P	NF	15	7143	7097	7059	7060	7057
P	AF	15	7111	7065	7031	7028	7029
P	DF	15	7119	6986	6948	6948	6955
Average FPR			7124				
Average FPD			1.722	20.75			
NP	NF	15	7280	7255	7228	7220	7209
NP	AF	15	7250	7230	7201	7198	7197
NP	DF	15	7240	7088	7061	7060	7056
Average FPR			7257				
Average FPD			2.130	25.67			

Table 15. Analysis of variance of freezing type and successive freezing treatments at the 1/3 atmosphere soil moisture tension level.

Soil	SMT			Puddled		Unpuddled	
				Variance	F	Variance	F
3044	1/3	Total	74	7.05		9.11	
		FT	2	3.46	0.17	10.58	0.38
		Rep	4	10.08		29.79	
		$Error_1$	8	19.89		27.06	
		SF	4	65.51	77.98**	52.38	24.91**
		SFxFT	8	1.64	1.95	0.81	0.38
		$Error_2$	48	0.84		2.11	
83	1/3	Total	74	10.71		13.05	
		FT	2	59.23	9.54**	56.86	2.49
		Rep	4	3.89		29.68	
		$Error_1$	8	6.21		22.83	
		SF	4	127.11	123.40**	110.21	109.10**
		SFxFT	8	6.40	6.21**	8.21	8.13**
		$Error_2$	48	1.03		1.01	
377	1/3	Total	74	10.28		14.47	
		FT	2	31.49	11.33**	11.42	0.63
		Rep	4	17.57		23.94	
		$Error_1$	8	2.78		18.04	
		SF	4	132.29	64.88**	174.85	89.20**
		SFxFT	8	5.42	2.85	1.76	0.90
		$Error_2$	48	1.90		1.96	

Table 16. Analysis of variance of freezing type and successive freezing treatments at the 1 atmosphere soil moisture tension level.

Soil	SMT			Puddled		Unpuddled	
				Variance	F	Variance	F
3044	1	Total	74	9.60		42.64	
		FT	2	46.46	3.29	230.01	1.13
		Rep	4	25.51		128.99	
		$Error_1$	8	15.28		202.60	
		SF	4	71.82	107.20**	112.95	59.44**
		SFxFT	8	9.18	13.70**	7.31	3.84**
		$Error_2$	48	0.67		1.90	
83	1	Total	74	9.54		36.81	
		FT	2	84.99	33.19**	606.78	14.84**
		Rep	4	1.97		21.70	
		$Error_1$	8	2.56		40.88	
		SF	4	106.65	190.40**	177.86	157.40**
		SFxFT	8	6.77	12.10**	41.35	36.59**
		$Error_2$	48	0.56		1.13	
377	1	Total	74	27.32		74.68	
		FT	2	1.22	0.10	70.94	6.89*
		Rep	4	4.11		5.15	
		$Error_1$	8	11.75		10.19	
		SF	4	458.90	392.00**	56.40	64.10**
		SFxFT	8	2.16	1.85	5.12	5.82*
		$Error_2$	48	1.17		0.88	

Table 17. Analysis of variance of freezing type and successive freezing treatments at the 5 atmosphere soil moisture tension level.

Soil	SMT			Puddled		Unpuddled	
				Variance	F	Variance	F
		Total	74	681.9		1384.8	
		FT	2	2048.5	2.67	10824.3	3.83
		Rep	4	1652.6		3709.0	
3044	5	$Error_1$	8	767.6		2824.9	
		SF	4	8135.8	709.00**	8279.8	403.50**
		SFxFT	8	63.8	55.60**	1149.7	56.00**
		$Error_2$	48	11.5		20.5	
		Total	74	225.9		1029.4	
		FT	2	1118.3	5.54*	17962.5	22.20**
		Rep	4	704.5		533.2	
83	5	$Error_1$	8	201.6		808.5	
		SF	4	2324.3	624.80**	5776.3	644.67**
		SFxFT	8	71.3	19.17**	1005.3	112.20**
		$Error_2$	48	3.7		9.0	
		Total	74	77.1		244.8	
		FT	2	560.3	29.52**	5061.8	24.41**
		Rep	4	8.4		16.5	
377	5	$Error_1$	8	19.0		20.8	
		SF	4	995.2	581.90**	1123.0	192.30**
		SFxFT	8	42.5	24.80**	359.7	61.60**
		$Error_2$	48	1.7		5.8	

Table 18. Analysis of variance of freezing type and successive freezing treatments at the 15 atmosphere soil moisture tension level.

Soil	SMT			Puddled Variance	Puddled F	Unpuddled Variance	Unpuddled F
3044	15	Total	74	55,178		Data Incomplete	
		FT	2	29,013	3.6		
		Rep	4	14,590			
		$Error_1$	8	8,042			
		SF	4	45,559	163.0**		
		SFxFT	8	3,986	14.2**		
		$Error_2$	48	280			
83	15	Total	74	31,843		Data Incomplete	
		FT	2	39,268	23.6**		
		Rep	4	3,032			
		$Error_1$	8	1,664			
		SF	4	23,207	23.9**		
		SFxFT	8	4,261	4.3**		
		$Error_2$	48	97			
377	15	Total	74	3,990		6,802	
		FT	2	56,720	32.8**	136,961	16.2**
		Rep	4	865		665	
		$Error_1$	8	1,725		8,426	
		SF	4	35,299	240.1**	26,597	16.6**
		SFxFT	8	2,044	13.9**	5,449	3.4**
		$Error_2$	48	147		1,601	

