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FIELD LYSIMETER TEST FACILITY: PROTECTIVE BARRIER TEST RESULTS (FY 1990, THE THIRD YEAR)

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EXECUTIVE SUMMARY

The Field Lysimeter Test Facility (FLTF) was constructed to test protective barriers for isolating low-level radioactive and hazardous wastes from the biosphere. Protective barriers are specially configured earth materials placed over near-surface wastes to prevent intrusion of water, plants, and animals. Low-level radioactive waste is stored in near-surface repositories at the Hanford Site and can be transported into the biosphere by water, plants, and animals. Permanent, safe waste isolation depends on some form of exclusion, such as 1) protective barriers, 2) in situ vitrification, or 3) deep repository burial. Among these options, the Record of Decision 52 FR 12449 commits to placement of protective barriers over near-surface radioactive waste. Only protective barriers were considered in this work.

The purpose of the FLTF is to measure water balance within barriers as precipitation is partitioned to evaporation (including transpiration), storage, and drainage. Runoff was prevented by raised edges on the lysimeters. Water balance in protective barriers depends on the water-holding capacity of the soil, the gradient of a potential, and the conductivity of the underlying capillary barrier. Current barrier design uses soil with a high water storage capacity and a capillary barrier underlying the soil to increase its water storage capacity. This increased storage capacity is to hold water, which would normally drain, near the surface where evaporation can cycle it back to the atmosphere.

As constructed, the capillary barrier increased storage an average of about 10.5 vol%. This increased storage is enough to hold the average annual precipitation at the Hanford Site. The water moved downward through the silt loam soils when 26 vol% was exceeded. The capillary barrier prevented drainage from soil when water content just above the capillary barrier was less than 43 vol% and water near the soil surface was less than 30 vol%. Over an annual cycle, evaporation alone from the bare soil surfaces removed water until the soil moisture just above the barrier dropped to about 25 vol%. Thus, about 16 cm of water that would normally drain was recycled to the atmosphere instead.

Vegetation was transplanted on 10 of the lysimeters, and 8 lysimeters had no vegetation. Compared with bare lysimeters, those with vegetation demonstrated nearly twice the water loss rates and amounts. Root growth rates were about 1.41 cm/d for sagebrush (*Artemisia tridentata*). This rapid growth rate allowed root intrusion to the full depth of the moist soil in one growing season, followed by rapid water removal to the plant extraction limit near 8 vol%.

After leak-test drainage was complete, protective barrier treatments did not lose water by liquid drainage but did lose water each summer by vapor-phase transport. The observed drainage closely approximated the predicted downward vapor transport of about 2.5 kg computed from thermal gradients and ambient water contents.

ACKNOWLEDGMENTS

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1.0 INTRODUCTION

Low-level radioactive waste is stored in near-surface repositories at the U.S. Department of Energy's (DOE's) Hanford Site. A potential exists for the waste in these repositories to move through the biosphere. Three methods of isolating radioactive waste are 1) covering with a protective barrier, 2) in situ vitrification, and 3) translocation to a deep repository (DOE 1987). Among these three, Record of Decision 52 FR 12449 commits to placement of a protective barrier over near-surface radioactive waste for permanent, safe waste isolation.

This research examines water balance in protective barriers designed to isolate radioactive and hazardous wastes. The protective barriers are designed to limit intrusion of water, plants, and animals into waste. A series of field tests have been designed at the Hanford Site to evaluate the performance of the protective barriers. The Field Lysimeter Test Facility (FLTF) contains a set of protective barriers enclosed in lysimeters near the Hanford Meteorological Station (HMS) (see Figure 1.1).

The FLTF concept was developed jointly by Pacific Northwest Laboratory (PNL)(a) and Westinghouse Hanford Company. The facility was designed by Kaiser Engineers Hanford and constructed by Dellenger Enterprises during FY 1987 (November 1986 through June 1987). The facility is operated by PNL (Kirkham et al. 1987; Gee et al. 1989; Campbell et al. 1990).

The purpose of the FLTF is to assess the effectiveness of protective barriers in controlling water infiltration, thereby preventing leaching to groundwater. The lysimeters at the FLTF are designed to measure water balance and thus test barrier performance.

The barriers were constructed with silt loam soil overlying sand to increase the water-holding capacity of the soil, with the intent of holding

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(a) PNL is operated for the U.S. Department of Energy by Battelle Memorial Institute.

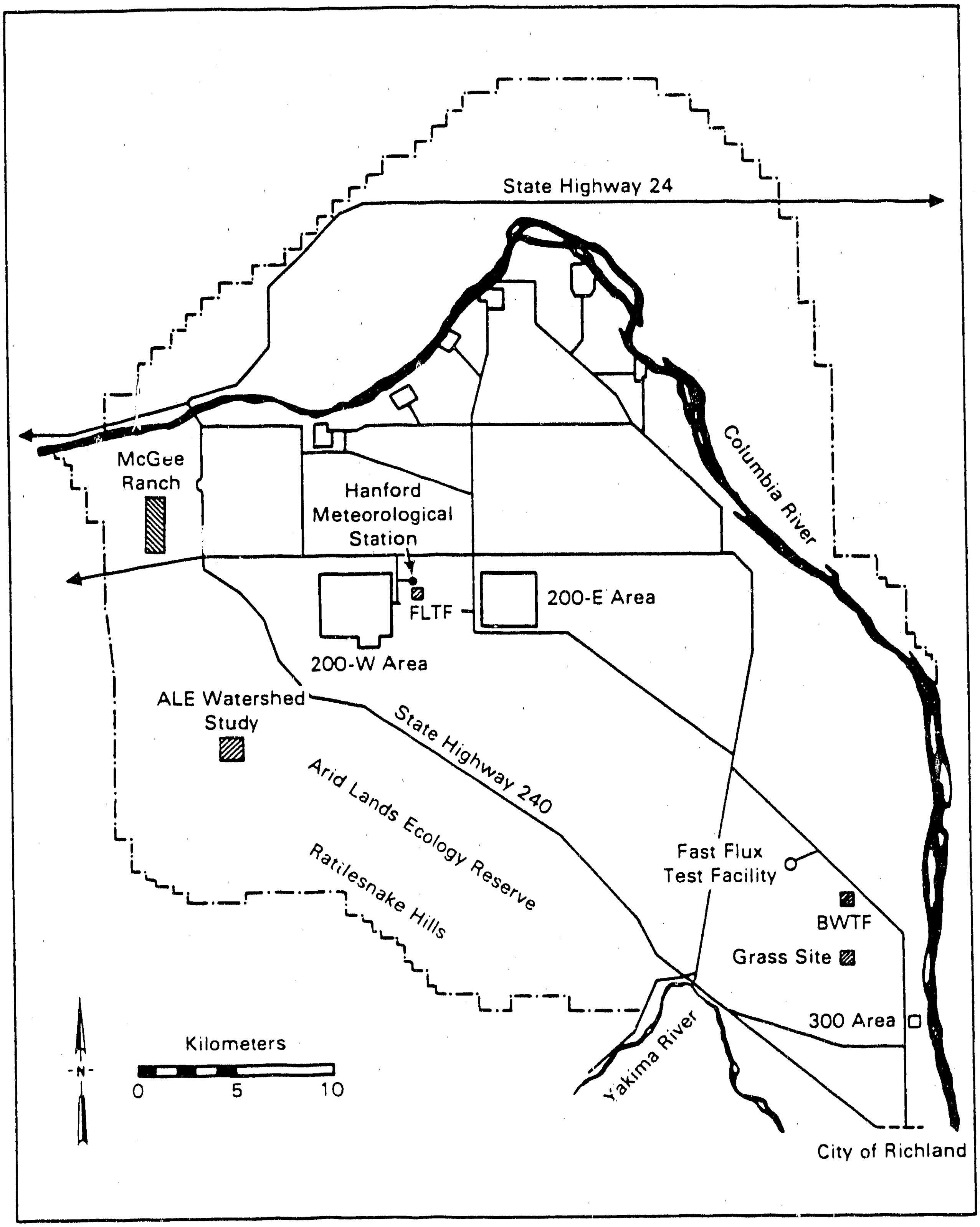


FIGURE 1.1. Location of the Field Lysimeter Test Facility (FLTF) Adjacent to the Hanford Meteorological Station Between the 200 Areas on the Hanford Site

the water in the near-surface soil to let it evaporate instead of draining to groundwater. Vegetation was transplanted on 10 lysimeters, and 8 lysimeters had no vegetation.

We used HMS weather data, lysimeter weights, soil water measured by neutron probe, irrigation and precipitation, and drainage to obtain water balance in the protective barriers at the FLTF. Lysimeter water balance measurements permitted computer model calibration to predict water behavior within barriers.

This report presents results from the third year of protective barrier tests at the FLTF. The impacts of water-related treatments on measured and modeled water balance are the main focus of this report. Because this report has a limited focus, a bibliography is included to assist readers in locating closely related literature (see Section 6). Specifically, detailed information about construction and the first 2 years of operations at the FLTF are available in the reports prepared by Kirkham et al. (1987), Gee et al. (1989), and Campbell et al. (1990).

All of the soil moisture profile measurements made by the neutron probe are shown in the appendix.

2.0 DESCRIPTION AND OPERATION OF THE FLTF

A diagram of the FLTF is shown in Figure 2.1. The FLTF is below ground level with only the tops of the lysimeters protruding 0.05 m above the soil surface. The barrier configurations at the FLTF consist of a textural break between a 1.0-m or a 1.5-m layer of Warden silt loam soil (Xerollic Camborthid) and a 0.05-m layer of washed, No. 20-30 sand.

Treatments include three levels of water applications, two soil profile depths, two vegetative cover conditions, and two surface armor treatments. A variety of vegetation (11 species) was transplanted into the lysimeters as shown in Figure 2.2. Both the soil and the vegetation were obtained from McGee Ranch, about 1 km northwest of the Yakima barricade.

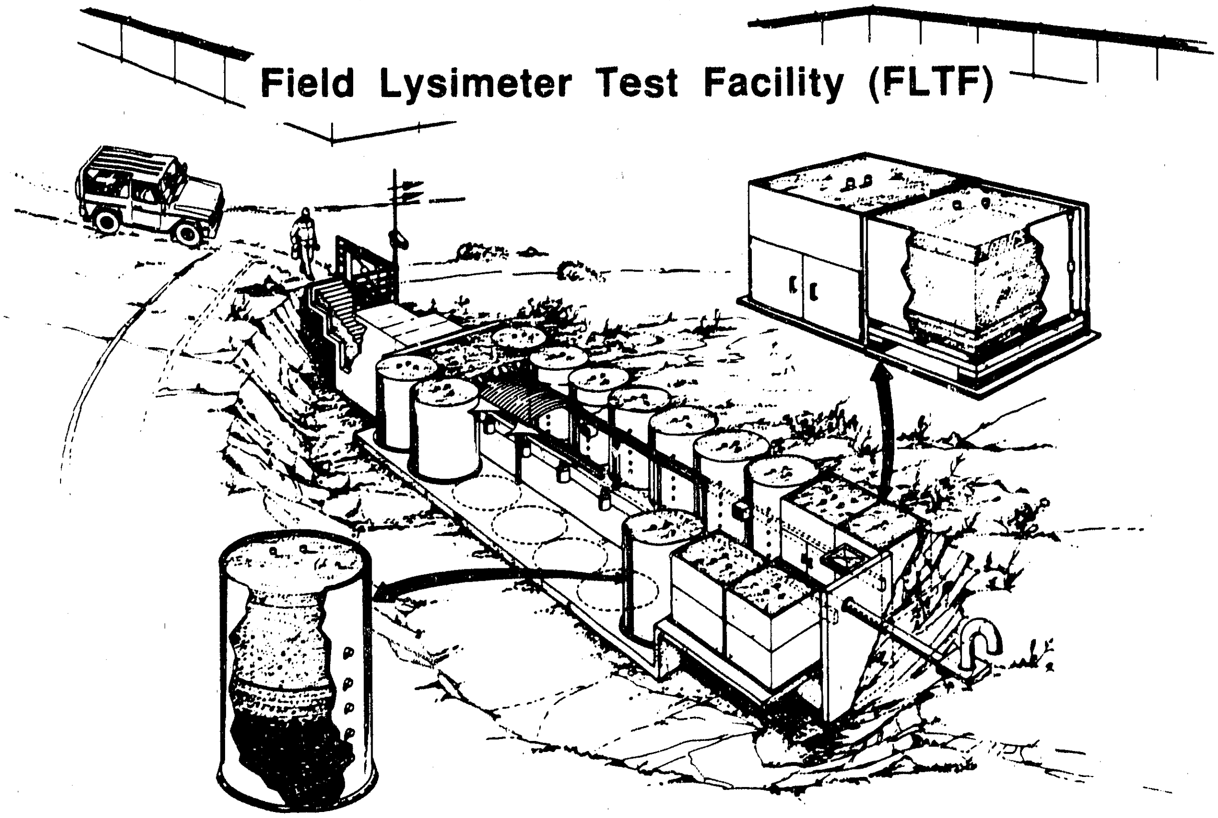


FIGURE 2.1. Cutaway Drawing of FLTF

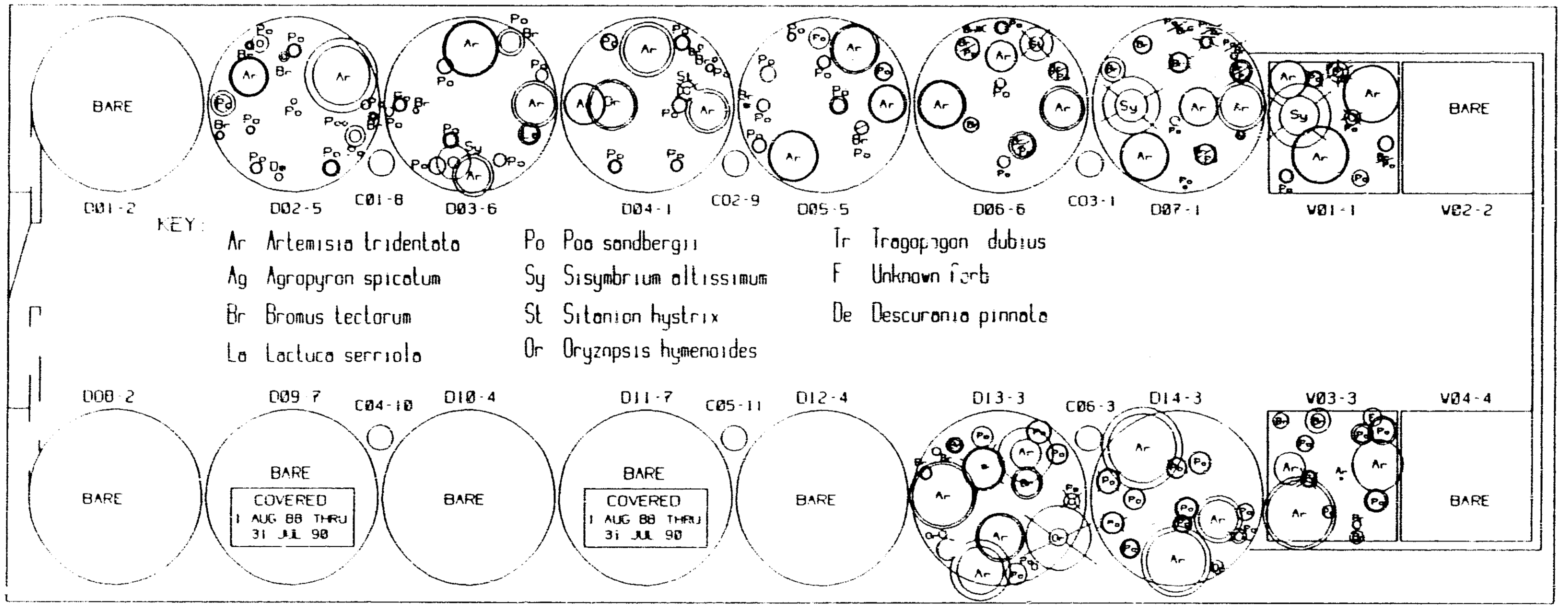


FIGURE 2.2. Vegetation by Relative Size and Locations on Lysimeters (1989 and 1990)

Within the facility, there are now 14 drainage lysimeters, 4 weighing lysimeters, and 6 clear-tube lysimeters (4 clear-tube lysimeters were added in FY 1990). These lysimeters are described in the following subsections.

2.1 EXPERIMENTAL DESIGN AND METHODS OF ANALYSIS

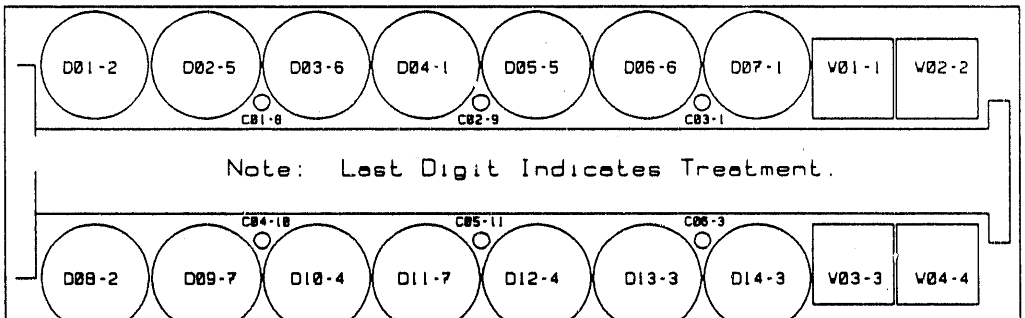
Seven treatments were applied to the barriers in the FLTF to demonstrate the main influences on barrier performance. These seven treatments are shown with the FLTF plan view in Figure 2.3.

Leak tests were performed during and following construction, as described by Kirkham et al. (1987) and Gee et al. (1989). Each lysimeter received a weighed amount of water for a specified time. The water was then drained for a specified time, weighed, and reinstalled for a specified time. The water was drained again for the same time as the previous drainage, weighed on the same scale, and discarded. The difference between the last two weights was treated as loss, and the cause of loss was investigated. Stoppers were inserted in drain hoses of all lysimeters to accumulate drainage water.

Drainage, subsequent to leak tests, was collected each time the neutron probe was used to measure soil moisture in the barrier profiles. The water was weighed with a precision of ±1 g using a 120-kg Sauter®[a] platform scale.

Precipitation was measured by the HMS. Although lysimeter weights changed with precipitation, they were biased by evaporative losses over the interval. Furthermore, weight change alone is always biased by evaporation unless evaporation is absolutely prevented for the entire interval of precipitation and weight measurements begin and end the interval. More importantly, HMS weather data provide consistency between past, current, and future weather measurements, and will, therefore, be used as the basis for the barrier tests.

(a) ®Sauter is a registered trademark of Mettler Instrument Company, Hightstown, New Jersey.



	Precipitation			Surface				Soil	Thickness			
Treatment	A(a)	2A(b)	B(c)	Bare	Veg	Admix	Gravel	Texture	1.0 m	1.5 m	3.0 m	Lysimeter #
1	X				X			Si L		X		V01-1, D04-1, D07-1, C03-1
2	X			X				Si L		X		V02-2, D01-2, D08-2
3		X			X			Si L		X		V03-3, D13-3, D14-3, C06-3
4		X		X				Si L		X		V04-4, D10-4, D12-4
5	X				X	X		Si L		X		D02-5, D05-5
6	X				X			Si L	X			D03-6, D06-6
7			X	X				Si L		X		D09-7, D11-7
8	X						X	S			X	C01-8
9	X				X			S			X	C02-9
10		X					X	S			X	C04-10
11		X			X			S			X	C05-11

(a) Ambient precipitation
(b) Twice-average precipitation
(c) Precipitation until breakthrough

FIGURE 2.3. Plan View of the FLTF with Treatment Designations

Irrigation was applied by a spray bar to lysimeters D09-7 through W04-4. Lysimeters D09-7 and D11-7 were covered and sealed with plastic from August 1988 through July 1990, after which covers and plastic seal were removed. Each lysimeter irrigated had a plastic precipitation gage next to it. Irrigation was scheduled to remove deficits at the beginning and middle of each month. Total water applied was the sum of irrigation plus natural precipitation required to equal twice average. Irrigations, except the last one each year, were short of the twice-average target to leave room for one average rainstorm without exceeding the target amount. The water year is from November 1 through October 31, with the first measurements taken in 1987.

Weighing lysimeters were calibrated near the end of summer when soil moisture is lowest. However, the calibration range was extended from 454 kg (1000 lb) to 909 kg (2000 lb) to make sure that water accumulation would not exceed the calibration upper limit. As with other recent calibrations, the data were processed to reveal deviations of scale readings from the calibration standards. The calibration factor for each weighing lysimeter was then used to process all weight data. The dataloggers used to monitor the weighing lysimeters were also used in the calibration process so that each system was calibrated as a system.

Soil moisture measurements by the neutron probe were scheduled every 2 weeks. The neutron probe was lowered at 0.15-m intervals into the north access tube in each lysimeter, and a measurement of soil moisture content was made. These data were recorded automatically as counts by the direct readout unit on the probe and manually in the log book. Both records were checked as the automatic data were dumped into the computer at the end of the day. Errors of transposition, common to the log book, were corrected by automatic data records. Errors of position, common to the automatic data, were corrected by manual data. Thus, the two most common sources of error were eliminated. Recalibration of the probe was unnecessary because we used the transfer standards and calibration checking methods reported by Campbell et al. (1990).

Soil profile temperatures were measured by thermocouples (see Figure 2.4). These temperatures were processed to obtain gradients from which to estimate vapor transport. Both diurnal and annual cycles were recorded and analyzed.

Soil moisture tension, or matric water potential, was measured by tensiometers (available from Soil Moisture Equipment Corporation, 801 S. Kellogg Avenue, Goleta, California 93117). Thermocouple psychrometers (TCPs) (available from Wescor, Incorporated, 459 S. Main St., Logan, Utah 84321) were also used to measure soil water potential. Tensiometers measured water potentials reliably in fine-textured soil from 0 to about -0.06 MPa. TCPs measured total water potentials from -0.2 to -6 MPa, the plant extraction limit. Soil water potentials measured were assumed to be equivalent because the soil was relatively salt free. Tensiometers readings were recorded using

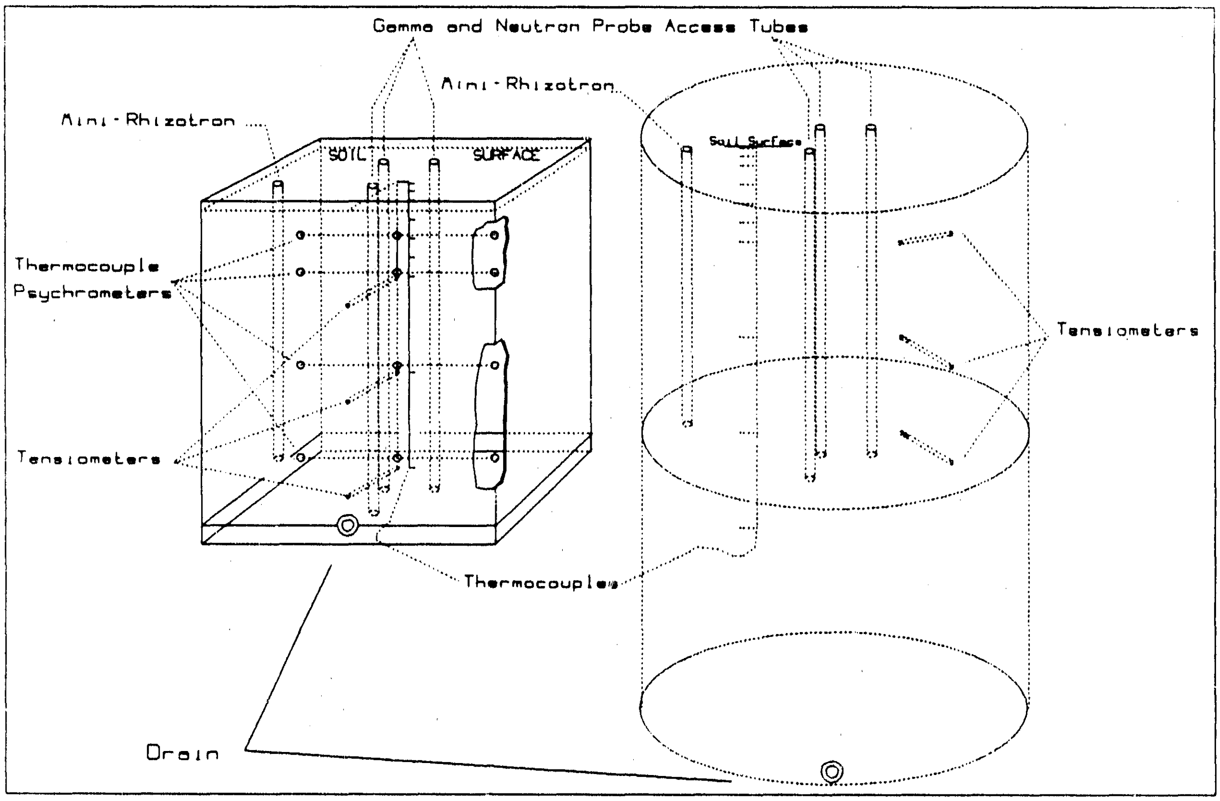


FIGURE 2.4. Instrument Location in Lysimeters

a Tensimeter®[(a)] at the time of neutron probe measurements. TCPs were measured about once a month using the CR7X datalogger®.[(b)]

2.2 DRAINAGE LYSIMETERS

Each drainage lysimeter is a steel cylinder with a 0.95-cm (3/8-in.) wall, 2 m in diameter and 3 m deep, with the top half (1.5 m or 1.0 m) filled with soil and the bottom half filled with a filterbed and riprap. The drainage lysimeters contain about 6600 kg of silt loam soil (1.5 m deep), except the two in treatment 6, which contain about 4400 kg (1.0 m deep). Below the No. 20-30 sand layer, which is 0.05 m deep, is a filterbed, graded

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(a) ®Tensimeter is a trademark of Soil Measurement Systems, Las Cruces, New Mexico.
(b) ®CR7X datalogger is a registered trademark of Campbell Scientific Instruments, Inc., Logan, Utah.

from No. 8 sand through 0.1-m-diameter rock to 0.15-m-diameter basalt riprap, designed to keep fine solids from moving downward while allowing drainage of excess water.