Table 19. Analysis of variance of freezing type and successive freezing at each soil texture, puddling and moisture tension level

Soil Acc. No.	Puddling	Source of variation	Variance ratio 1/3[a] F	1[a] F	5[a] F	15[a] F
3044	Puddled	FT	0.2	3.3	2.7	3.6
		SF	78.0**	107.2**	709.0**	163.0**
		SFXFT	2.0	13.7**	55.6**	14.2**
	Unpuddled	FT	0.4	1.1	3.8	---
		SF	24.9**	59.4**	403.5**	---
		SFXFT	0.4	3.8**	56.0**	---
83	Puddled	FT	9.5**	33.2**	5.5*	23.6**
		SF	123.4**	190.4**	624.8**	23.9**
		SFXFT	6.2**	12.1**	19.2**	4.4**
	Unpuddled	FT	2.5	14.8**	22.2**	---
		SF	109.1**	157.4**	644.7**	---
		SFXFT	8.1**	36.6**	112.2**	---
377	Puddled	FT	11.3**	0.1	29.5**	32.9**
		SF	64.9**	392.0**	581.9**	240.1**
		SFXFT	2.9*	1.9	24.8**	13.9**
	Unpuddled	FT	0.6	6.9*	24.4**	16.2**
		SF	89.2**	64.1**	192.3**	16.6**
		SFXFT	0.9	5.8*	61.6**	3.4**

[a] Soil moisture tension level in atmospheres

FT = Freezing type, F = Variance ratio

SF = Successive freezing

* Significant at 5 percent level (19:1)

**Significant beyond 1 percent level (99:1)

Table 20. Pooled analysis of variance of soil texture, puddling, freezing type, and successive freezing treatments at the 1/3 atmosphere soil moisture tension level.

Source of Variation	Degrees of Freedom	Sums of Squares	Mean Square	F Value
Total	449	7,583.77	16.89	
S	2	1,563.67	781.89	
P	1	830.69	830.69	
SxP	2	479.40	239.70	
FT	2	45.30	22.65	1.33
FTxS	4	118.77	29.69	1.74
FTxP	2	34.88	17.44	1.02
FTxSxP	4	72.75	18.19	1.06
Error (1)	72	1,230.12	17.08	
SF	4	2,441.21	610.30	435.93**
SFxS	8	128.67	16.08	11.49**
SFxP	4	15.00	3.75	2.67*
SFxFT	8	70.20	8.78	6.27**
SFxFTxS	16	90.24	5.64	4.02*
SFxFTxP	8	6.69	0.84	0.60
SFxSxP	8	28.99	3.62	2.58**
SFxFTxSxP	16	3.91	1.49	1.60
Error (2)	288	403.28	1.40	

Table 21. Pooled analysis of variance of soil texture, puddling, freezing type, and successive freezing treatments at the 1 atmosphere soil moisture tension level.

Source of Variation	Degrees of Freedom	Sums of Squares	Mean Square	F Value
Total	449	34,838.87	77.59	
S	2	7,775.81	3,887.91	
P	1	11,736.13	11,736.13	
SxP	2	5,413.07	2,706.53	
FT	2	1,138.38	569.19	13.57**
FTxS	4	450.22	112.56	2.67*
FTxP	2	235.72	117.86	2.81
FTxPxS	4	253.17	63.29	1.50
Error (1)	72	3,019.17	41.93	
SF	4	3,395.15	848.78	816.13**
SFxS	8	104.72	13.09	12.58**
SFxP	4	73.21	18.30	17.54**
SFxFT	8	374.47	46.81	45.00**
SFxSxP	8	365.73	45.72	43.96**
SFxFTxS	16	98.31	6.14	5.90**
SFxFTxP	8	42.81	5.35	5.14**
SFxFTxSxP	16	62.50	3.91	3.75**
Error (2)	288	300.30	1.04	

Table 22. Pooled analysis of variance of soil texture, puddling, freezing type, and successive freezing treatments at the 5 atmosphere soil moisture tension level.

Source of Variation	Degrees of Freedom	Sums of Squares	Mean Square	F Value
Total	449	1,336,533	2,977	
S	2	324,497	162,249	
P	1	688,043	688,043	
SxP	2	52,937	26,468	
FT	2	34,781	17,390	20**
FTxS	4	5,843	1,461	2
FTxP	2	29,907	14,954	17**
FTxPxS	4	4,619	1,155	1
Error (1)	72	65,[illegible]34	584	
SF	4	89,991	22,477	1,605**
SFxS	8	14,553	1,819	130**
SFxP	4	951	238	17**
SFxFT	8	14,675	1,834	131**
SFxSxP	8	1,040	130	9**
SFxFTxS	16	1,104	69	5**
SFxFTxP	4	4,012	501	35**
SFxFTxSxP	16	1,759	109	8**
Error (2)	288	4,207	14	

Table 23. Summary of analysis of variance where the error has been pooled for analysis at three soil moisture tension levels.

Source of Variation	Soil Moisture Tension Level			
	1/3	1	5	15 1/
	Statistical Significance			
S				
P				
SxP				
FT		**	**	
FTxS		*		
FTxP			**	
FTxPxS				
SF	**	**	**	
SFxS	**	**	**	
SFxP	*	**	**	
SFxFT	**	**	**	
SFxFTxS	*	**	**	
SFxFTxP		**	**	
SFxSxP	**	**	**	
SFxFTxSxP		**	**	

1/ Data were not sufficiently complete for analysis.
* Significant at 5 percent level (19:1).
** Significant beyond 1 percent level (99:1).