The 14 drainage lysimeters are arranged with seven of them on each side of an access/instrument tunnel, as shown in Figure 2.1. Each lysimeter has a sloping floor and a stoppered drain hose to allow draining water to be caught. Each lysimeter is in intimate contact with the soil on the half that faces out from the tunnel, to help preserve temperature regimes natural in the soil. The tunnel side is insulated and not in contact with the soil. The lysimeter interior is steel coated with coal-tar epoxy on the bottom and up 20 cm on the sides.

Figure 2.4 shows instrument locations. Transducers or access ports were provided in all drainage lysimeters. Minirhizotrons, thermocouples, thermocouple psychrometers, tensiometers, and neutron probe access tubes are located as shown in Figure 2.4.

2.3 WEIGHING LYSIMETERS

Each weighing lysimeter is 1.5 x 1.5 x 1.7 m and contains about 5900 kg of soil (1.5 m deep) placed on top of a 0.05-m sand filterbed that permits drainage of leachate from the bottom. Each weighing lysimeter rests on a 9000-kg (20,000-lb) capacity, Weigh-Tronix®(a) platform scale. Scale weights were recorded every 20 s on a CR7X datalogger®.

Four weighing lysimeters are located at the FLTF, two on each side of the access/instrument tunnel but isolated from the tunnel by access doors. Unlike the drainage lysimeters, the weighing lysimeters are not in intimate contact with the soil and are not insulated. Like the drainage lysimeters, each weighing lysimeter has a sloping bottom and a drain port at the low point. The weighing lysimeter instrumentation, as shown in Figure 2.4,

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(a) ®Weigh-Tronix is a registered trademark of Weigh Tronix, Inc., Fairmont, Minnesota.

monitors water content, water potential, soil temperature, and root distribution. Clear-glass root observation tubes 5 cm in diameter and 1.5 m long are located in lysimeters W01-1 and W03-3. They are called minirhizotrons.

2.4 CLEAR-TUBE LYSIMETERS

The six clear-tube lysimeters are for visual water and root observations only and are not part of the original, replicated seven-treatment design. The last four installed are assigned treatment numbers C01-8, C02-9, C04-10, and C05-11. The first two clear tubes installed were designated C03-1 and C06-3 to denote treatments similar to 1 and 3, but they are not included in water balance calculations. The six clear-tube lysimeters are equipped with drain ports.

The clear-tube lysimeters were made from 1.83-m (6 ft) sections of cast Acrylic®[a] plastic. The 0.3-m-diameter (12-in.) plastic sections, with 0.0063-m (0.25-in.) wall thickness, were fastened together with plastic solvent and cut into 3-m lengths. Stainless steel screw clamps were fastened around the tubes at the joints.

Three clear-tube lysimeters were installed on each side of the instrument/access tunnel in the FLTF with the top edges protruding 0.05 m above the soil surface. Opaque plastic collars were fabricated from gray polyvinyl chloride (PVC) pipe and installed around the top of each clear-tube lysimeter to exclude light. Low-pressure caps were installed on the bottoms of the clear-tube lysimeters and cemented in place with silicone rubber caulk. Drain ports were drilled in the sides of the caps at the bottom edges, and drain tubes with plugs were attached.

Four of the lysimeters (C01-8, C02-9, C04-10, and C05-11) were installed in October 1989 and filled with pit-run Hanford gravelly sand in the bottom half and with screened Hanford sand in the top half. Lysimeters C01-8 and C04-10 were topped with 0.15 m of coarse gravel to suppress solar loading and evaporation. Lysimeters C02-9 and C05-11 received small sagebrush (Artemisia tridentata) transplants. Lysimeters C03-1 and C06-3 were

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(a) ®Acrylic is a registered tradename of Port Plastics, Portland, Oregon.

installed and filled in mid-1988 with basalt riprap, capped by a filterbed in the lower half, and Warden silt loam soil (Xerollic Camborthid) from McGee Ranch in the top half, similar to the drainage lysimeters. Small sagebrush (Artemisia tridentata) were transplanted from the McGee Ranch into C03-1 and C06-3. We have observed root growth in C03-1 and C06-3 for the past 2 years.

2.5 WEATHER STATION AND METEOROLOGICAL DATA

The FLTF was constructed near the HMS because of the long-term weather history at this site. The long-term data are used in modeling water balance for the protective barriers. The current weather data are combined with design data to determine the treatment. That is, long-term average precipitation minus the year-to-date precipitation yields the amount of water to be applied to meet design standards.

Barrier design and function are linked irrevocably to soil water status and to factors that influence it. Essential measurements included

1. air temperature
2. net radiation
3. wind run
4. relative humidity
5. precipitation
6. soil water content and distribution
7. soil moisture tension
8. soil temperatures
9. evaporation
10. drainage
11. runoff (prevented by top lip on lysimeter).

Data from the first five items in the above list are measured hourly at the HMS and transported via phone to a laboratory (at PNL's Sigma V) for processing. We prevented runoff and measured these five items by dataloggers and by neutron probe measurements in the soil profiles. Based on these measurements, we developed a water budget for each lysimeter to account for precipitation, evaporation (including transpiration), storage, and drainage. Although drainage depends on precipitation, evaporation, and storage, these three factors depend both on driving forces of temperatures and tensions acting within the barrier and on solar radiation, wind, humidity, and temperatures acting on the soil surface. Measurements of these elements that affect water budget are used to show how and why the hydraulic barriers function and how to improve their design. Because of its overriding significance in barrier performance, drainage measurement was emphasized.

3.0 RESULTS AND SIGNIFICANCE OF TESTS

3.1 LEAK TESTS AND DRAINAGE

Drainage is the most important aspect of water balance in protective-barrier performance. Drainage is the source of all of the water that can leach waste into groundwater and cycle the waste into the biosphere. Leakage of any of the lysimeters could invalidate drainage data by diverting the drainage to a sink without detection or measurement. Lost drainage would result in underprediction of drainage potential and overprediction of barrier capability. Thus, successful leak tests were required preceding drainage tests. In addition, presaturation of all materials below the soil was necessary so that all drainage water would arrive at the drain instead of filling a deficit in the filter bed or the riprap. However, this pretreatment disposed the lysimeters to some drainage under the influence of seasonal temperature change. These factors complicated the data analyses because no clear distinction could be made between pretreatment drainage and post-treatment drainage. In fact, failure to recover leak-test water from lysimeters D02-5 and D06-6 is probably related to incomplete pretreatment wetting. Leak test results reported by Gee et al. (1989) are updated in summary form here.

Net drainage following leak tests is shown in Table 3.1. Water from the leak tests remained in some lysimeters following leak tests, especially in D02-5 and D06-6. None showed external evidence of leakage, though all are on a concrete pad that slopes slightly toward the access tunnel.

Soil moisture in D02-5 and D06-6 was below average. Rock content in D06-6 was above average, and the overlying mantle of soil was thinner, causing a colder lower soil surface on which to condense moisture. Leak tests were done during the fall and winter when the relatively warmer water vapor would be most likely to condense on the colder overlying soil. Also, the 35 kg of water involved would have had little influence on the soil water content, about 1.1 vol%. We believe, therefore, that the water remaining unaccounted from the leak tests was adsorbed on the lower soil overlying the filterbed, and that it was driven there by thermal gradients acting from the

TABLE 3.1. Drainage Record from Lysimeter Leak Tests, Showing Water Remaining in Lysimeters (kg). (Negative values in the last column result from subtracting column 4 from column 5, which shows water unrecovered from leak tests. Positive values in the last column represent net drainage after leak-test water was recovered.)

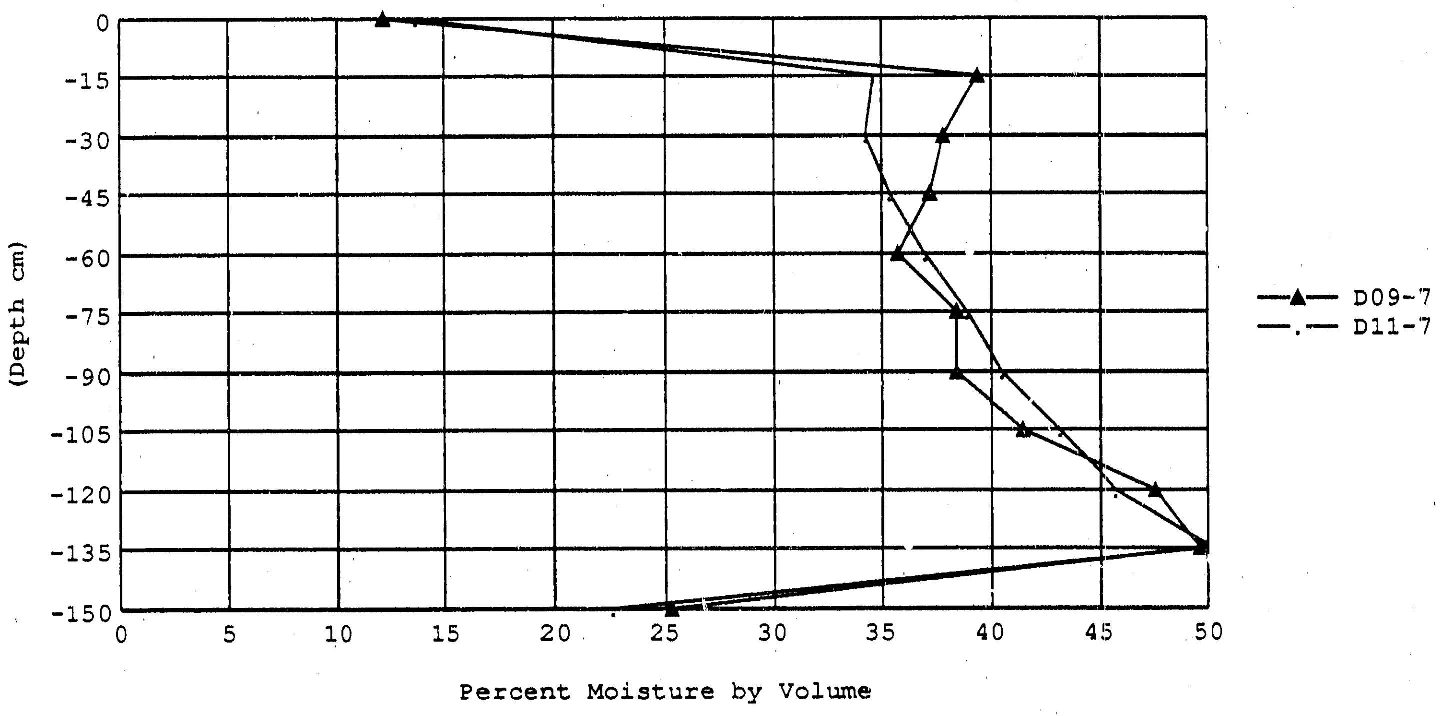
Drainage Lysimeter	TEST 1	TEST 2	TEST 3	Total Residual	Drainage by 4/3/90	Net Drainage
D01-2		5.678	13.806	19.484	19.076	-0.408
D02-5		7.482	15.130	22.612	6.420	-16.192
D03-6		4.759	12.477	17.236	20.355	3.119
D04-1		2.920	10.864	13.784	18.693	4.909
D05-5		2.150	8.449	10.599	20.354	9.755
D06-6		21.615	13.421	35.036	6.142	-28.894
D07-1		3.625	12.475	16.100	21.274	5.174
D08-2	1.826	2.396		4.222	13.644	9.422
D09-7	1.431	1.400		2.831	9.091	6.260
D10-4	1.316	3.622		4.938	6.153	1.215
D11-7	0.004	1.242		1.246	13.315	12.069
D12-4	1.423	1.528		2.951	8.108	5.157
D13-3	1.367	1.541		2.908	5.926	3.018
D14-3	1.454	0.880		2.334	8.409	6.075

Average drainage = 4.228
(Excluding D09-7, D11-7, D02-5, and D06-6)

warm water surface to the nearly-frozen overlying soil. This residual water is discussed further in connection with periodic drainage measurements.

Following 3-day drainage, the leak tests were terminated. Drain tubes were stoppered to begin collecting any water that penetrated the protective barriers. On April 14, 1988, treatment 7 was covered and water applied each week to obtain breakthrough (see Figure 3.1). The first detected breakthrough occurred on June 6, 1988, as reported by Gee et al. (1989). This filling and breakthrough process provided the soil moisture profile in Figure 3.1, based on neutron probe measurements. Other barrier profiles may be compared with the treatment 7 profile if potential for drainage is in question.

Drainage was measured each time soil moisture was measured. The drainage measurements were tabulated periodically as shown in Table 3.2. The



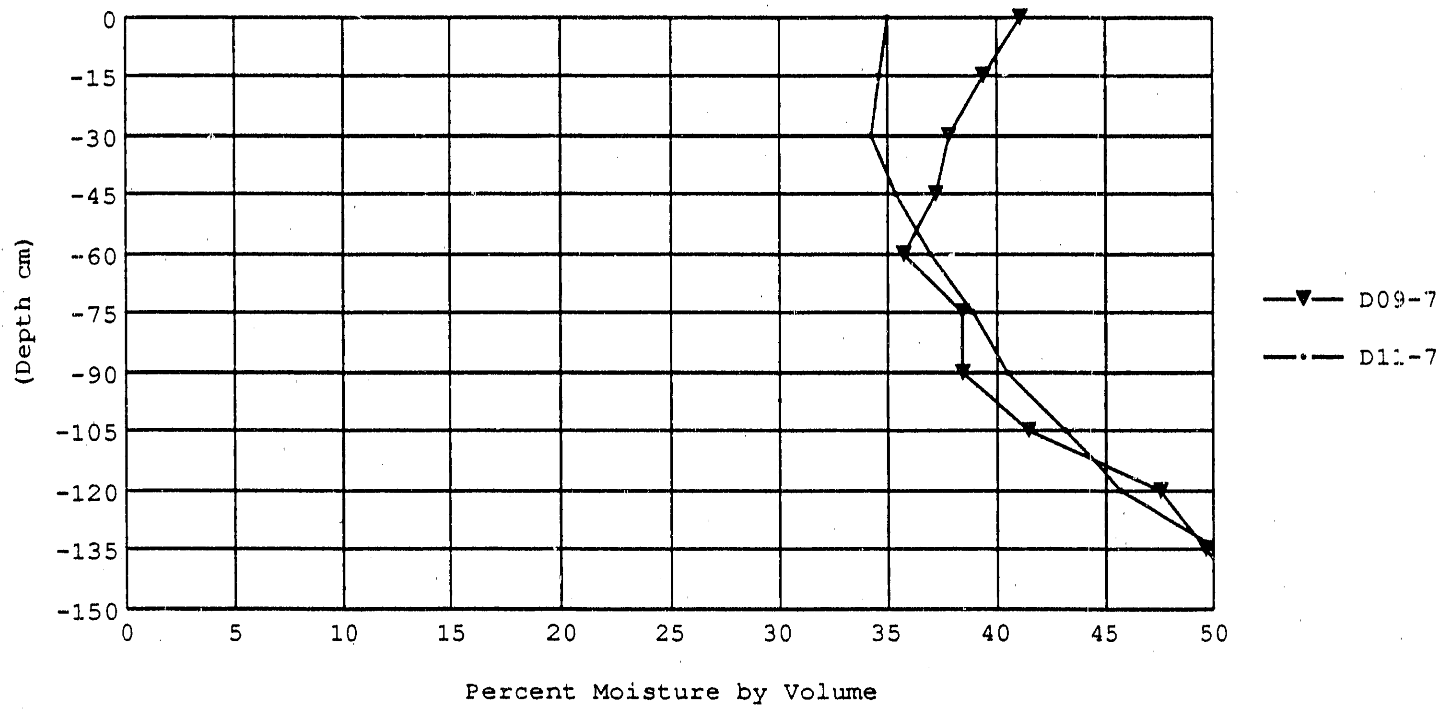


FIGURE 3.1. Neutron Probe Profile of Soil Water in D09-7 and D11-7 at Breakthrough on 6 June 1988. (Bottom graph shows upper and lower boundaries extended from two adjacent readings. See p. 3.12 for explanation.)

TABLE 3.2. Summary of Lysimeter Drainage Measurements (Water remaining in lysimeters from leak tests, kg)

Drainage Lysimeter	Test End	4/21/88	9/14/88	10/6/88	8/25/89	4/3/90
D01-2	19.484	13.320	2.258	1.423	0.921	0.408
D02-5	22.612	18.947	16.629	16.193	16.192	16.192
D03-6	17.236	8.553	-2.107	-3.090	-3.119	-3.119
D04-1	13.784	6.444	-0.592	-1.909	-2.118	-2.118
D05-5	10.599	4.517	-5.281	-6.334	-6.746	-6.746
D06-6	35.036	33.086	33.077	33.071	33.026	33.026
D07-1	16.100	7.648	-3.417	-5.053	-5.174	-5.174
D08-2	4.222	2.186	-0.844	-1.547	-2.373	-3.006
D09-7	2.831	1.404	0.257	-1.667	-6.666	-7.407
D10-4	4.938	3.206	0.544	0.018	-0.652	-1.215
D11-7	1.246	-1.266	-2.476	-5.662	-12.171	-13.279
D12-4	2.951	1.074	-2.344	-3.019	-4.683	-5.157
D13-3	2.908	1.087	-2.354	-2.894	-3.018	-3.018
D14-3	2.334	0.453	-5.200	-5.905	-6.045	-6.075

mean and standard deviation of drainage (1.364 ± 0.784 kg) between September 14, 1988 and April 4, 1990 are similar among treatments. Similarity among the six treatments confirms that something more uniform than the treatments caused the drainage. Water from the six treatments drained mainly during the summertime, when barrier soil profiles were driest. Soil water potentials just above the hydraulic break were all negative from -0.03 MPa. Because water treatments were uniform and none of the profiles closely approached those of treatment 7, liquid drainage was ruled out. Another transport mechanism was sought. [Treatment 7 was excluded from comparisons with the other lysimeters because of unrecorded drainage during breakthrough and because soil was added following subsidence, as reported by Campbell et al. (1990).]

3.2 TEMPERATURE PROFILES AND VAPOR TRANSPORT

Temperature gradients in wet soil move water in both liquid and vapor phases, from points of higher temperature to points of lower temperature. Vapor transport apparently has the capacity to transport water across the protective barrier and deliver it in significant amounts within the region to be protected by the barrier. One main objective of this work is to measure the thermal driving forces and the drainage water to deduce the magnitude, the path, and significance of all drainage. The very low drainage target level of 0.05 cm/yr will be examined in light of the combined vapor and liquid transport potential.

Temperature profiles that were measured in all barrier treatments were output as hourly and daily averages. A typical example of the annual temperature cycle is shown in Figure 3.2.

The expected thermal lag with depth is evident in all four graphs. Wave amplitude appears damped with depth, as expected. Average temperature gradients computed on both hourly and daily temperature data ranged to ±0.09°C/cm, with zeros near May and November and extremes near February and August. Based on these extremes, the maximum vertically-downward flux of water vapor is expected between mid-July and early September. Drainage is recorded in Table 3.2. Some of the early drainage apparently was residual water from the leak tests, released by reversing thermal gradients. Later drainage seems to have been more a consequence of thermal pumping.

Equations (3.1) and (3.2) were adapted from Equation (5.19) of Nielsen et al. (1972) to compute water vapor flux.

$$\beta = -1.62 + 0.4367\,\Theta - 0.00949\,\Theta^2 \tag{3.1}$$

where β accounts for air-filled pore volume, tortuosity, and thermal gradient shifts across pore air space, and Θ is soil water content in vol%.

$$J_{WV} = -\beta\,(1.56 \times 10^{-5}\,T^2 + 2.73 \times 10^{-3})\,\delta T/\delta x \tag{3.2}$$

where J_{WV} is water vapor flux in mm/hr, T is average temperature, and $\delta T/\delta x$ is the change in temperature in °C/cm. Water vapor transport computed by Equation (3.2) is shown in Table 3.3; computed values should agree with measured values within a factor of 2 or 3. Both hourly and daily data were used, but their agreement was within about 20%, so only the daily data were

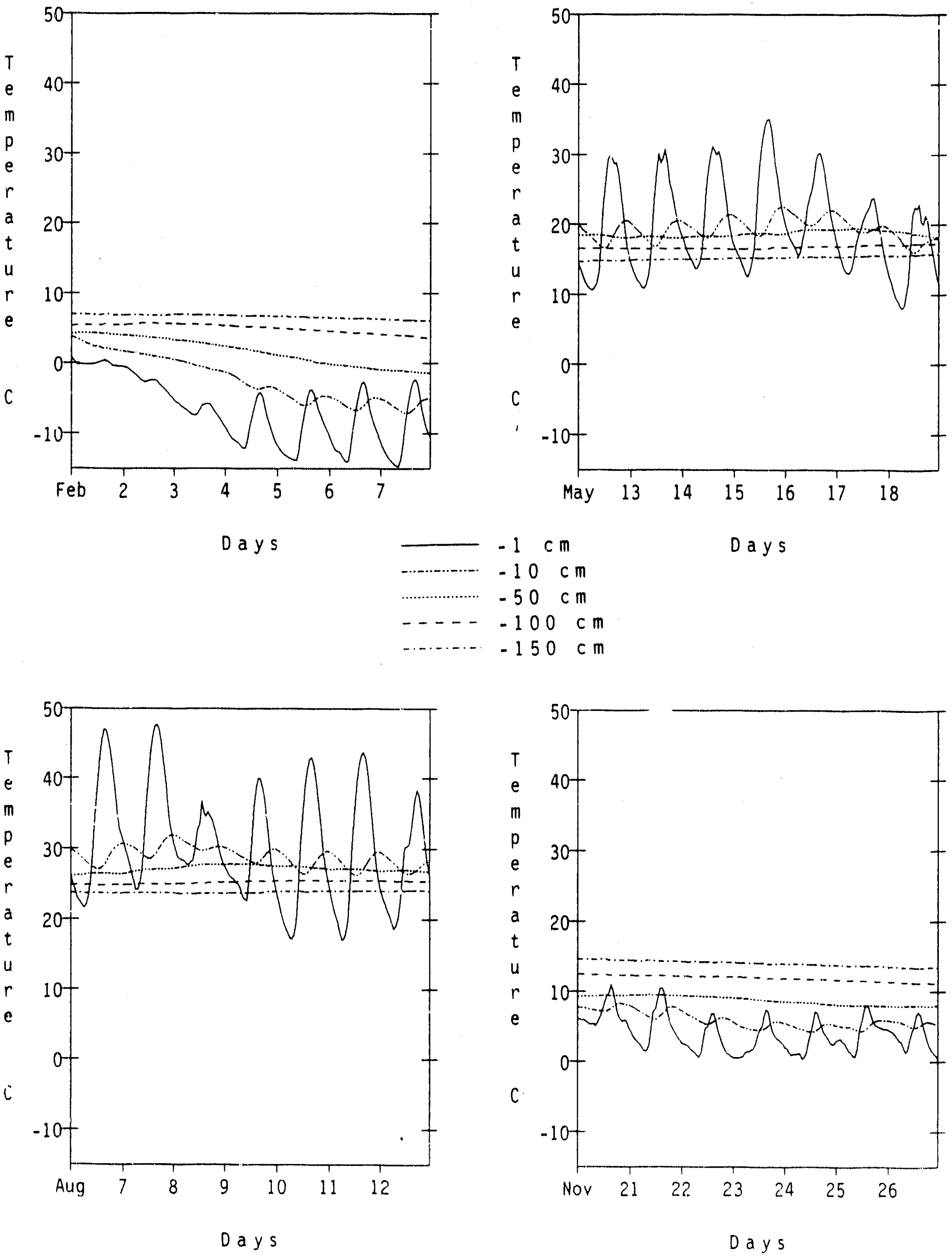


FIGURE 3.2. Temperature Cycles at Four Times in Drainage Lysimeter D04-1

TABLE 3.3. Modeled Water Vapor Transport in Lysimeters by Treatment from (a) November 7, 1987 to July 5, 1990 and from (b) September 14, 1988 to April 4, 1990

	Calculated	
Treatment	(a) Vapor Transport (kg)	(b) Vapor Transport (kg)
1	7.148	0.861
2	18.458	2.952
3	5.208	-1.227
4	8.502	-2.444
5	10.328	0.554
6	9.386	0.886

processed for the entire period. The main values of interest are the paired values, showing computed vapor transport and measured drainage. These values are shown in Table 3.4.

The measurements and the modeled transport indicate that barriers operating under moist conditions may transport more than the target 0.05 cm/yr and that vegetation has the capacity to reduce or eliminate the thermally driven water, partly by shading the barrier to reduce the thermal gradient and partly by drying the soil. Additional observations are needed to identify precisely the conditions for transport and to refine the model.

Weighing lysimeters yielded no drainage at any time. We believe that the lack of drainage from the weighing lysimeters further confirms evidence of thermal transport. Weighing lysimeters received dry treatments 1 and 2 as

TABLE 3.4. Computed Vapor Transport and Measured Drainage from (a) November 7, 1987 to July 5, 1990 and from (b) September 14, 1988 to April 4, 1990

	Calculated		
Treatment	(a) Vapor Transport (kg)	(b) Vapor Transport (kg)	Measured Drainage
1	7.148	0.861	1.641
2	18.458	2.952	1.299
3	5.208	-1.227	0.744
4	8.502	-2.444	2.286
5	10.328	0.554	0.951
6	9.386	0.886	0.531

well as wet treatments 3 and 4. No drainage means that neither liquid nor vapor transport (condensation) occurred. Thermal gradients in the weighing lysimeters were about half as large as in the drainage lysimeters, due to air circulation all around the lysimeter and to isolation of the soil column from the underlying soil. Figure 3.3 shows the largest differences in temperature profiles in the weighing lysimeters. Notice the near-vertical nature of the profiles. This feature suggests that the temperature deep in the profile is following the surface temperature instead of converging on a common temperature at the depth of the annual soil temperature cycle. Computed vapor transport is negligible. Thus, only vapor transport moved water across any of the hydraulic barriers at the FLTF, and this transport was small amounts. (See Section 3.7.1 for further explanation.)

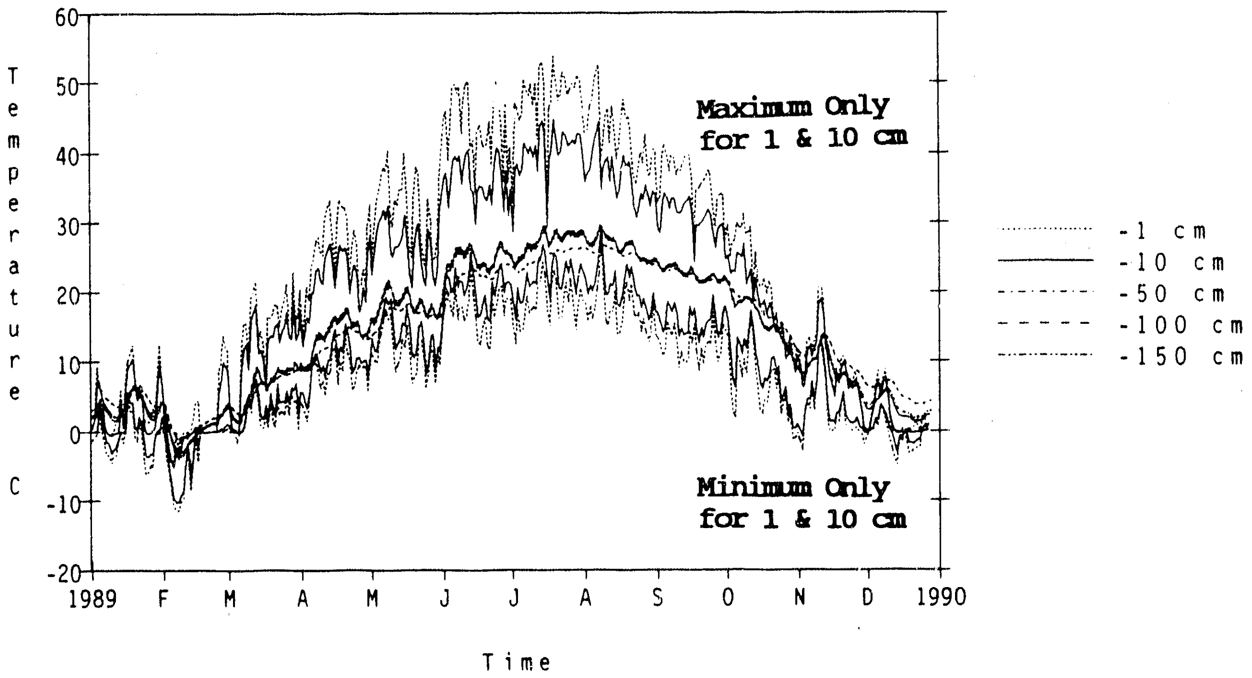


FIGURE 3.3. Annual Temperature Cycle in W01-1, Showing Temperature Change with Depth

3.3 LYSIMETER WEIGHT MEASUREMENTS

Lysimeter weight measurements offer the most precise and reliable information available on total water balance for the treatments being monitored at the FLTF. Time averaging yields a precision approaching 50 g (0.1 lb). Maximum errors detected during calibration confirm bias less than ±500 g (1 lb) over the 900-kg (2,000-lb) range of calibration. Figure 3.4 shows the calibration with deviations, including hysteresis. A major objective of using precision weighing lysimeters was to provide crosschecks against precipitation measured by HMS, evaporation modeled by UNSAT-H (Fayer et al. 1986), drainage measured by the Sauter balance, and profile moisture storage measured by the neutron probe.

Figure 3.5 shows the change in water storage in all four weighing lysimeters at the FLTF from the beginning of the water year in November 1987 through June 1990. The overriding influence of treatments is evident from the fact that, although all lysimeters started from a common soil moisture status, each approached a final state related to treatment. Second, both the

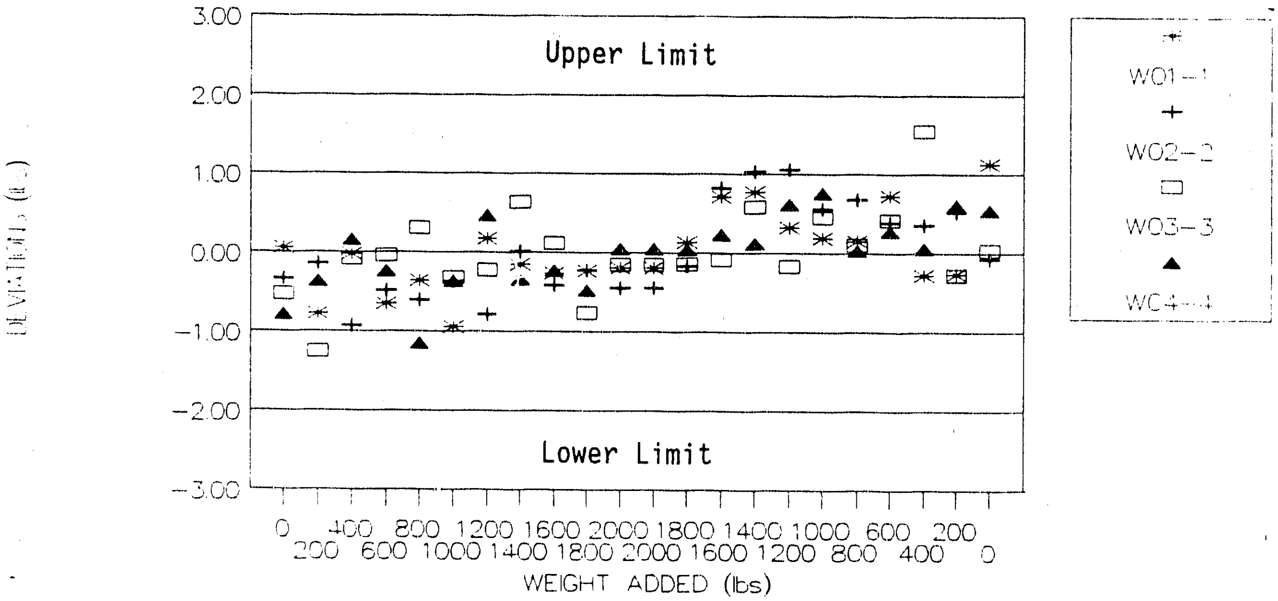


FIGURE 3.4. Calibration Weight Addition and Removal During Scale Calibration, with Upper and Lower Tolerance Limits Set at ±1.36 kg (±3 lb)

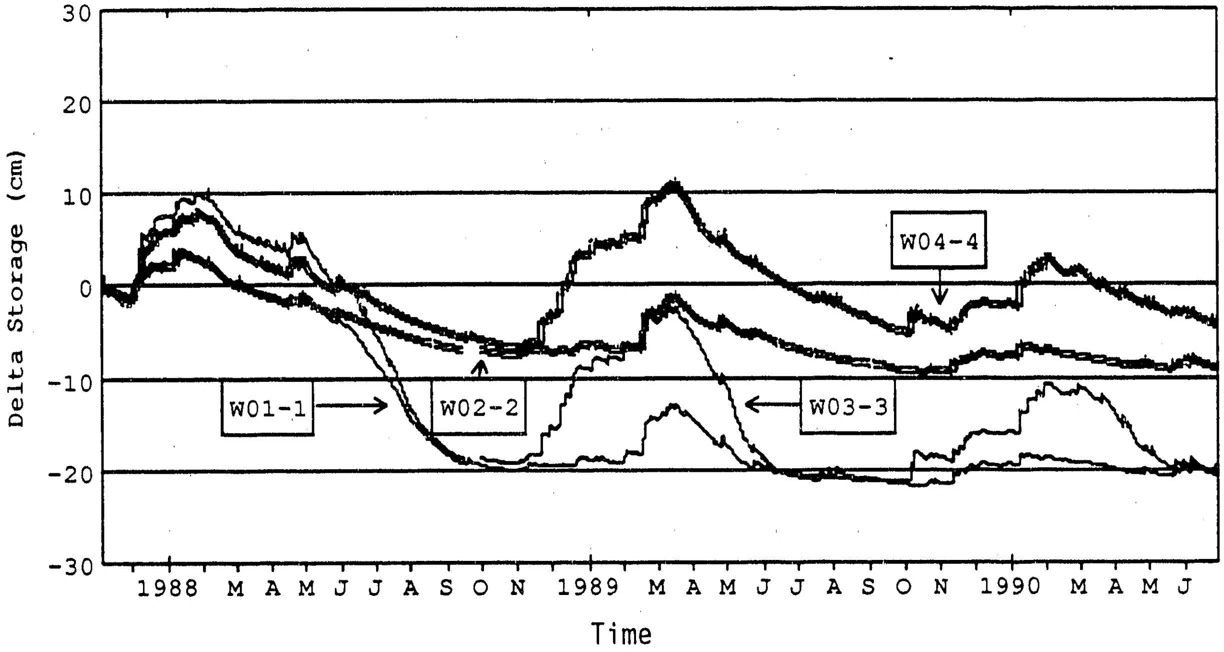


FIGURE 3.5. Water Storage Change in Weighing Lysimeters, November 1987 to June 1990

irrigated and the nonirrigated lysimeters with vegetation lost water until they reached similar water storage values during each of the three years. Third, lysimeters without vegetation lost different amounts of water, with more water remaining deep in the irrigated lysimeters, showing that water deep in the soil profile did not move up to evaporate as readily as near-surface moisture. Fourth, water-holding capacity of the silt loam soil was more than sufficient to hold residual water from the twice-average applications without breakthrough, even on the nonvegetated lysimeters.

The water content ranges from about 10 cm to about 44 cm. At the 10-cm water content, the plants cannot extract the water and dormancy prevails. At 44 cm, water moves downward until it is stopped by the hydraulic barrier. Water storage measured as weight is accurate for the instant of measurement but does not accurately reflect time-delayed events like rain or irrigation. Although precipitation and irrigation are evident in Figures 3.5 and 3.6, unrestricted evaporation biases the weight change record. This bias is the result of failure to retain all water received during the event. All losses

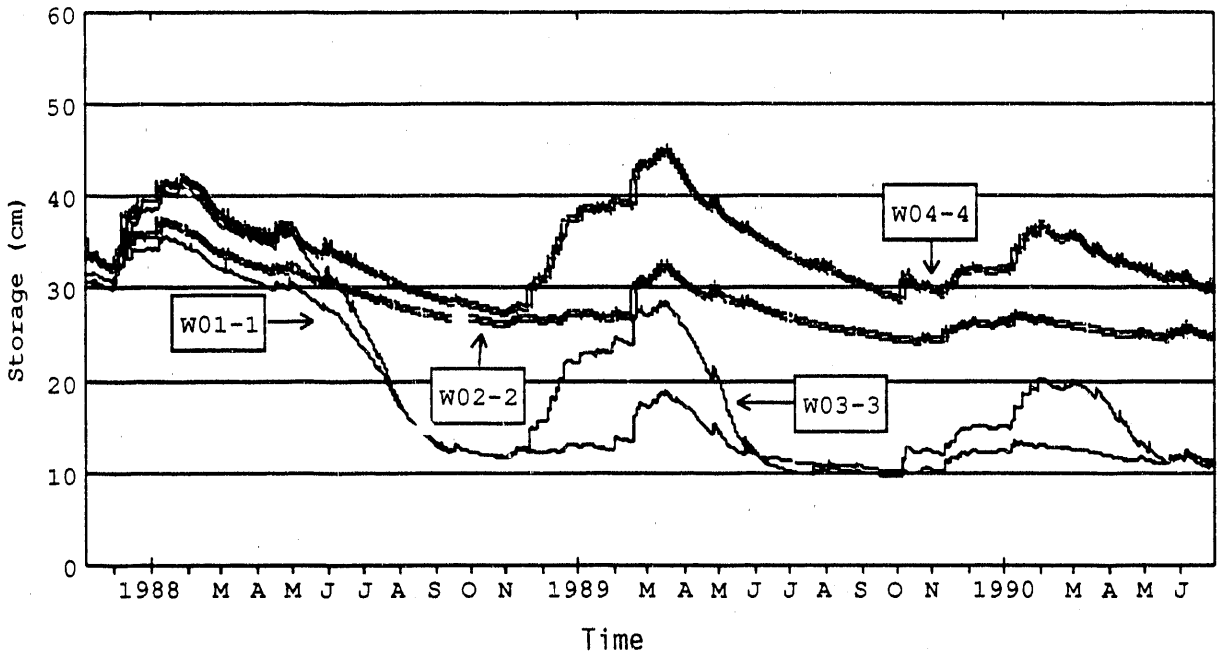


FIGURE 3.6. Water Storage in Weighing Lysimeters, November 1987 to June 1990

during precipitation, before the total is reached, diminish the measured total by the amount lost. There is no way to avoid this type of error without eliminating all loss during precipitation. Even short-interval measurements cannot avoid this bias.

3.4 SOIL WATER CONTENT FROM NEUTRON PROBE MEASUREMENTS

We measured soil moisture profiles with a neutron probe in all lysimeters twice each month. Figure 3.7 is an example of the neutron probe measurements taken on November 4, 1987.

Part (a) of Figure 3.7 shows moisture decline at the 0- and 150-cm depths. Part (b) shows the same information, but with the zero depth and 150-cm depth projected from their two nearest values. Thus, the zero-depth value came from projecting a line through the 15- and 30-cm measurements, likewise the 150-cm value from the 120- and 135-cm measurements. This process adjusts for half-sphere errors from the neutron probe as it passes

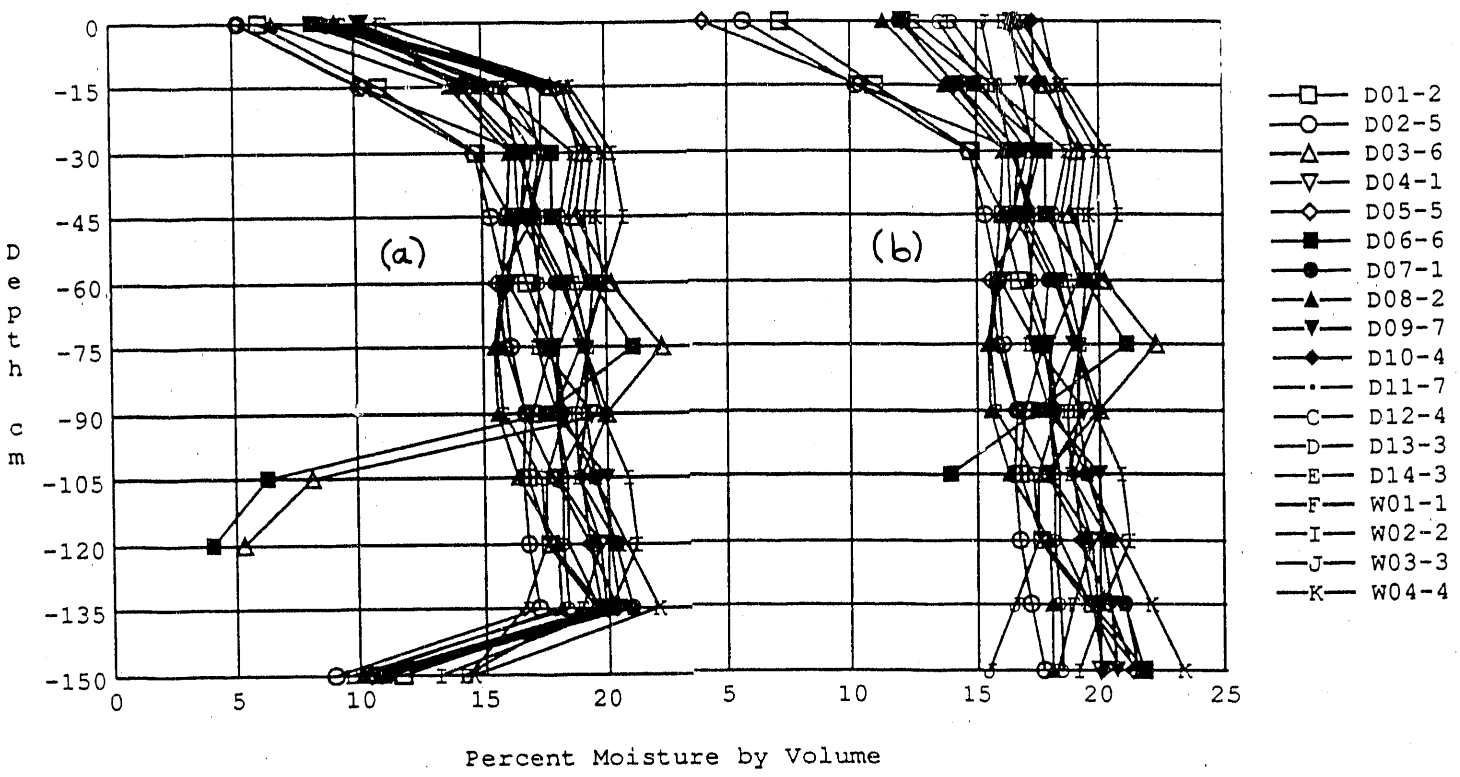


FIGURE 3.7. Neutron Probe Profiles of Soil Moisture in Lysimeters on November 4, 1987 (to show similarity of soil profiles, initially). Part (a) is actual measurement. Part (b) has "0" and "-150" depths projected from two nearest measurements.

through the upper and lower boundaries of the barrier. Initial soil moisture spreads horizontally about 5 vol% between the highest and lowest profiles. Integration of the area left of each curve from zero to 150-cm depth yields the soil water content that can be compared with lysimeter weights. Agreement between methods is displayed in Figure 3.8.

Once calibrated and crosschecked against the weighing lysimeters, the neutron probe was used to measure water profiles in all lysimeters. These profiles include all neutron probe measurements from November 4, 1987 to July 10, 1990 and are presented in the appendix. Like Figure 3.7, each pair of graphs represents all lysimeters for the date indicated.

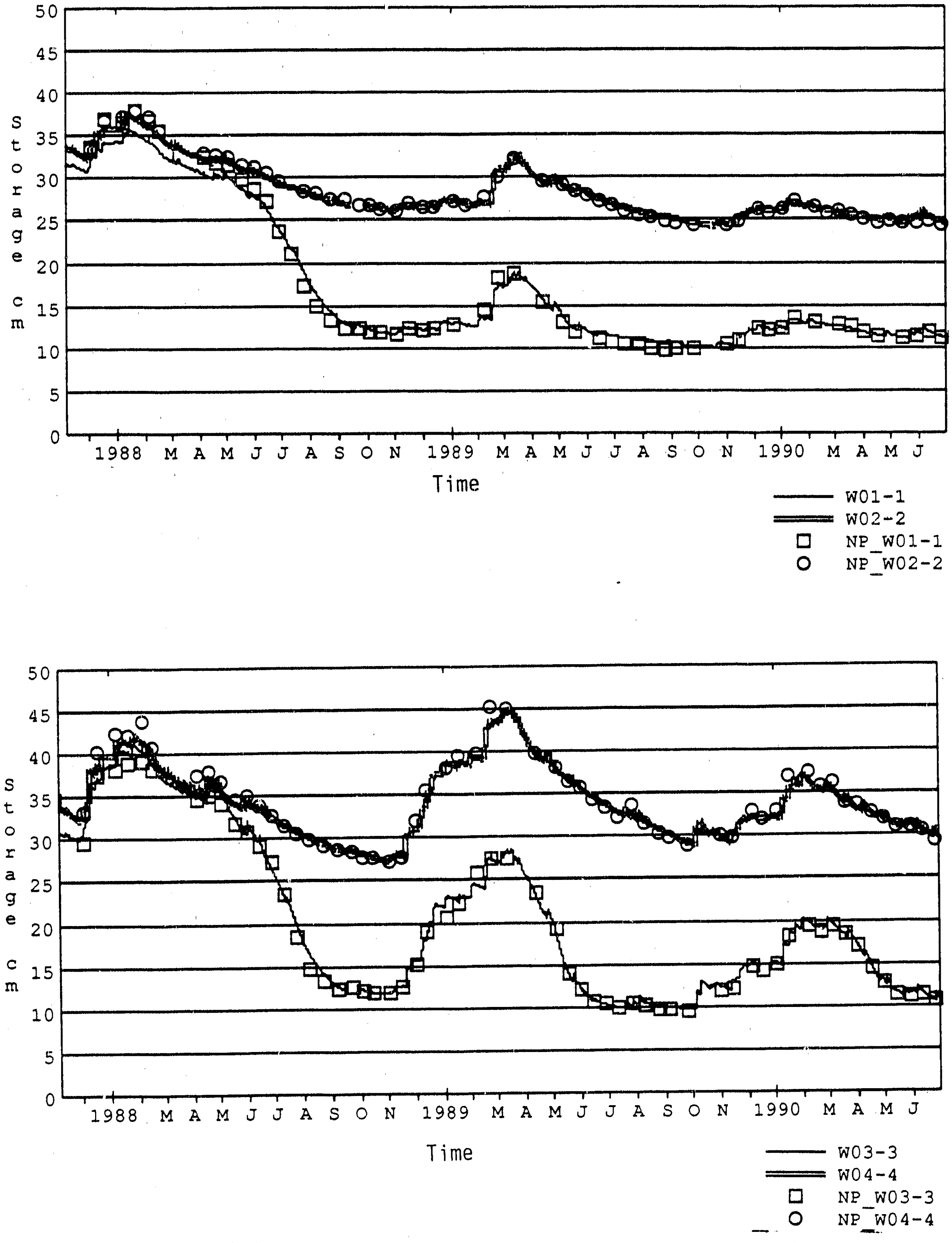


FIGURE 3.8. Calibration Crosscheck, Neutron Probe to Weighing Lysimeter

3.5 WATER BALANCE BY TREATMENT

Water balance is the accounting of all five partitions into which water may be divided. Equation (3.3) shows the partitions:

$$P = R + E + S + D \tag{3.3}$$

where P is total water received at a soil surface, R is runoff, E is total evaporation (including transpiration), S is net water storage for an interval, and D is drainage through the soil profile for all reasons. The value P includes snow, frost, condensation, irrigation, and rain. The value R was precluded at the FLTF by a 5-cm edge protruding upward on each lysimeter. The value E includes evaporation from the soil surface at a constant-rate stage of drying, evaporation at a falling-rate stage of drying, and transpiration from vegetation. Differences in treatments and in modeling have forced us to divide E into its components. The value S is treated in two ways: 1) net change in soil water content accounts for the amount of water partitioned to storage within the interval in question, and 2) total soil moisture content represents the amount of water in the soil after partitions P, E, and D have interacted.

Because the FLTF is used to demonstrate how much water will drain through the protective barriers and under what conditions, rigorous measurements of all components are necessary. Drainage is the factor of greatest importance. Seven treatments were imposed on the barriers at the FLTF. Treatment 7 has already been discussed. Water balances for treatments 1 through 7 are displayed in Figures 3.9 through 3.15.

These seven figures show drainage lysimeter water storage based on neutron probe measurements in the same way as Figure 3.6 shows water storage based on weight. The most prominent feature of these figures is that initial conditions of all lysimeters are definitely masked by the treatments, indicating the overriding impact of each treatment. Treatments 2 and 4 show the impact of the lack of vegetation on removing water, and treatment 4 also

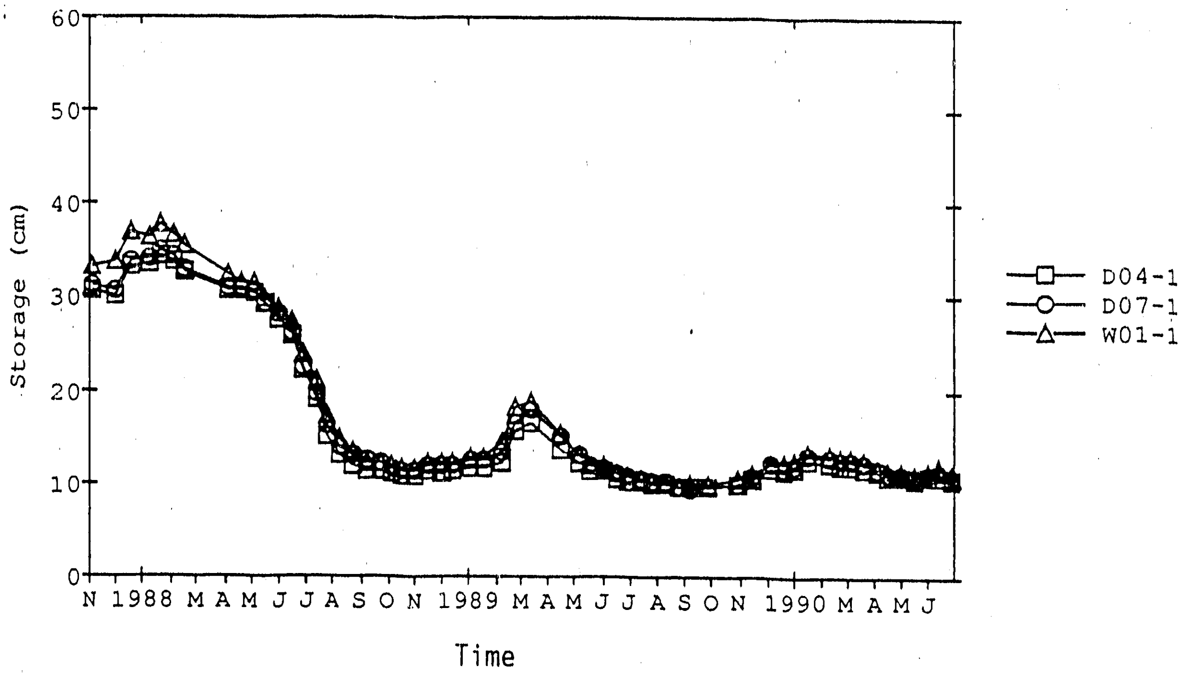


FIGURE 3.9. Water Storage in Treatment 1 Lysimeters (vegetation, ambient precipitation 1.5 m soil)

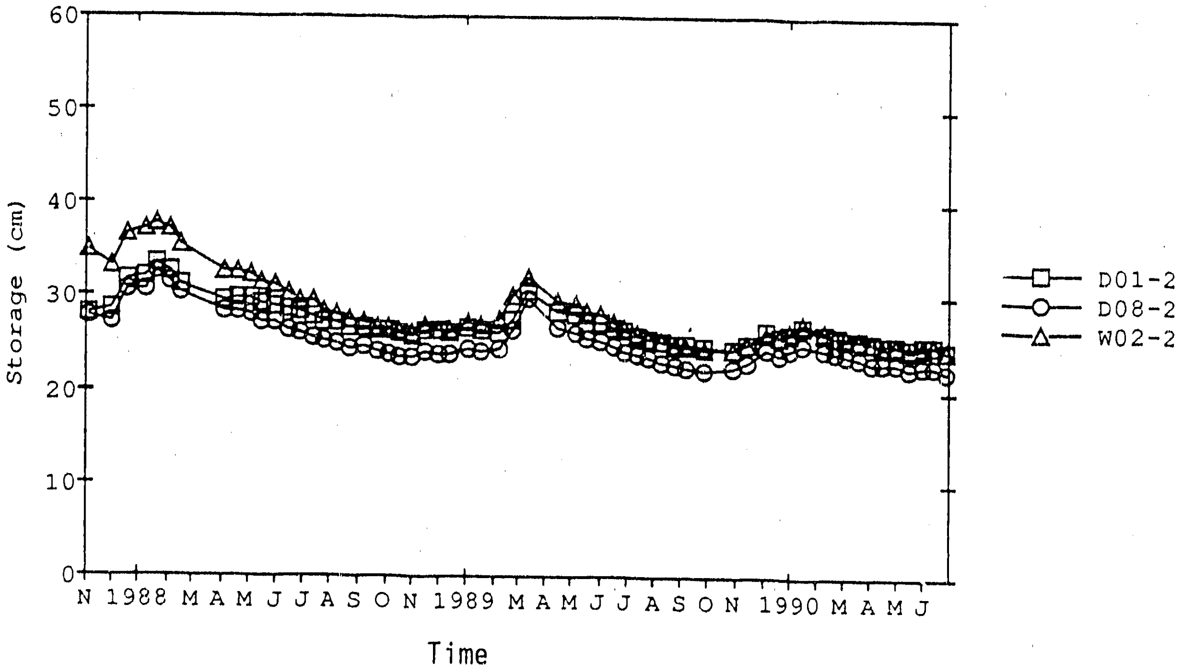


FIGURE 3.10. Water Storage in Treatment 2 Lysimeters (bare, ambient precipitation 1.5 m soil)

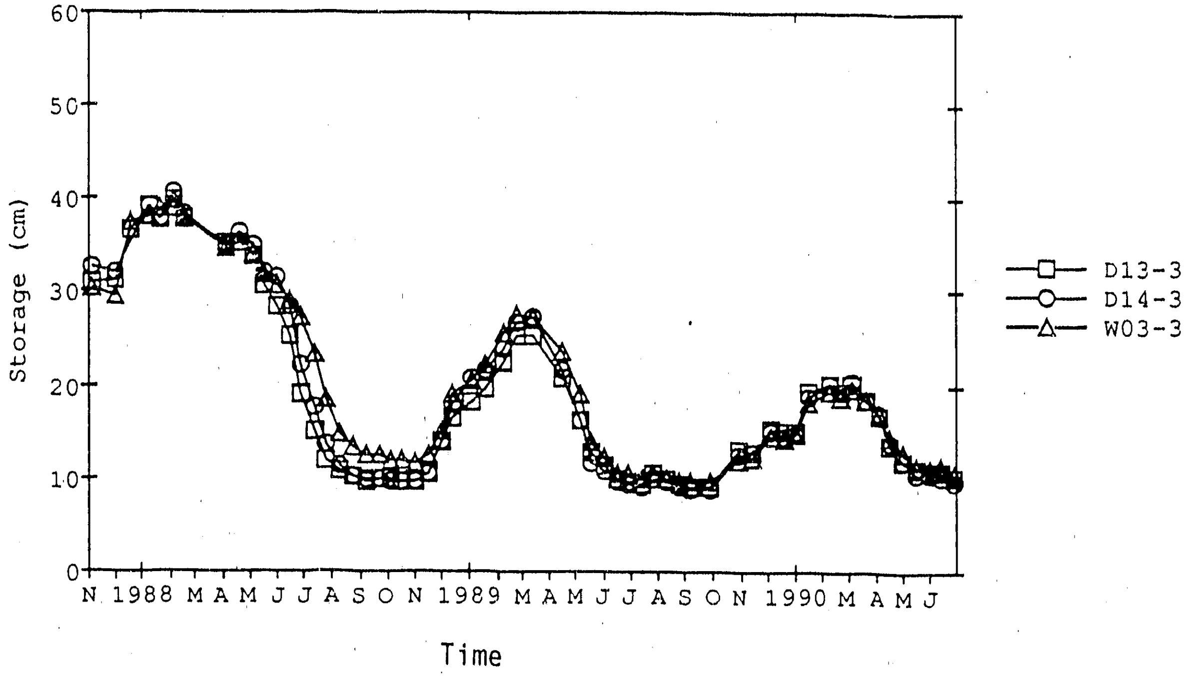


FIGURE 3.11. Water Storage in Treatment 3 Lysimeters (vegetation, twice-average precipitation 1.5 m soil)

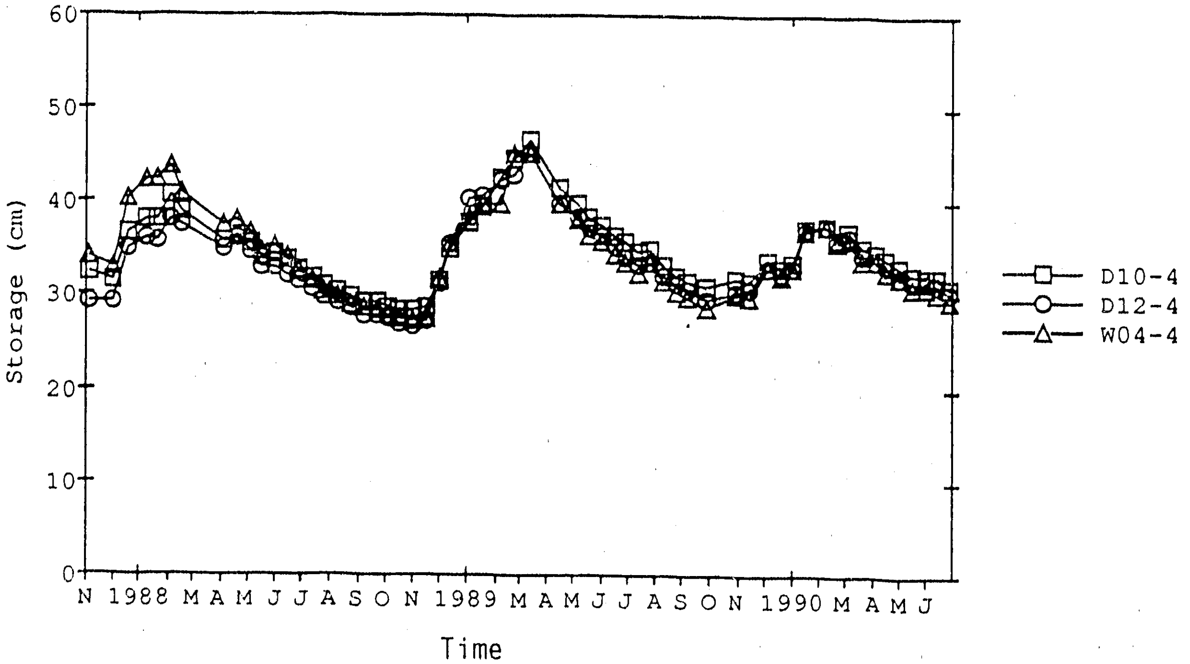


FIGURE 3.12. Water Storage in Treatment 4 Lysimeters (bare, twice-average precipitation 1.5 m soil)

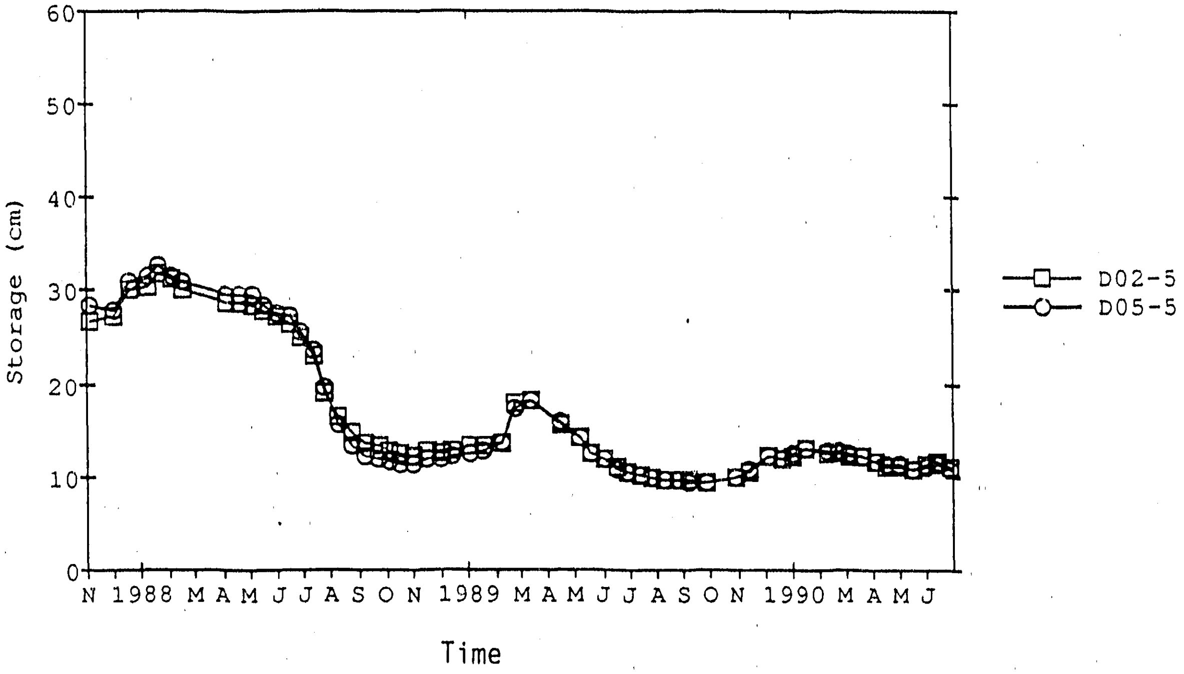


FIGURE 3.13. Water Storage in Treatment 5 Lysimeters (vegetation, ambient precipitation 1.5 m soil admix)

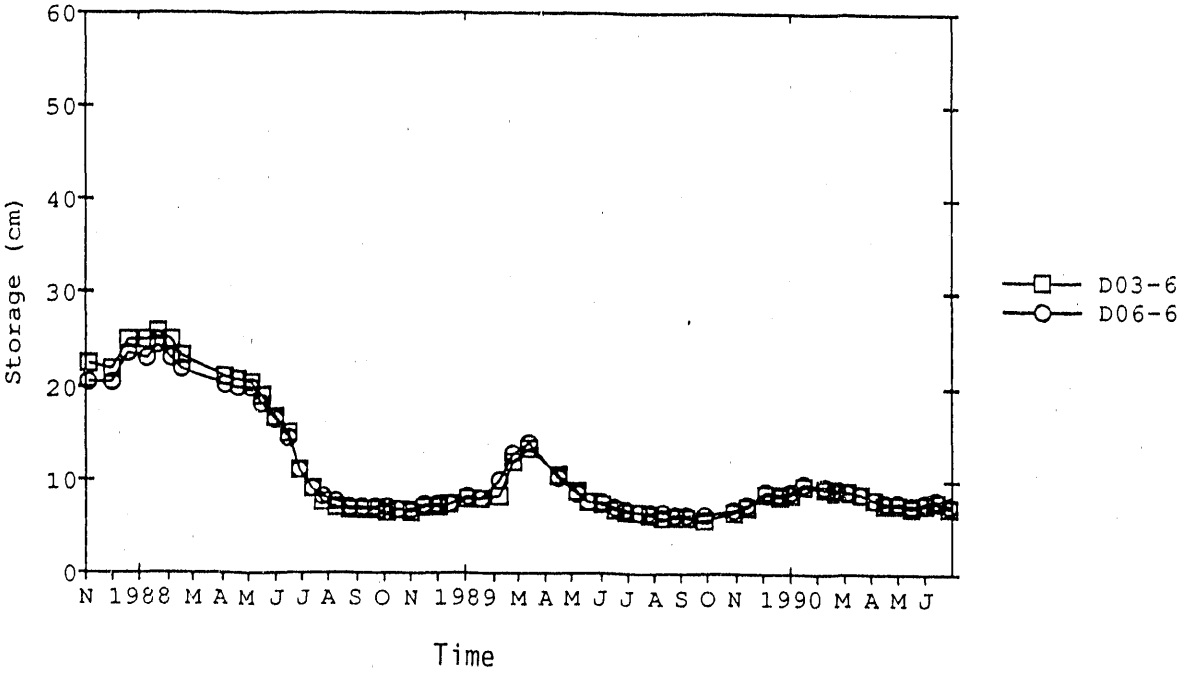


FIGURE 3.14. Water Storage in Treatment 6 Lysimeters (vegetation, ambient precipitation, 1 m soil)

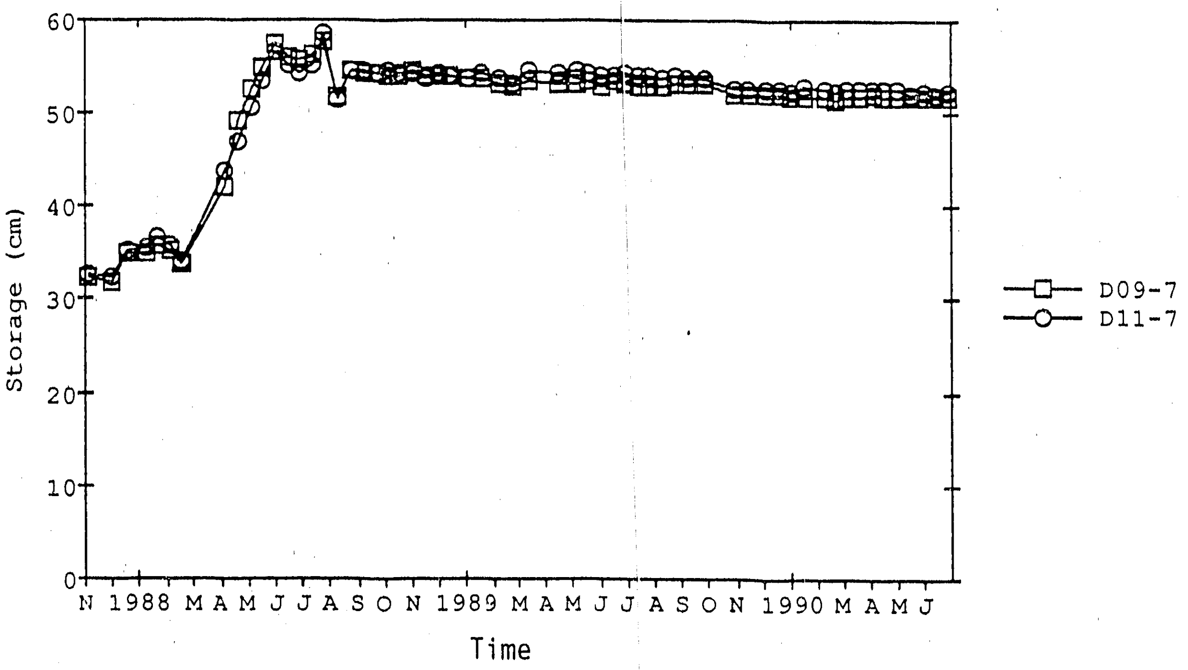


FIGURE 3.15. Water Storage in Treatment 7 Lysimeters (bare, precipitation to breakthrough, 1.5 m soil)

shows the impact of the twice-average water application coupled to a bare evaporative surface. Treatments 1, 3, 5, and 6 show the common impact of vegetation, which will be discussed next.

Water balance indicates that neither the ambient (natural precipitation) nor the twice-average treatments are gaining water. However, treatment 4, which receives twice-average precipitation and has no vegetation, appears to be operating near capacity for recycling water to the atmosphere. This confirms the finding by Campbell et al. (1990) based on second-year tests. Thus, the capacity of silt loam soil 1.5 m deep to cycle water back to the atmosphere at a rate of 32 cm/yr depends not only on soil storage capacity but also on storm timing and intensity.

3.6 VEGETATION INTERACTIONS AND WATER BALANCE

The influence of vegetation on water balance is profound, and vegetation is the most important factor in preventing drainage through the barrier. The vegetation removes water until the soil reaches a nearly uniform water content from top to bottom of the soil profile, unlike the nonvegetated soil.

Rapid root growth was observed in moist soils. Root elongation occurred rapidly in lysimeters C02-1, C05-3, and C06-3. These clear-tube lysimeters were thoroughly irrigated before sagebrush (Artemisia tridentata) was transplanted on them. When warm weather permitted root growth, the roots in these three lysimeters grew rapidly down through the moist soil until they reached some physical barrier. In adjacent clear-tube lysimeters that were not preirrigated, roots did not grow down into the dry soil; they stopped at the wetting front, extracting water from there until dormancy or death prevailed. Table 3.5 shows the root growth rate of sagebrush into the preirrigated soils of the three clear-tube lysimeters.

Sagebrush evidently sends roots down in moist soil at an average rate of 1.41 cm/d, showing a capability of extracting water from the bottom soil in the barrier within 100 days. This clearly enhances the prospect of recycling water to the atmosphere during any single season, thus reducing the hydraulic burden on the barrier.

Figure 3.16 shows the influences of different treatments on moisture profiles. The left-most profiles resulted from vegetative water removal. Second from left are the profiles that received ambient precipitation but had no vegetation. Third from left are the profiles that received twice-average precipitation but had no vegetation. The right-most profiles received water until breakthrough but had no vegetation and were sealed against evaporative loss to the atmosphere.

TABLE 3.5. Root Growth Rate in Clear-Tube Lysimeters (cm/d)

	C02-9	C05-11	C06-3
	Sand	Sand	Silt Loam
Average	1.40	0.89	1.96
Std. Dev.	0.69	0.30	0.59
Depth of Root Penetration			
	>2 m Growing	>1.5 m Growing	1.5 m Stopped at Break

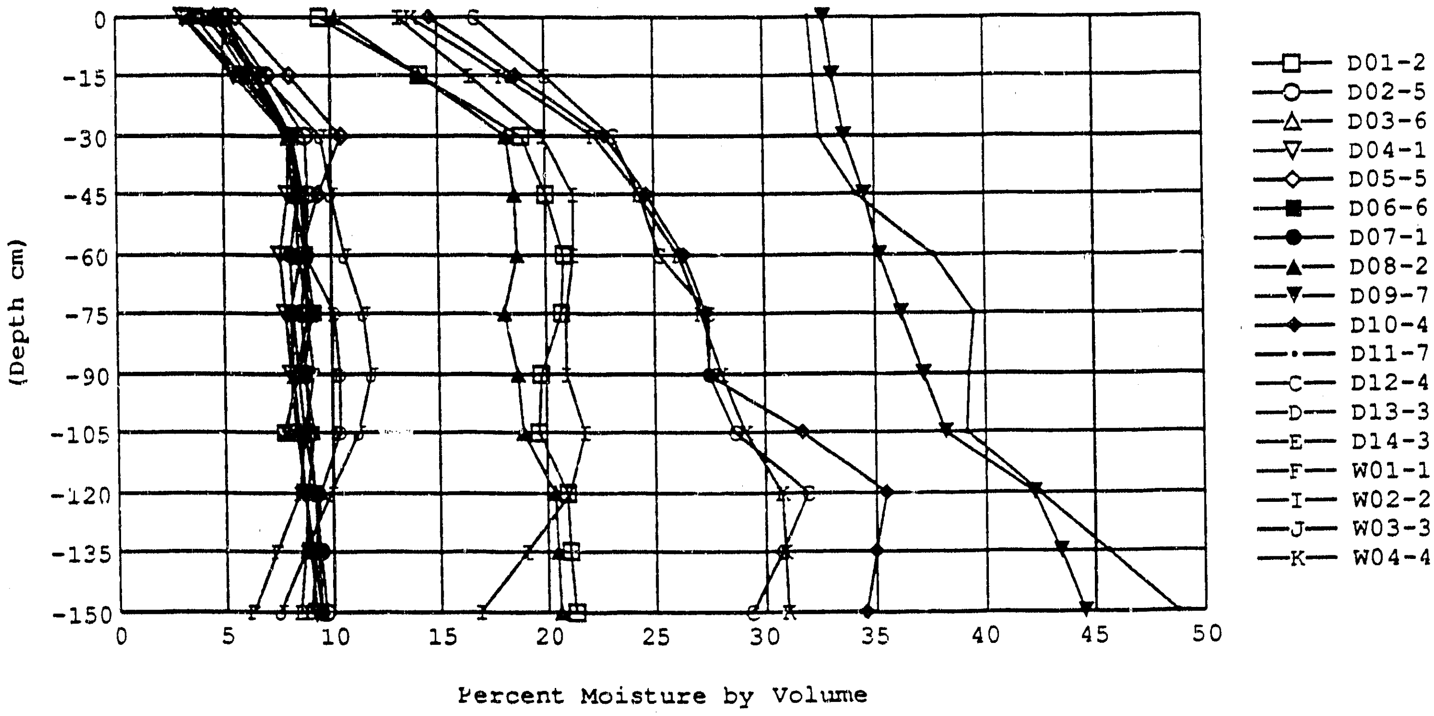


FIGURE 3.16. Influence of Treatments on Soil Moisture Profiles (compare with Figure 3.7)

Thus, vegetation had the largest impact on water balance and moisture distribution in the soil profile, even overriding the impact of the twice-average water application and making its influence disappear by the end of each water year. Clearly, the vegetated barriers could handle more water than the twice-average now being imposed, without risk of drainage. Just how much more water can be cycled to the atmosphere by the vegetation will be the subject of next year's research.

3.7 SOIL MOISTURE TENSION

The total impact of soil moisture within a protective barrier depends on its quantity and its energy relative to a fixed reference. The energy per increment of water is a measure of its potential to do work, or simply its potential. Thus, the total impact of water in the protective barrier is the product of its quantity multiplied by its potential. On a volume basis, water potential is defined in units of pressure, and it is usually negative for water held in soil in the vadose zone.

Tensiometers are commonly used to measure a narrow band of the least-negative pressures arising from water held in soil in the liquid phase, between 0 and -0.075 MPa. Thermocouple psychrometers or equivalent devices, operating in an equilibrium vapor phase, are used to measure the negative water potentials more negative than about -0.05 MPa, and ranging down to -8 MPa without special adaptations.

Water potential is important to protective barriers because it dictates whether, how, and where water will move within and through the barriers, regardless of the amount or location of the water present. We will therefore examine these measurements separately.

3.7.1 Tensiometers

Tensiometer measurements are considered first because all significant water movement in the liquid phase occurs at water potentials higher than -0.075 MPa. Water contents corresponding to -0.075 MPa in silt loam soil indicate that no liquid flow would occur below about 21 vol% and that almost negligible flow would occur between 21 and 26 vol% without a hydraulic barrier of any kind. Figure 3.16 coupled with Table 3.4 confirms that liquid-phase flow through the capillary barrier is negligible below 43 vol%.

The fact that all barriers except the two taken to breakthrough operated below 38 vol% indicates that no liquid flow should have occurred through the barrier. This observation also confirms that the measured drainage was not the consequence of liquid flow, and that vapor flow is a factor worthy of consideration in barrier design.

3.7.2 Thermocouple Psychrometers

The operation of the thermocouple psychrometer (TCP) is discussed briefly before presenting the data because understanding of TCP operation is essential to proper interpretation of the measurements. A TCP is shown in Figure 3.17, with two junctions of dissimilar metals enclosed by a permeable barrier that excludes soil solids but permits free passage of water vapor.

One junction has a much larger mass than the other and is therefore less susceptible to temperature change. The two junctions at the same temperature generate equal but opposite voltages. Thus, zero voltage is measured between

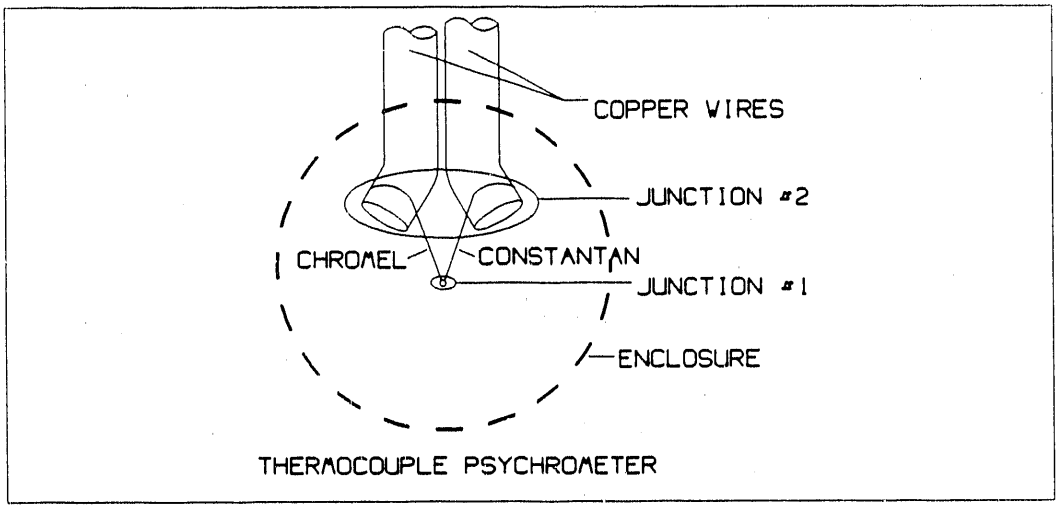


FIGURE 3.17. Thermocouple Psychrometer Diagram

the large and small junctions. When reverse normal current is input to the small junction, the junction is cooled until water vapor condenses on it to form a droplet of water. The large junction is simultaneously heated, but to a negligible degree because of its relatively large mass. When the cooling current is turned off, the small junction begins to warm until water from the condensed droplet suppresses further warming by evaporation. This shift from temperature dominated by thermocouple cooling and then rewarming to temperature dominated by water reevaporation produces an S-shape voltage output curve. The inflection point represents the lowest water potential of the surrounding water vapor into which the condensed water droplet is reevaporating. This inflection point is measured over osmotic salt solutions of known concentration and temperature to obtain a calibration that can then be used to measure water vapor of unknown potential, such as that in soil.

A TCP is useful for measuring soil water potentials between those at which flow can last occur and those at which plants can extract no more water. Thus, the TCP measures water potential over the range of plant use. Figure 3.18 shows soil water potentials in the soil just above the hydraulic barrier in three treatments.

Treatment 3 has vegetation and receives twice-average precipitation. Treatment 4 has no vegetation and receives twice-average precipitation.

Treatment 2 has no vegetation and receives ambient precipitation. Clearly, the vegetation in W03-3 has removed water far below the potentials found in the other two lysimeters. It is unnecessary to demonstrate treatments 1, 5, or 6 because they are also vegetated and were shown in Figure 3.16 to lose water to the same plant extraction limit as treatment 3.

The TCP measurements also confirm that normal liquid flow could not have crossed the protective barrier to produce drainage. Also, drainage from vegetated lysimeters had to come from vapor flow before the plants had removed water to their extraction limits, based on the maximum thermal gradients and the water contents discussed previously.

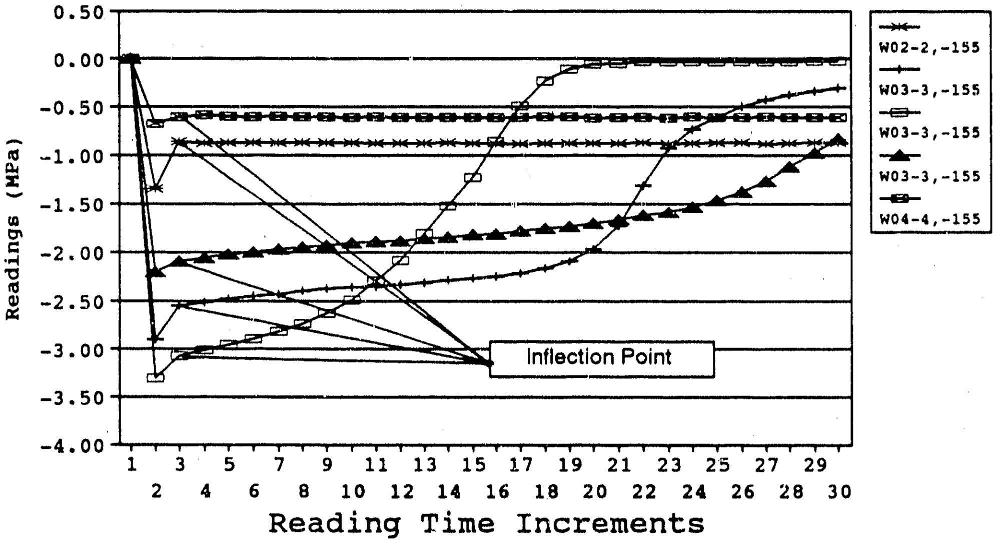


FIGURE 3.18. Example of TCP Measurements of Soil Water Potential (October 22, 1989)

4.0 CONCLUSIONS

Water collected as drainage must have been the result of vapor flow and not liquid transport across the protective barrier. Treatments 1 through 6 had soil water contents below 24 vol% where liquid flow should have been negligible even without a barrier. Even treatment 7, which is at 45 vol%, showed negligible drainage by liquid transport during the past year.

Vapor transport calculations agree within a few percent, whether based on hourly or daily temperature data. The hourly temperature gradients favor slightly more flux than the daily temperature gradients, but both are within the range of precision specified for the model used. There is also a reasonable agreement between measured drainage and calculated flux.

Twice-average precipitation produced no liquid breakthrough, even on nonvegetated treatments. Twice-average precipitation could produce breakthrough on nonvegetated treatments if the timing or intensity of storms changed slightly. Vegetated treatments completely masked the twice-average precipitation on an annual basis by removing all available water from both the ambient and twice-average treatments to a common water content and potential.

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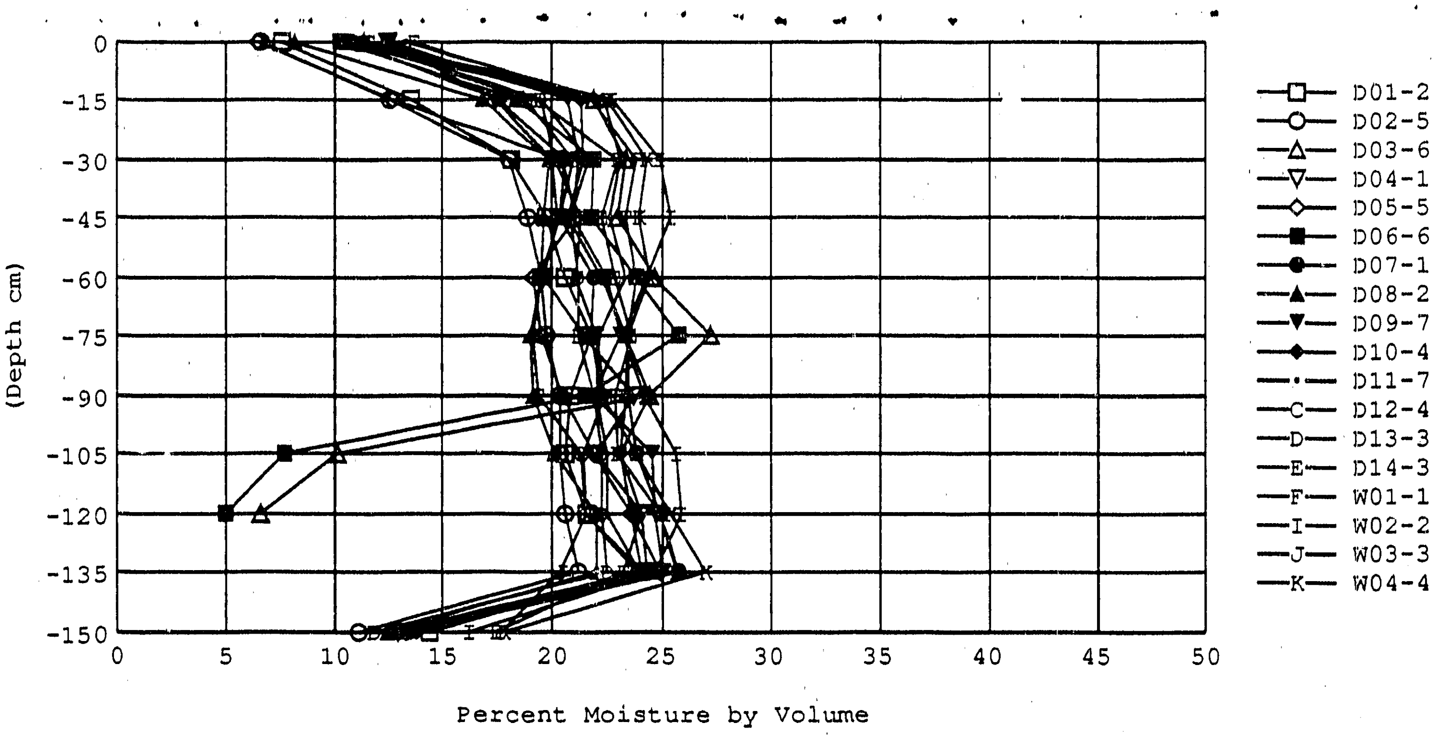
APPENDIX

SOIL MOISTURE PROFILES

APPENDIX

SOIL MOISTURE PROFILES

Profiles of soil moisture in the protective barriers at the FLTF are presented in this appendix. These profiles are based on neutron probe measurements. The second graph in each pair shows the result of extending the two adjacent readings to the upper and then the lower boundaries to eliminate boundary influence on readings. All readings taken from November 1987 to July 1990 are represented and can be used in rapid succession to observe water movement through the soil profile.



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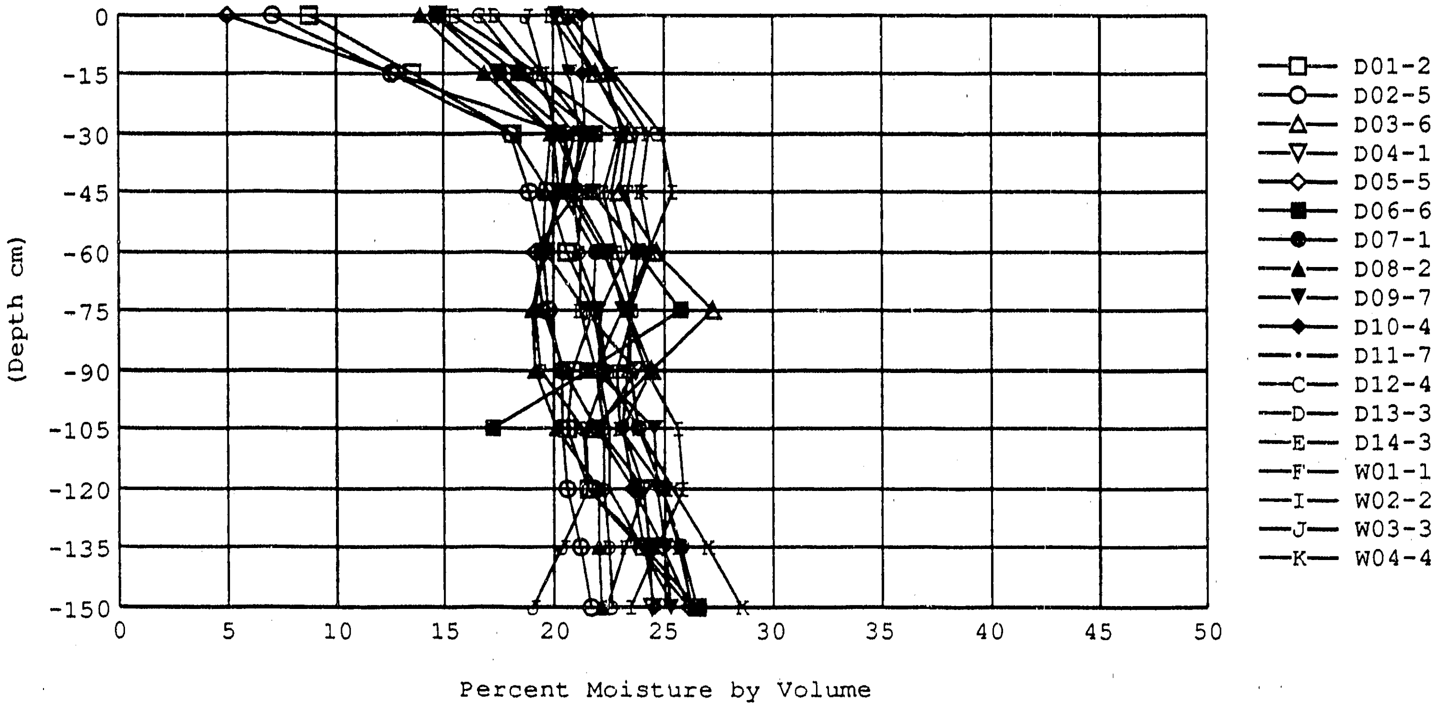

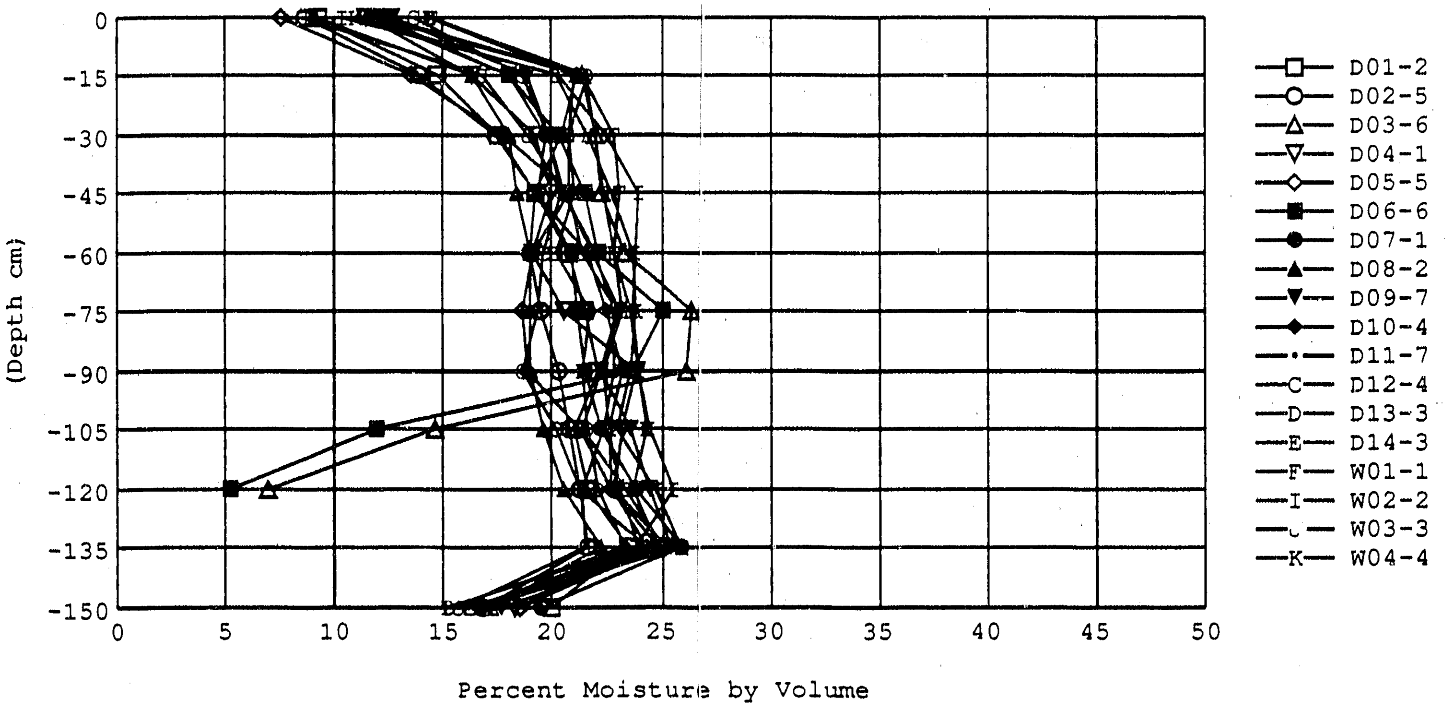

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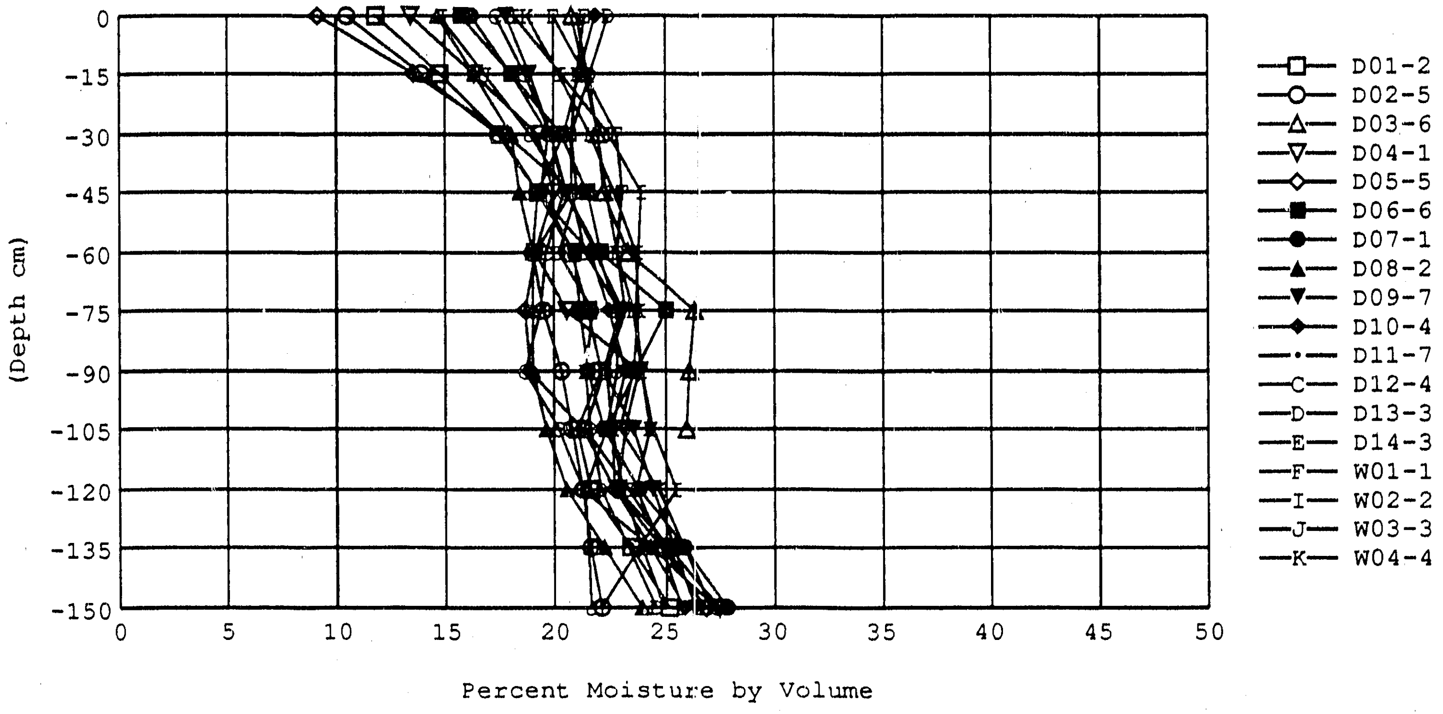

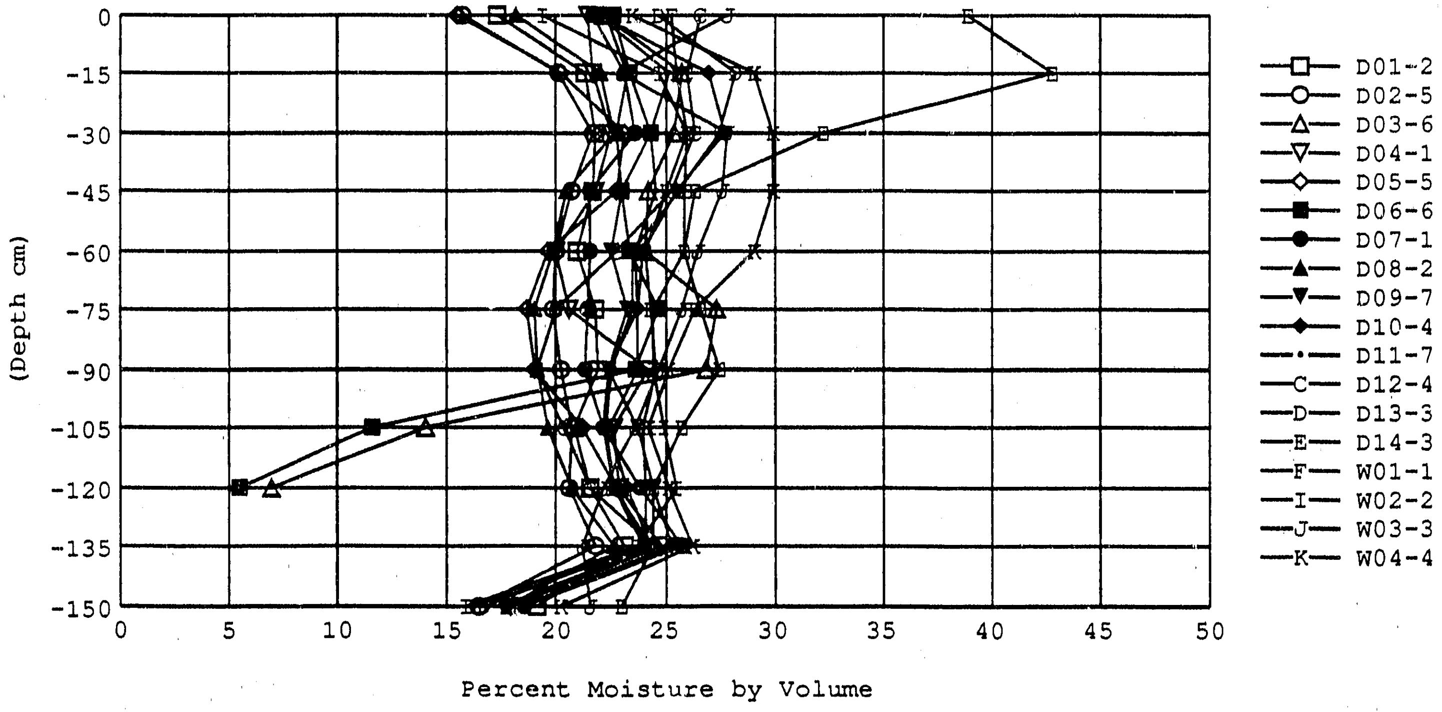

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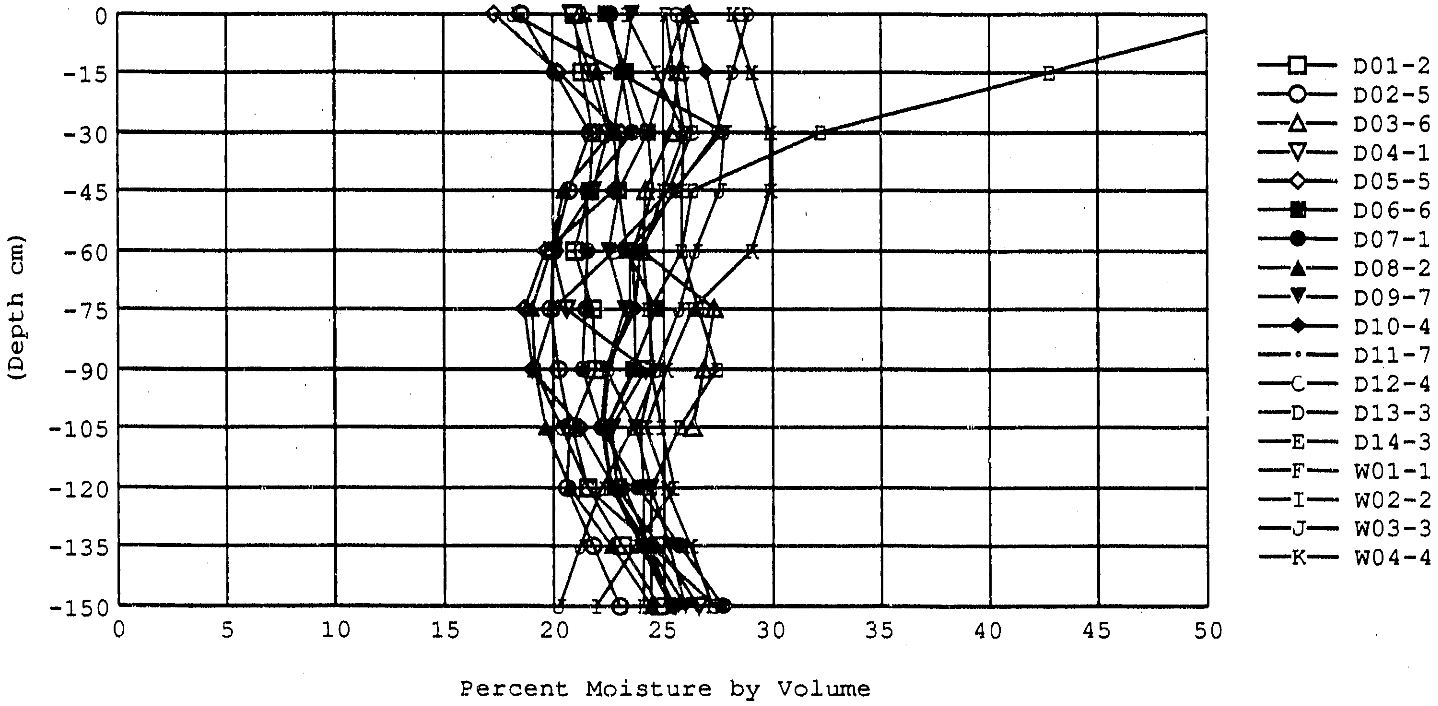

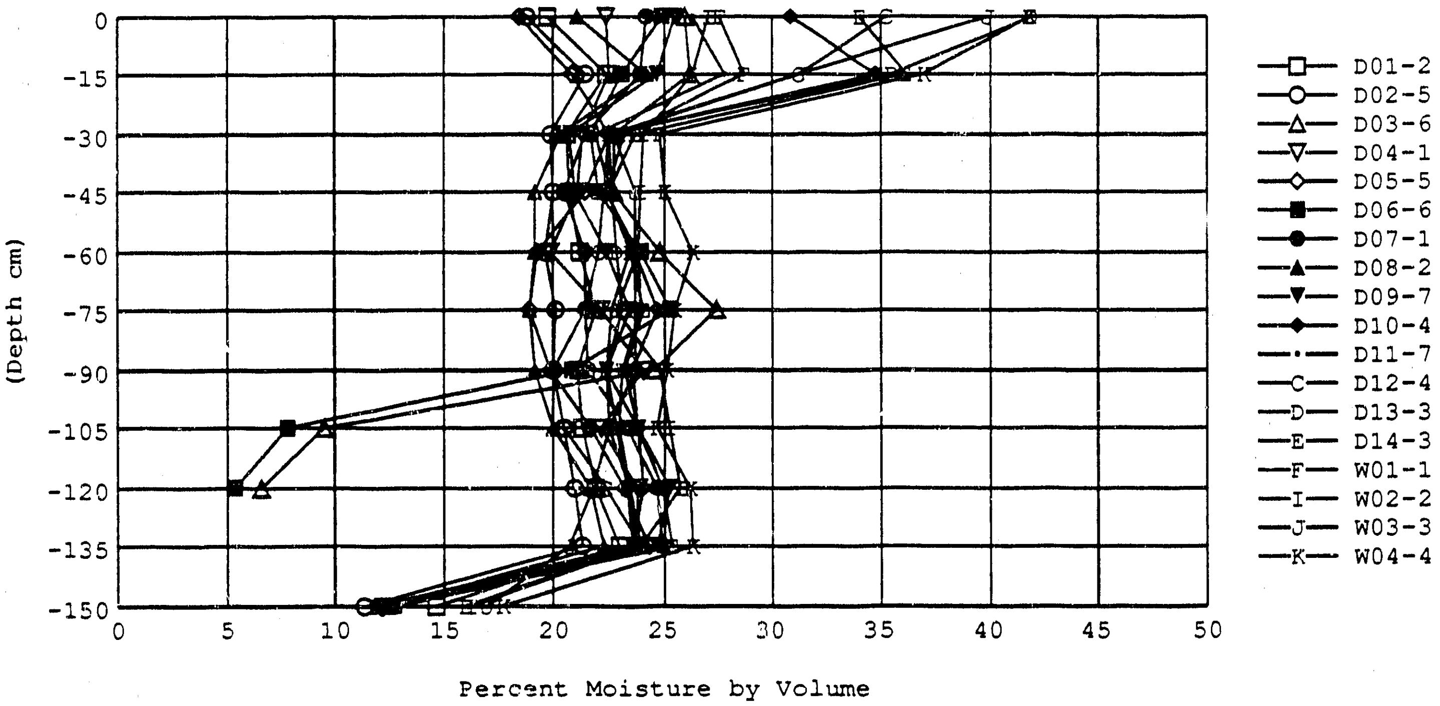

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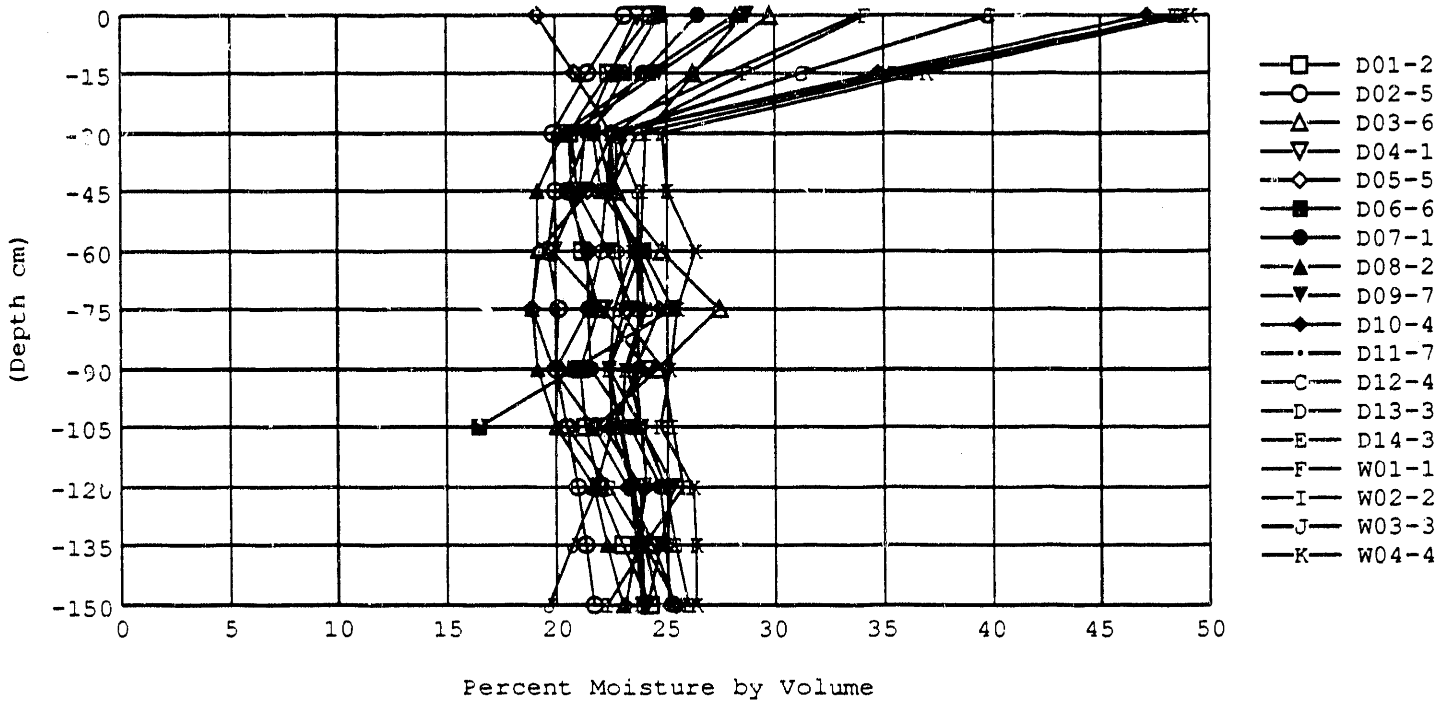

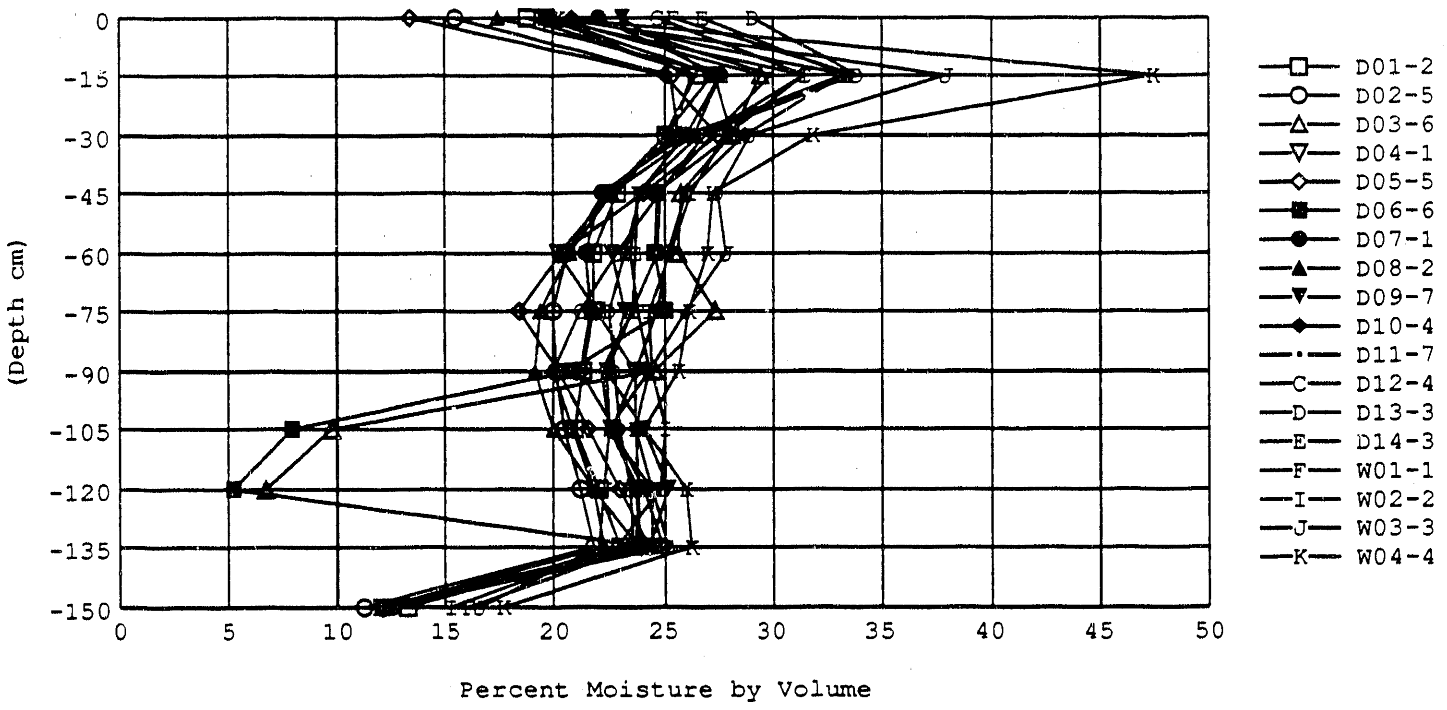

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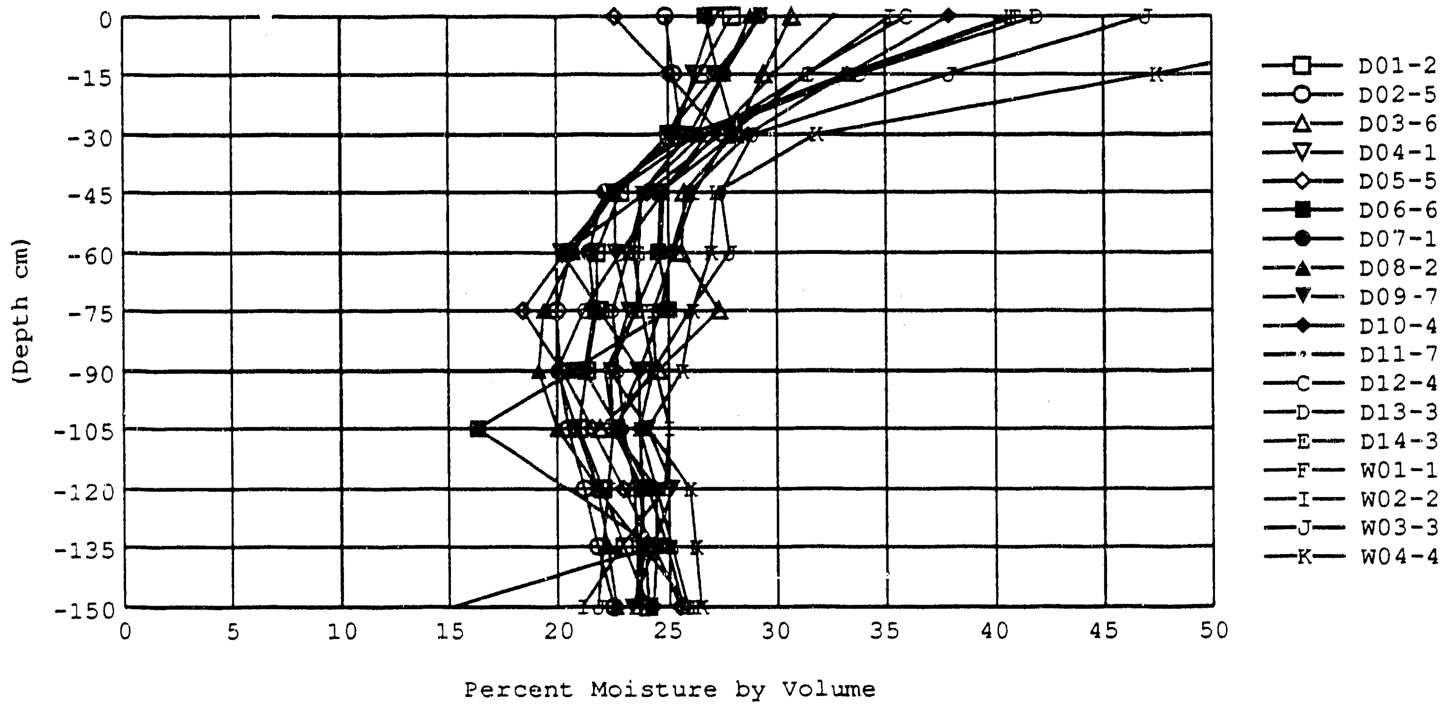

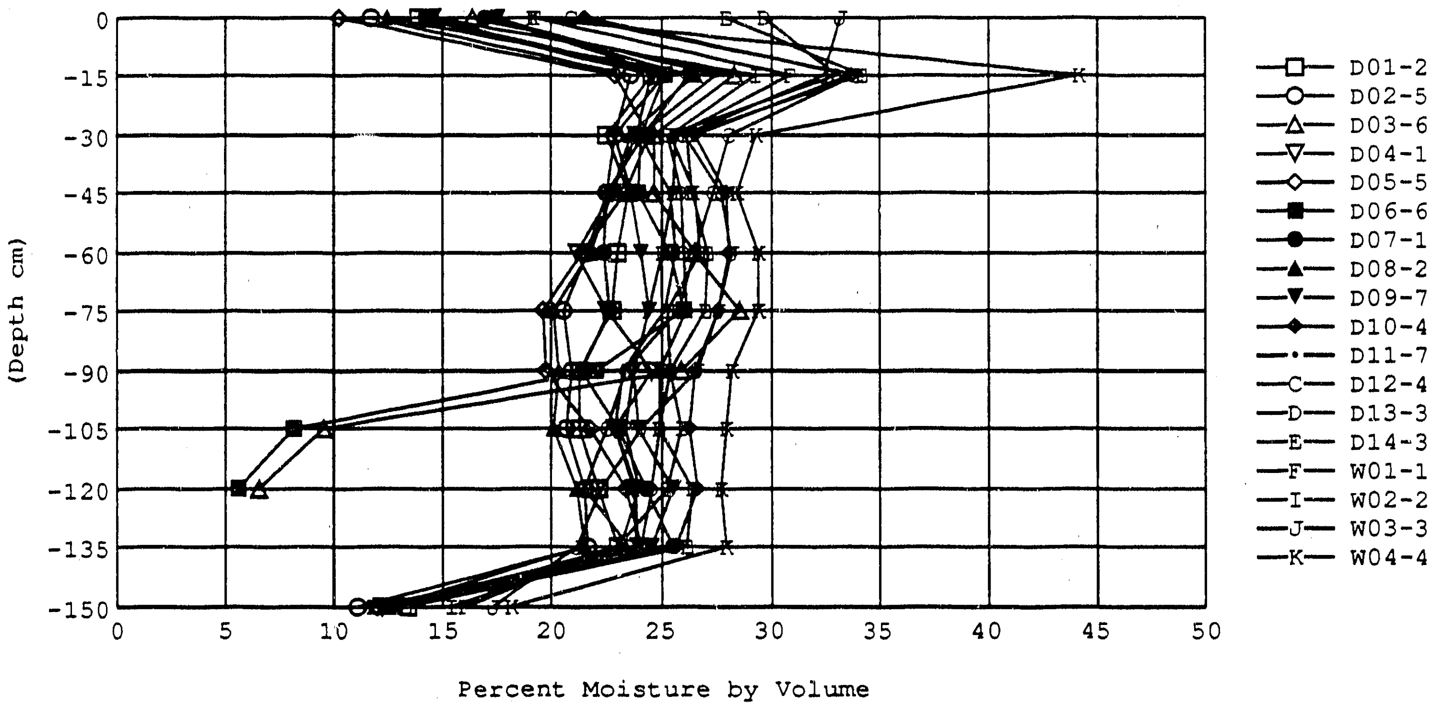

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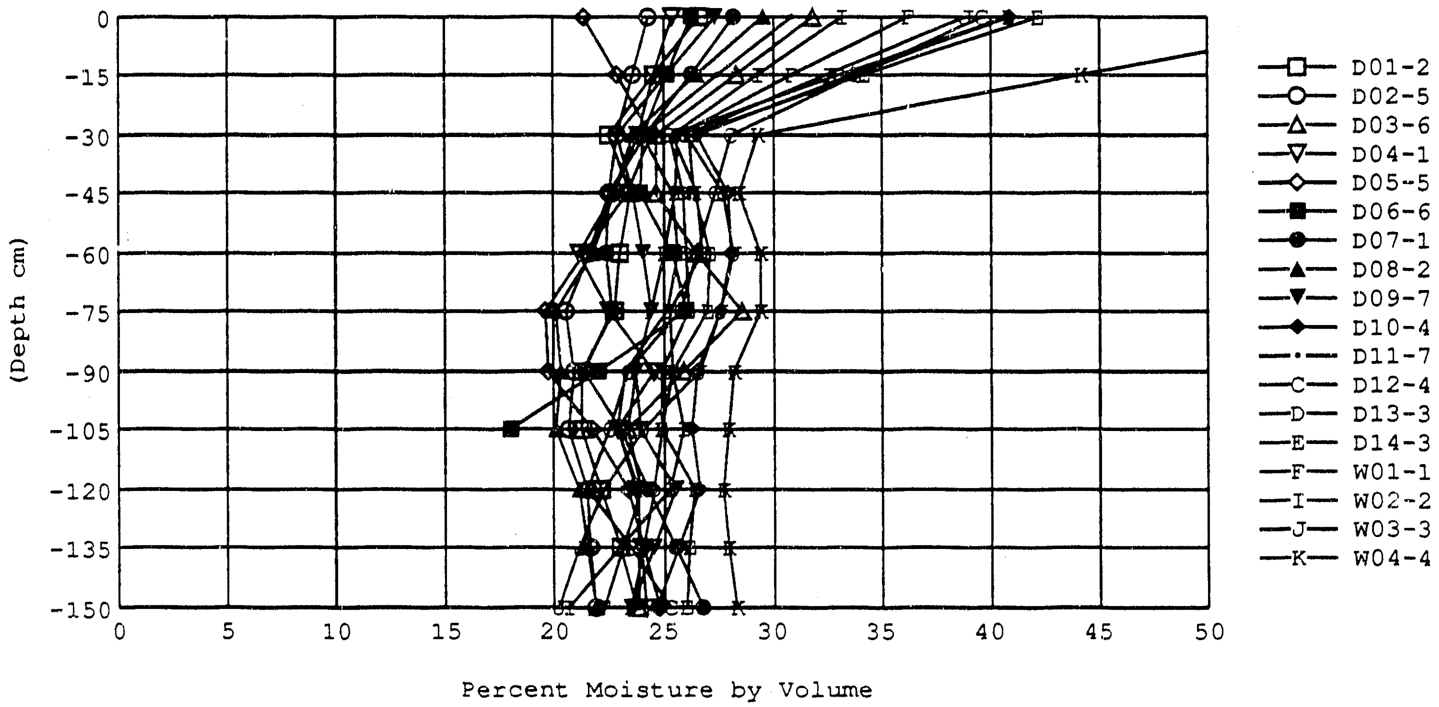

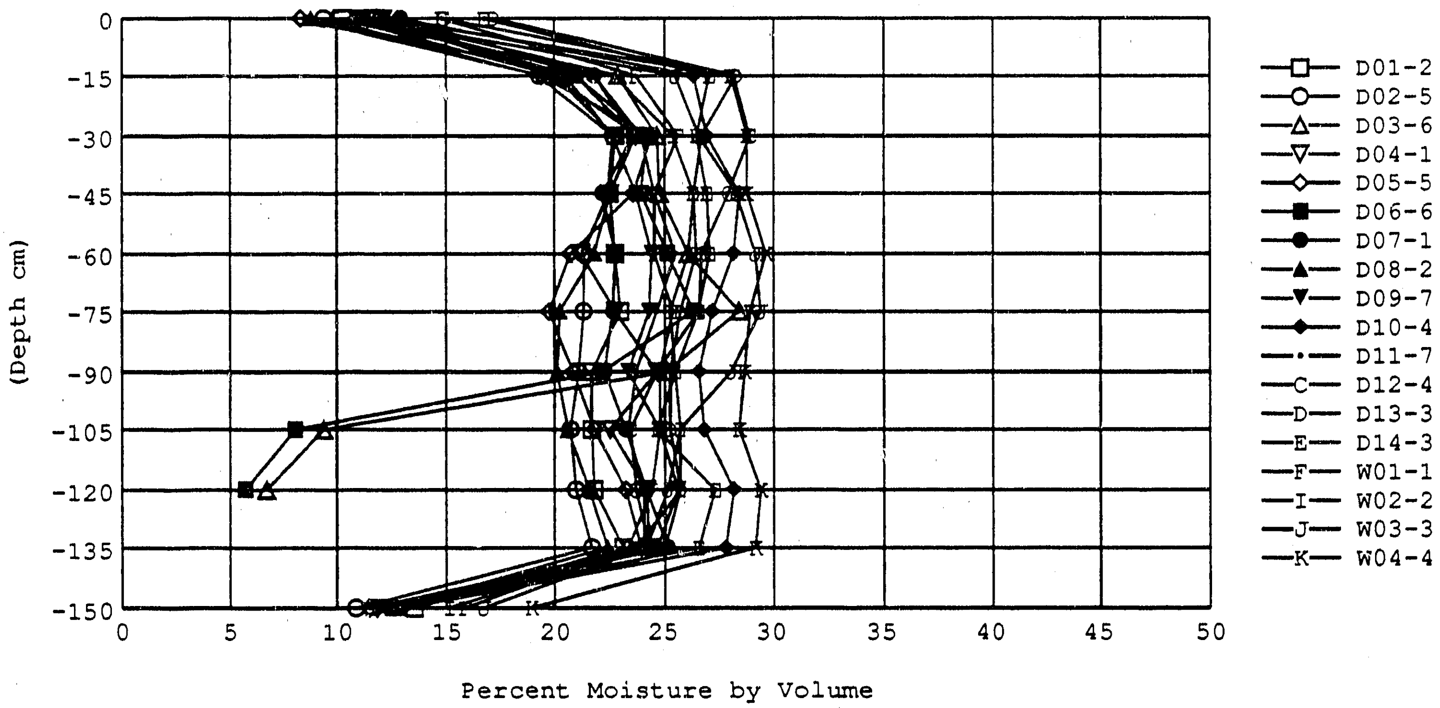

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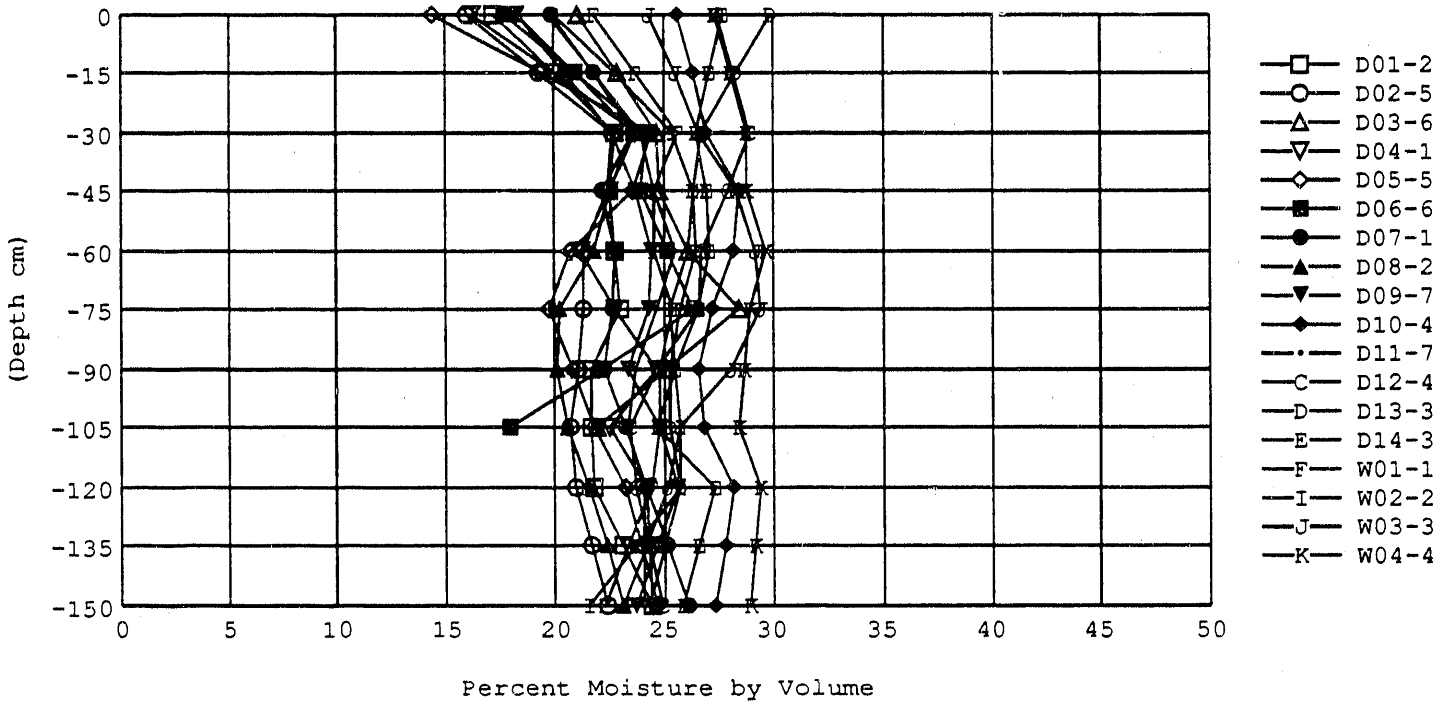

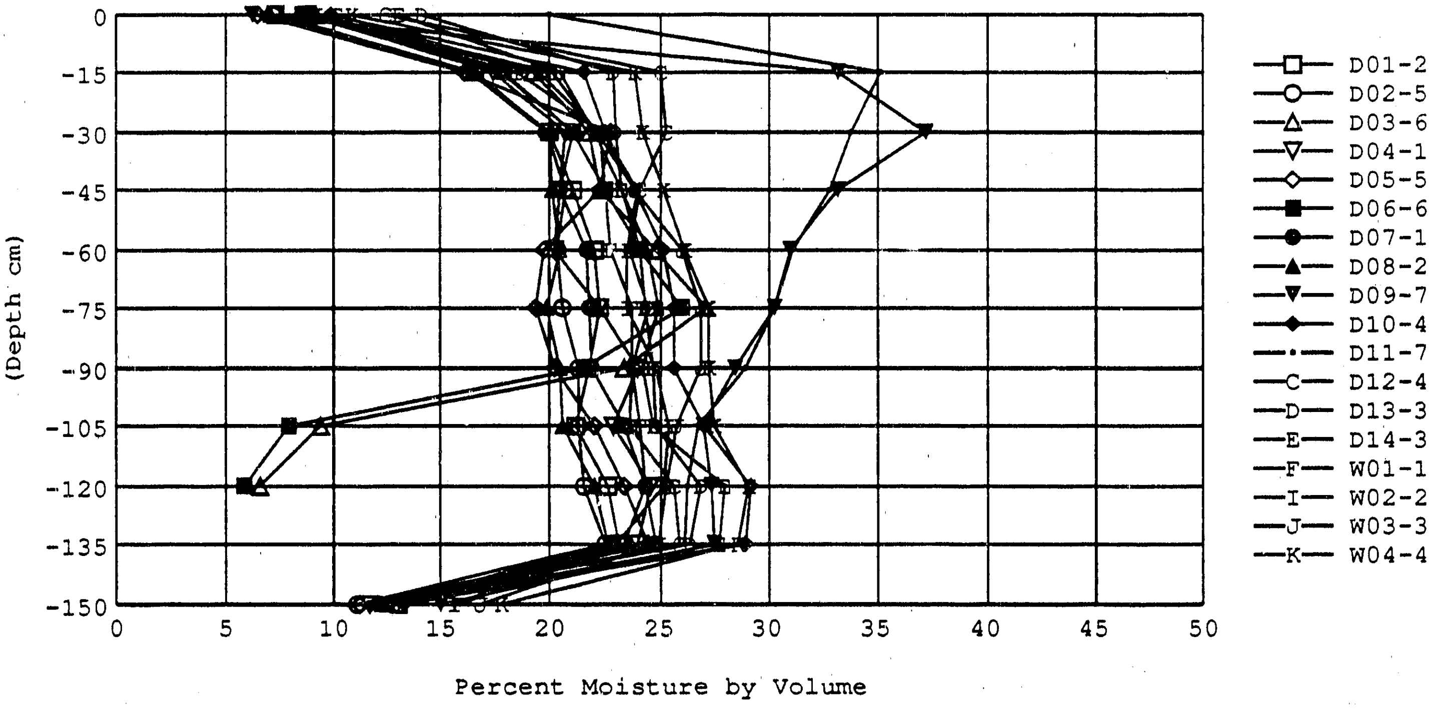
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Percent Moisture by Volume
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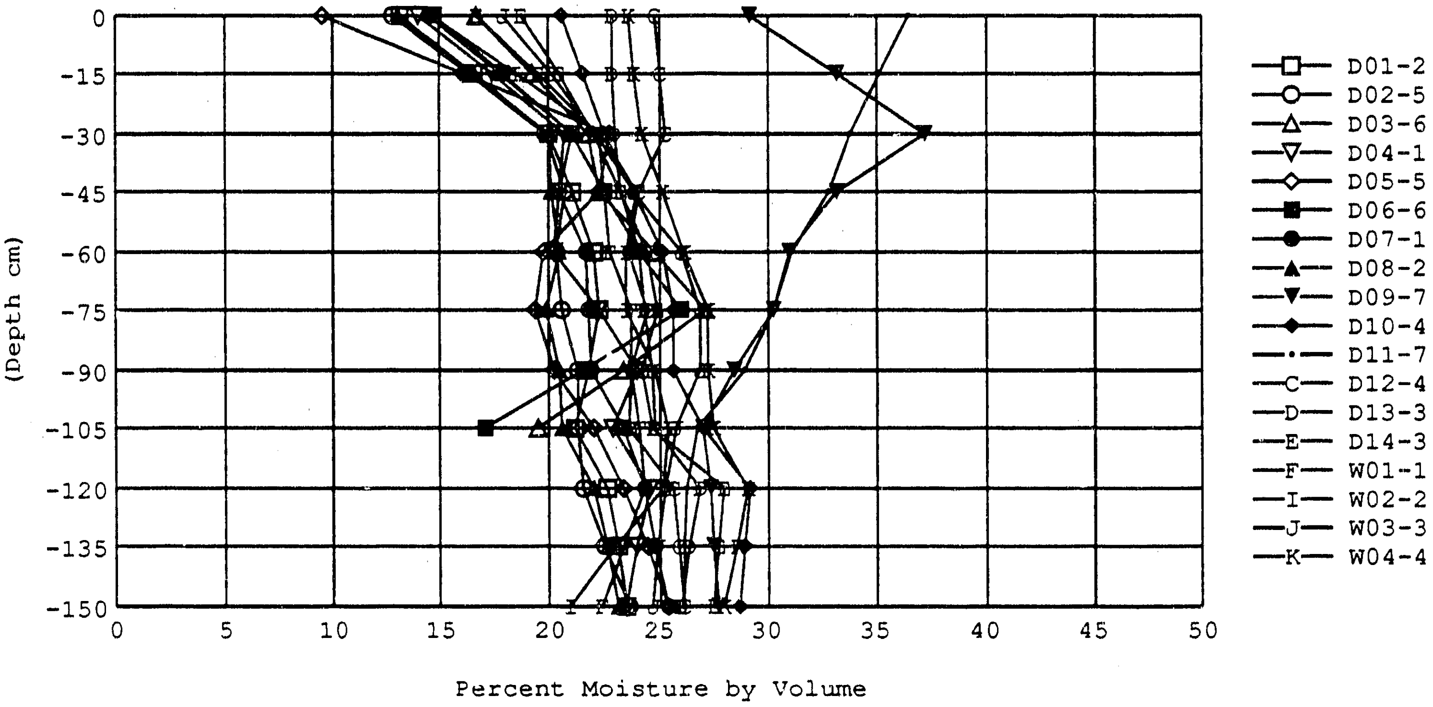
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Percent Moisture by Volume
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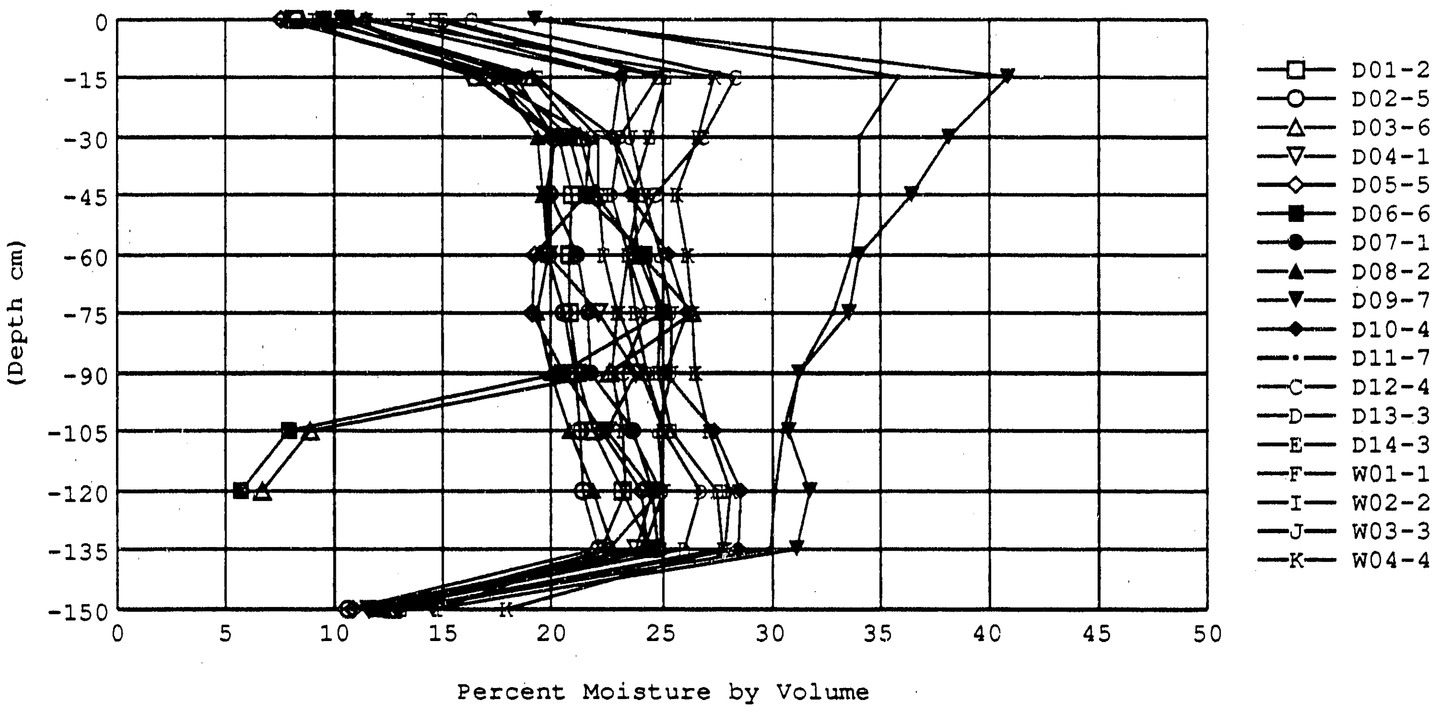

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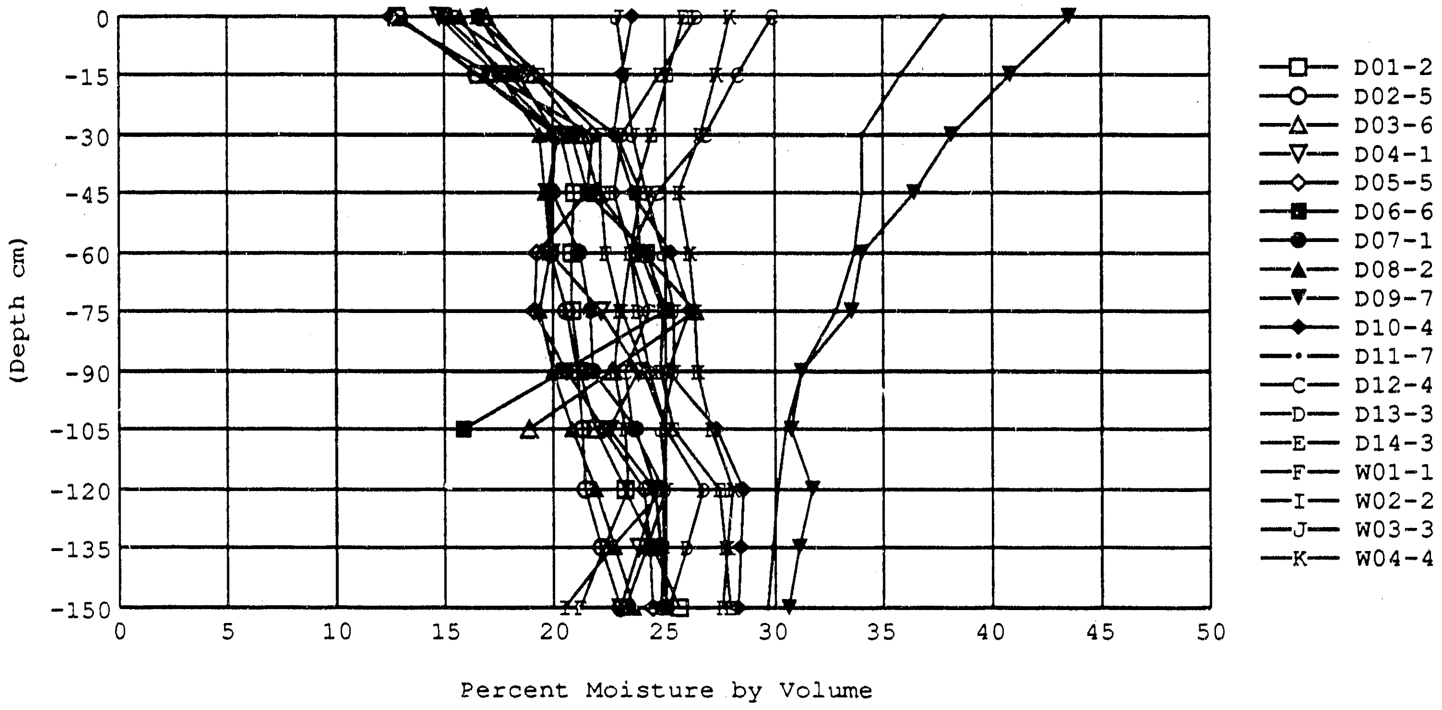

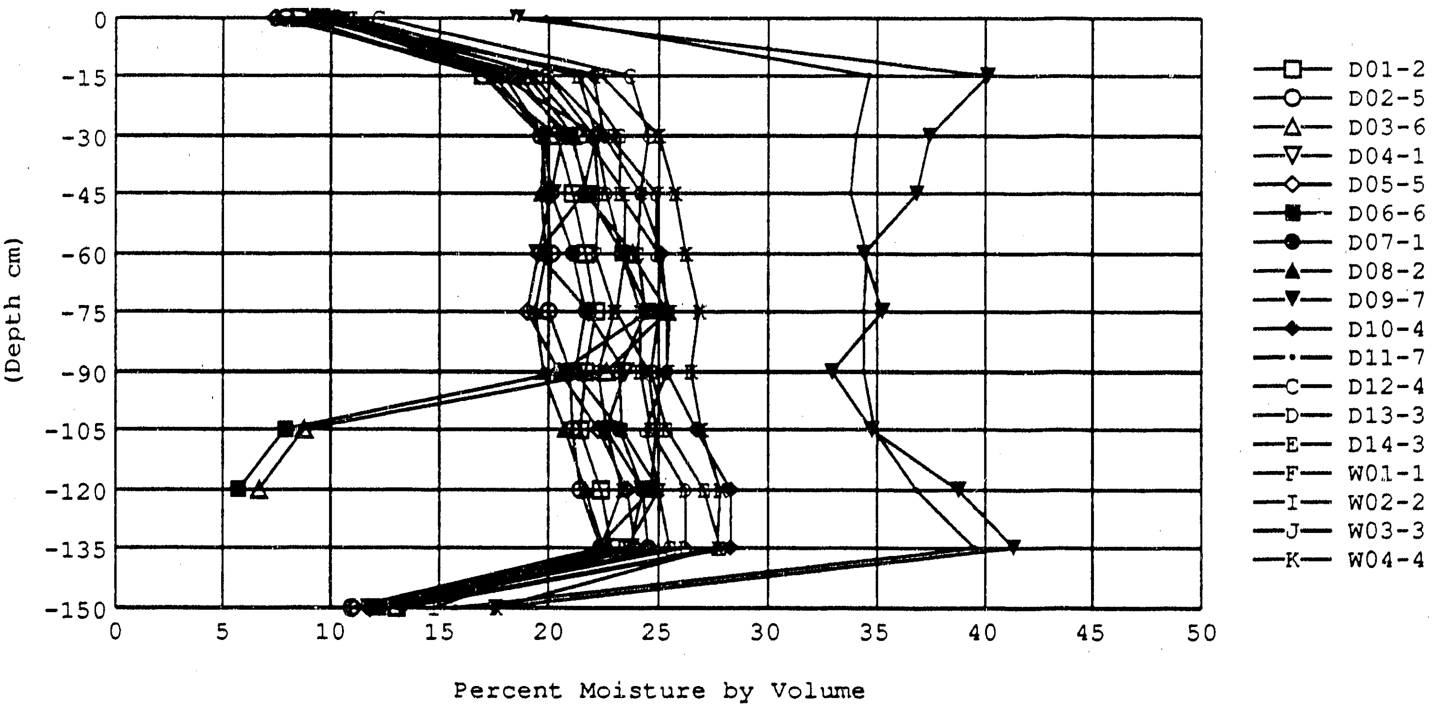
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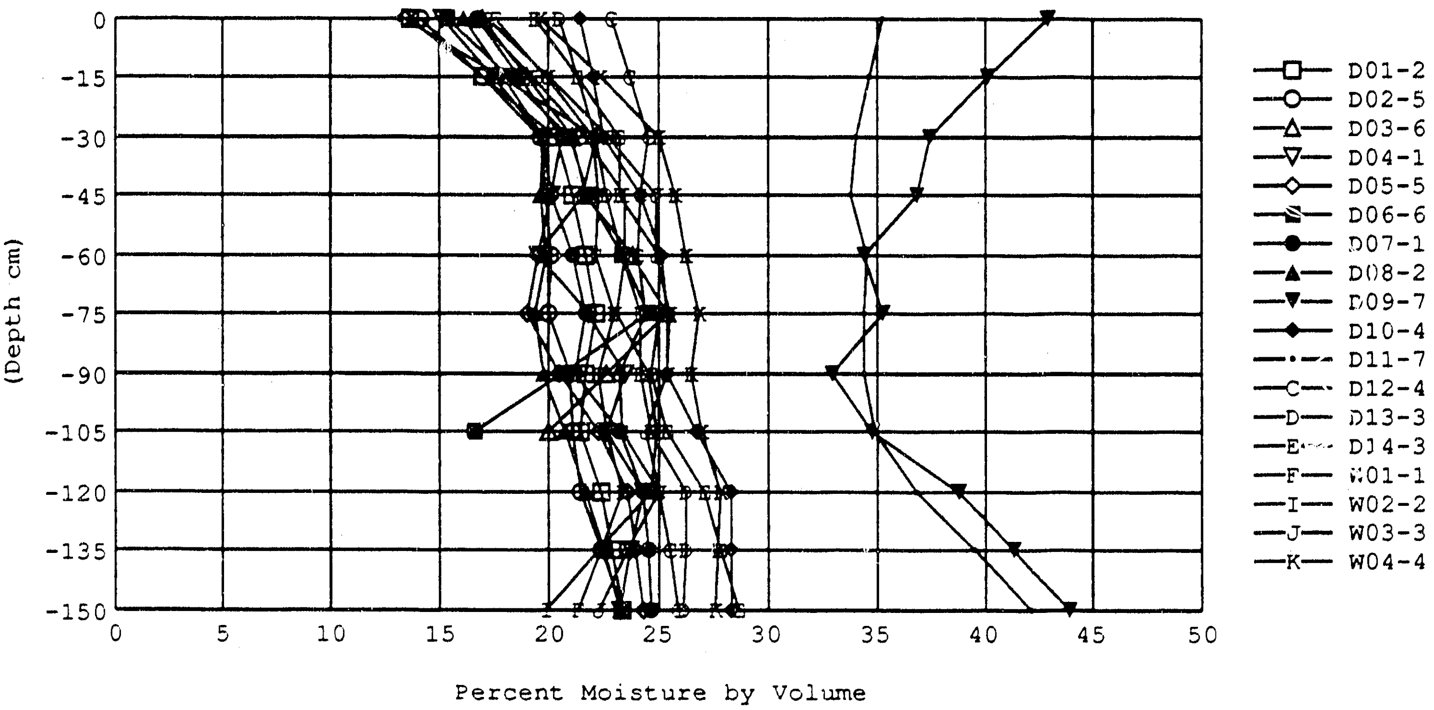
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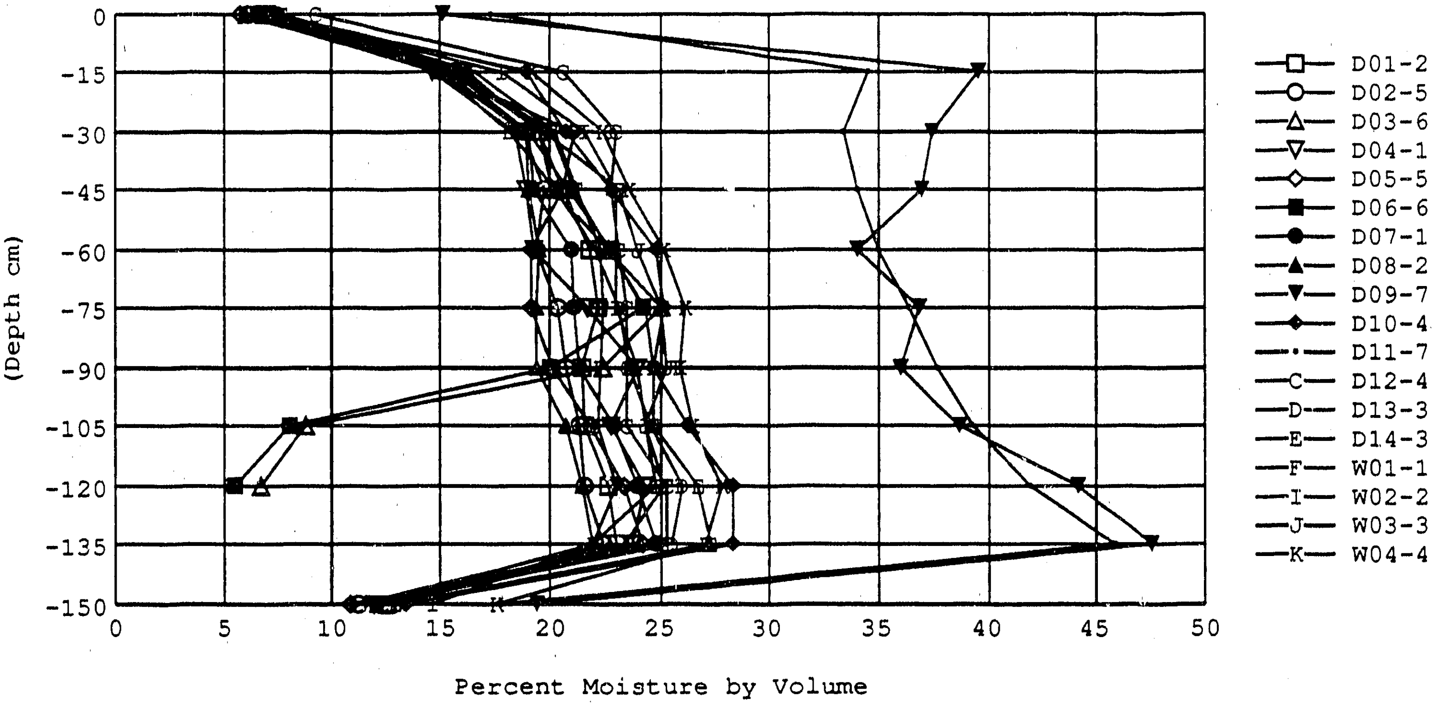
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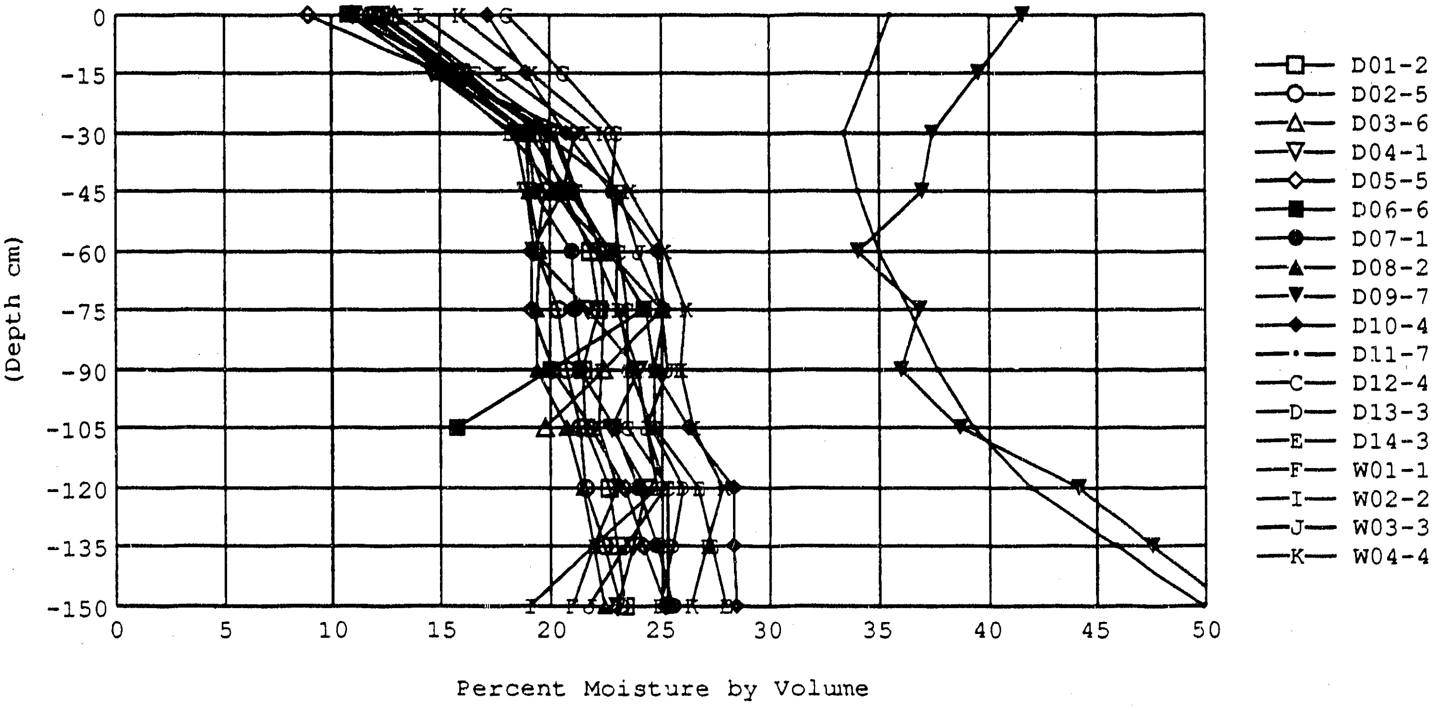
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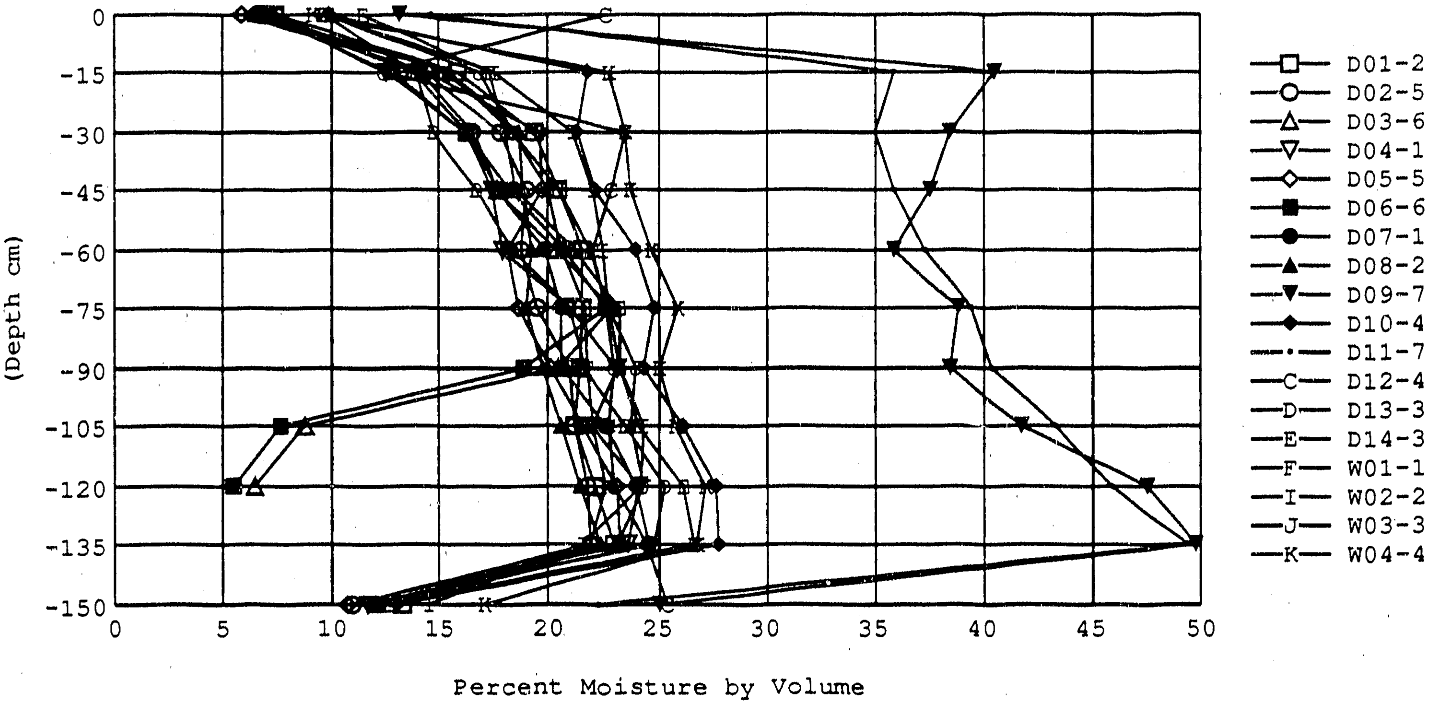
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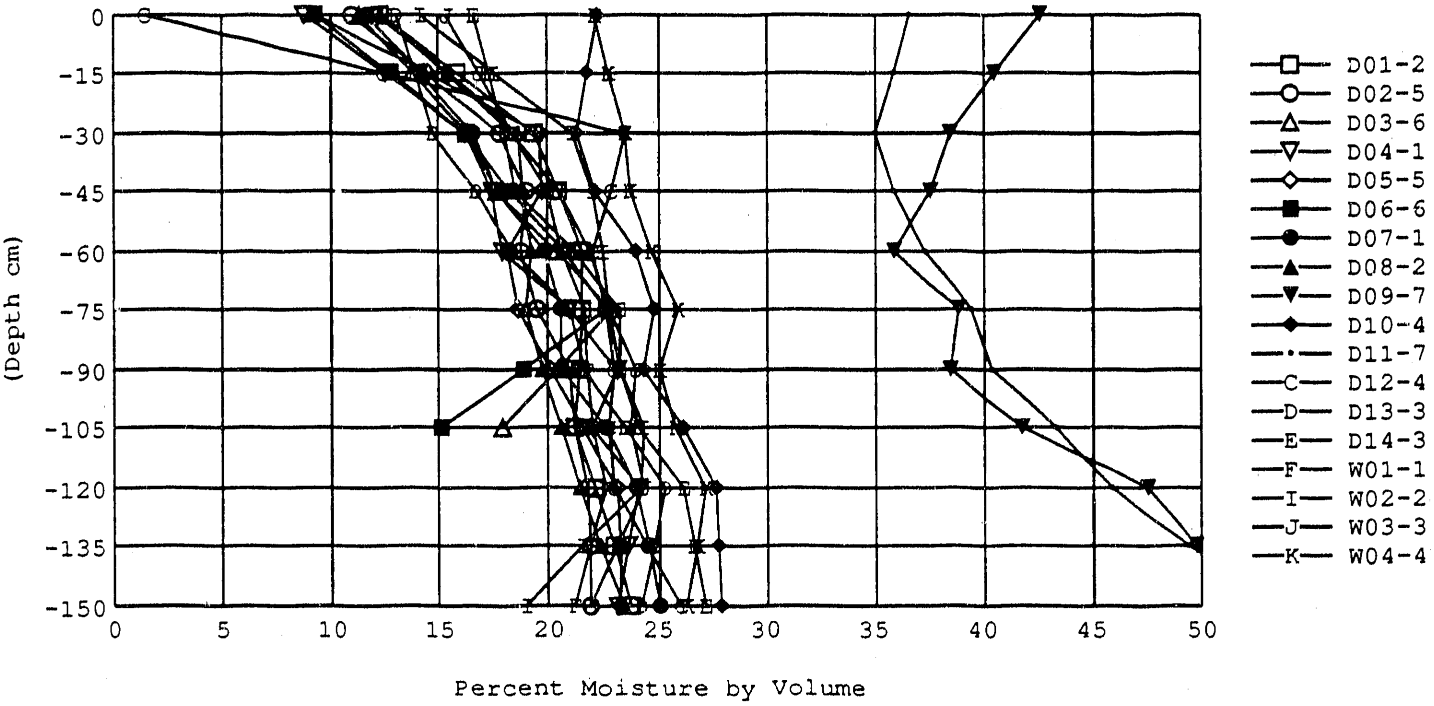
2 June 1988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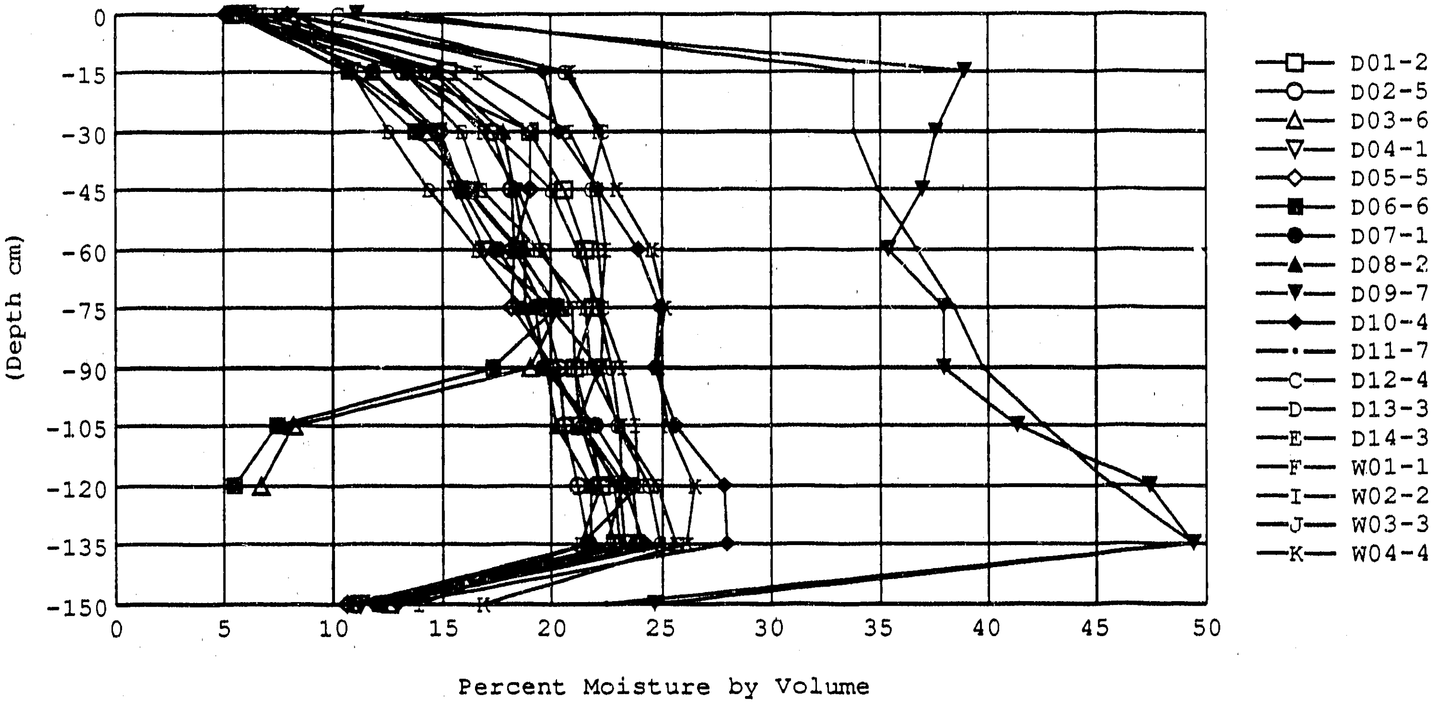
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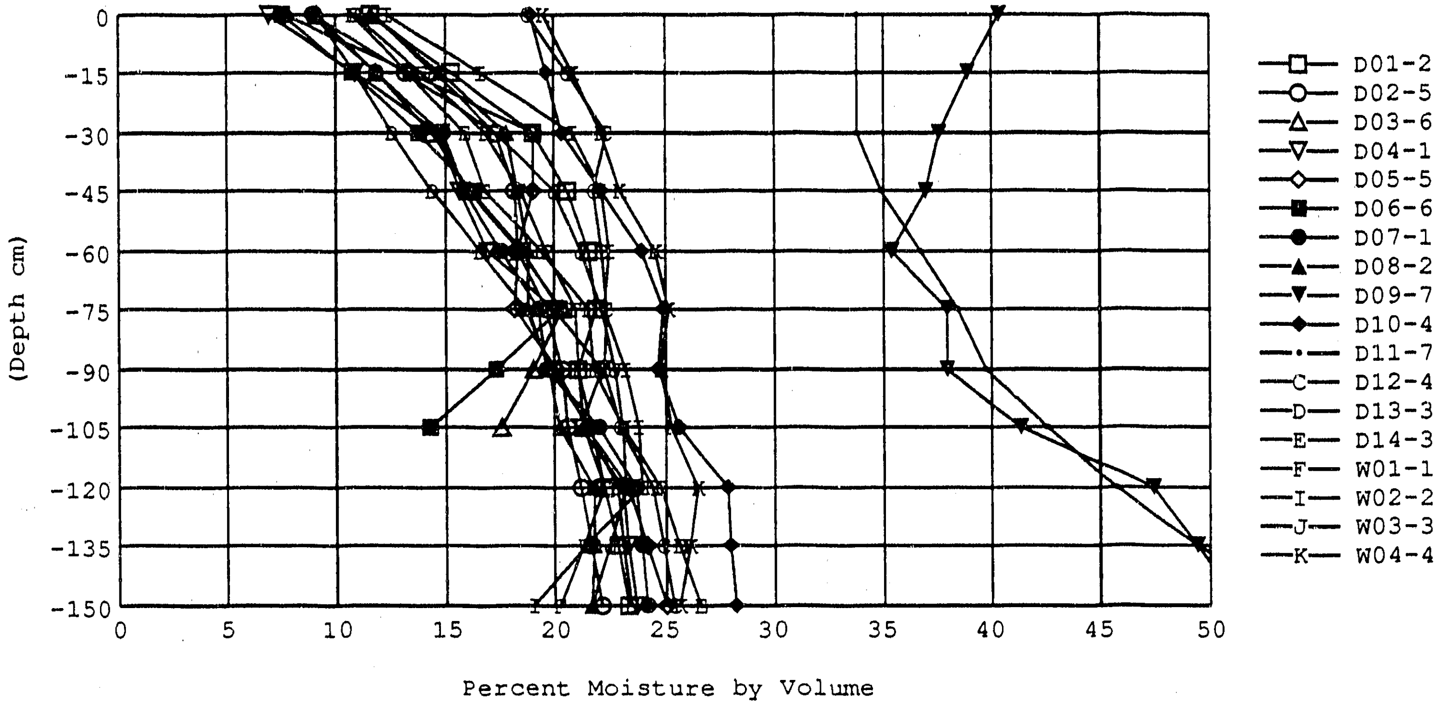
15 June 1988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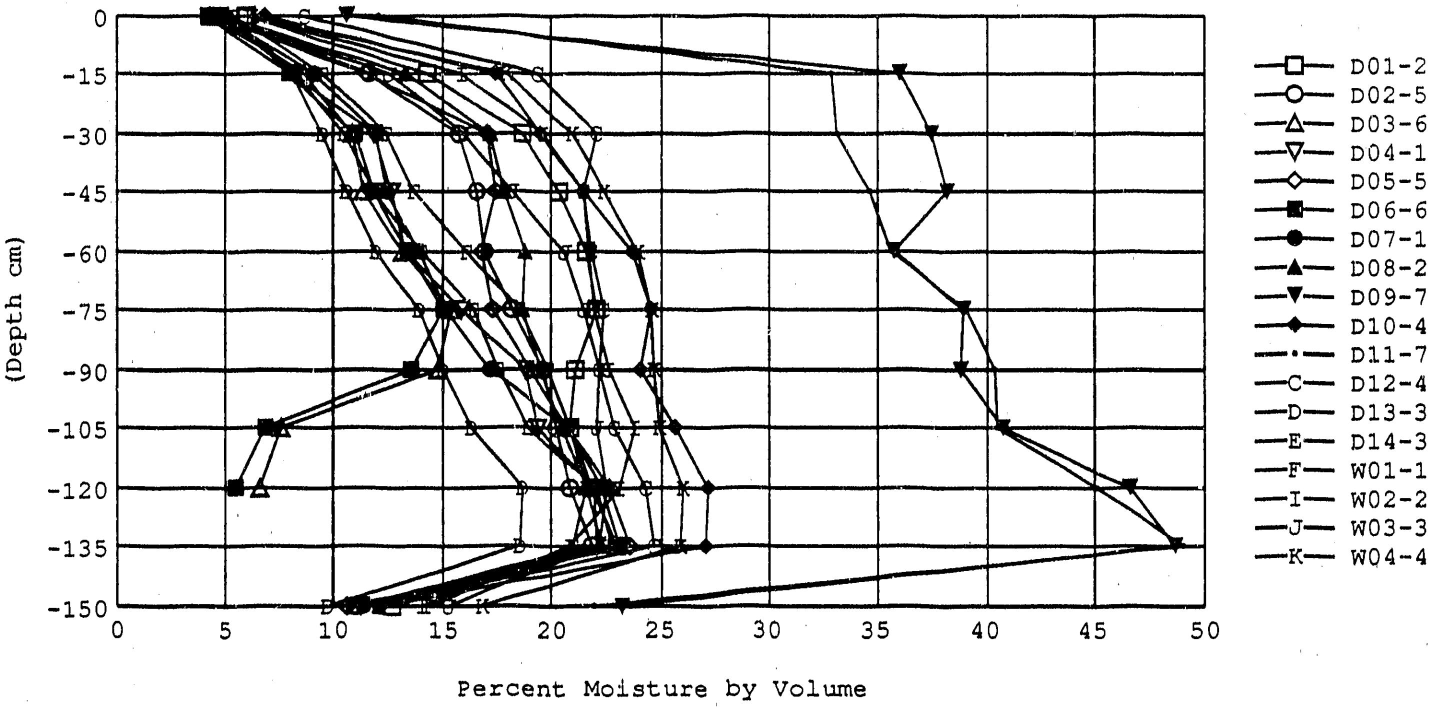
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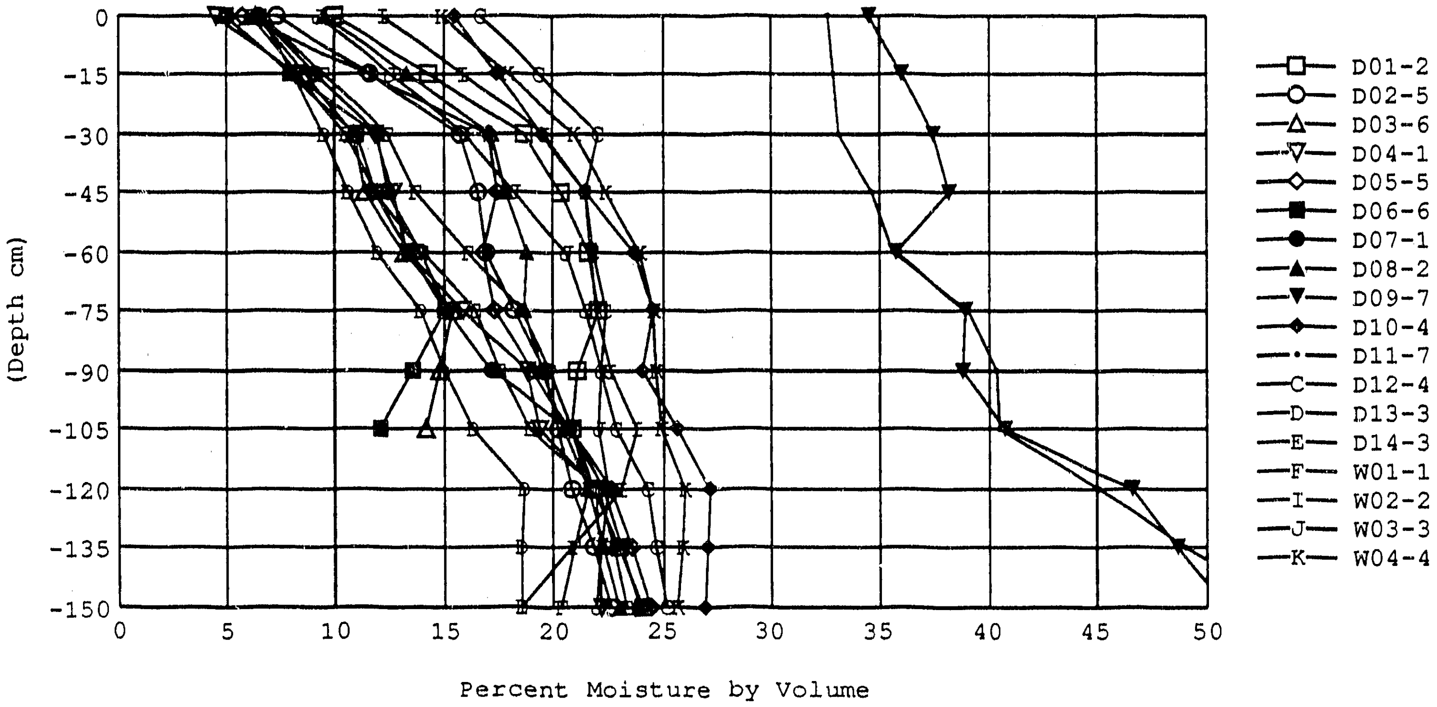
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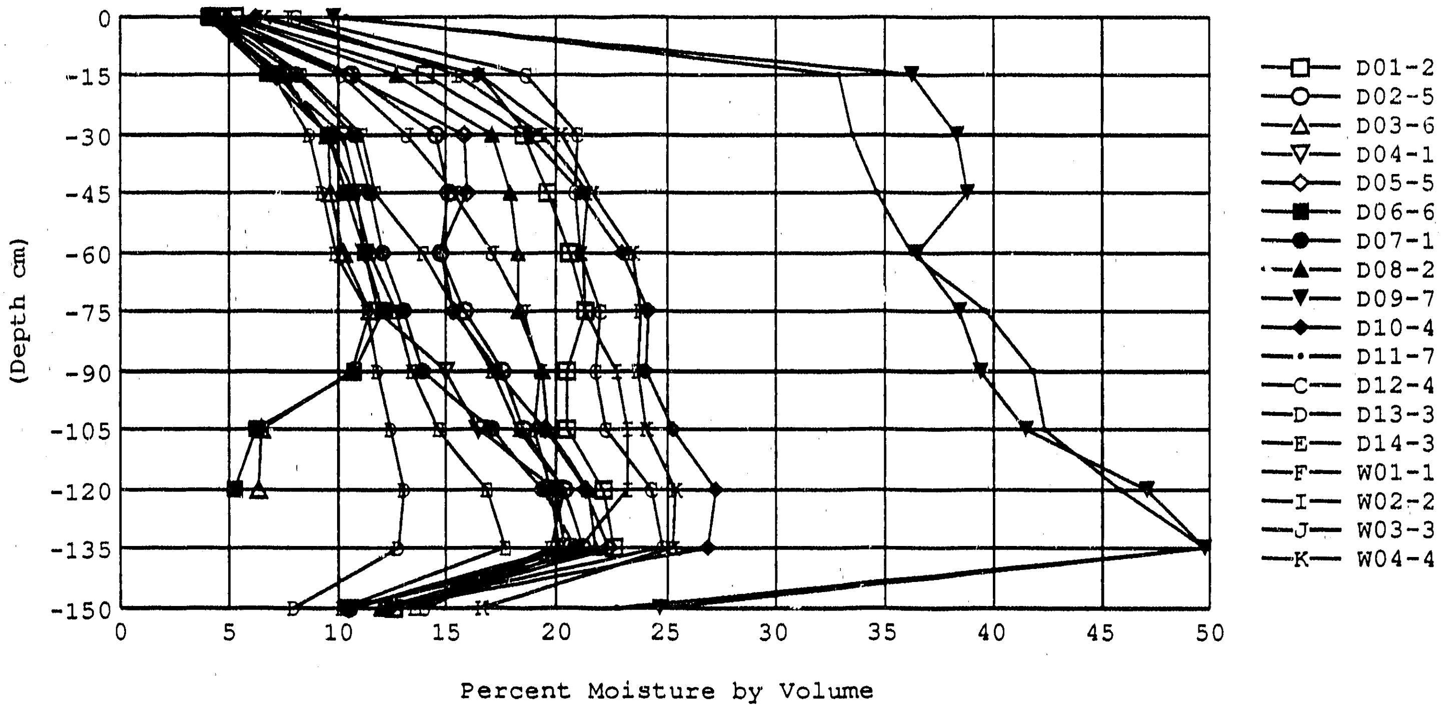
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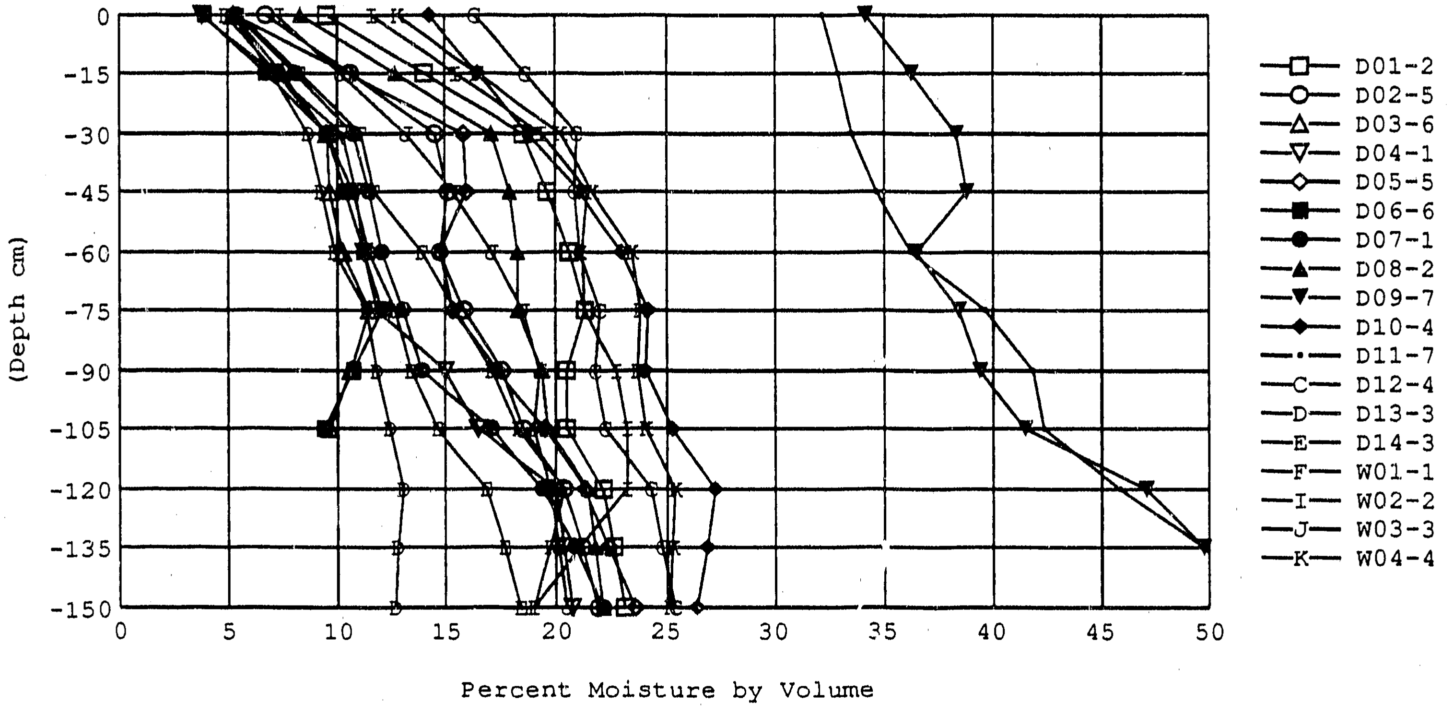
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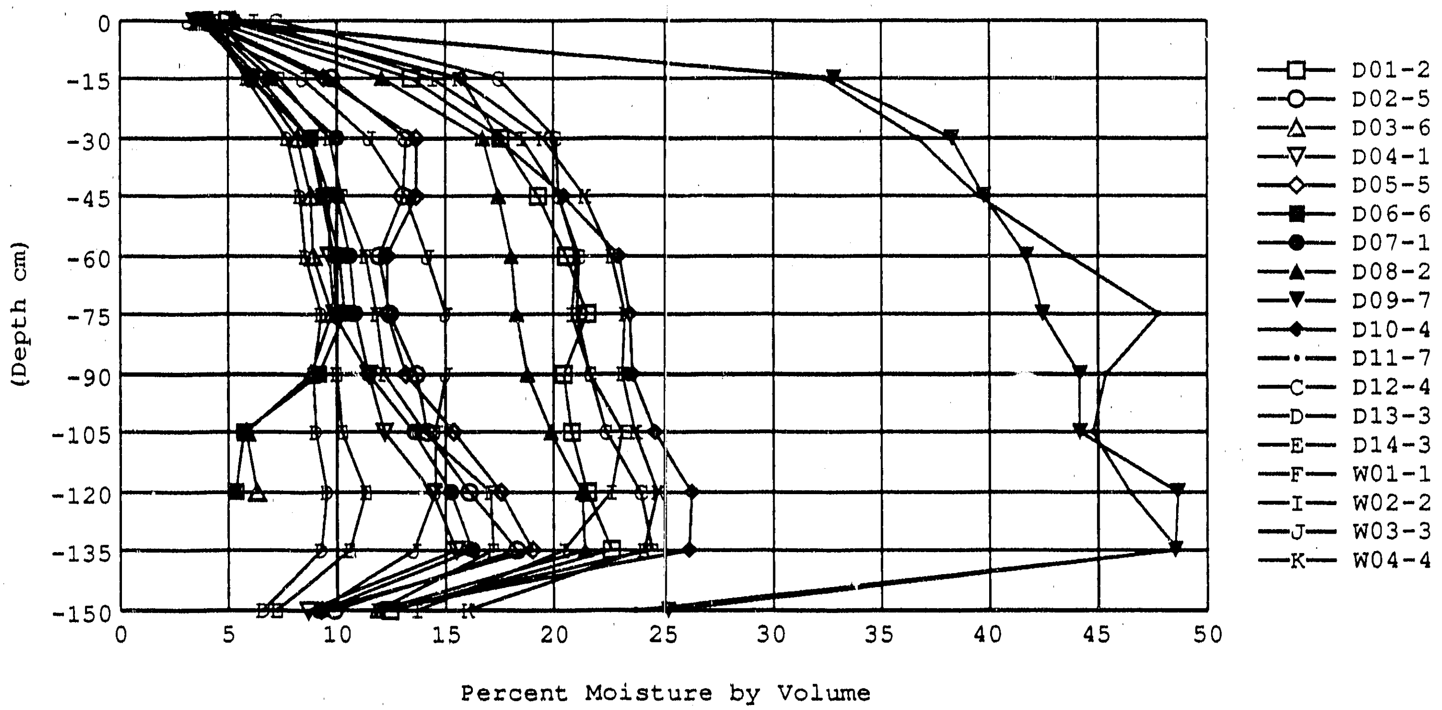
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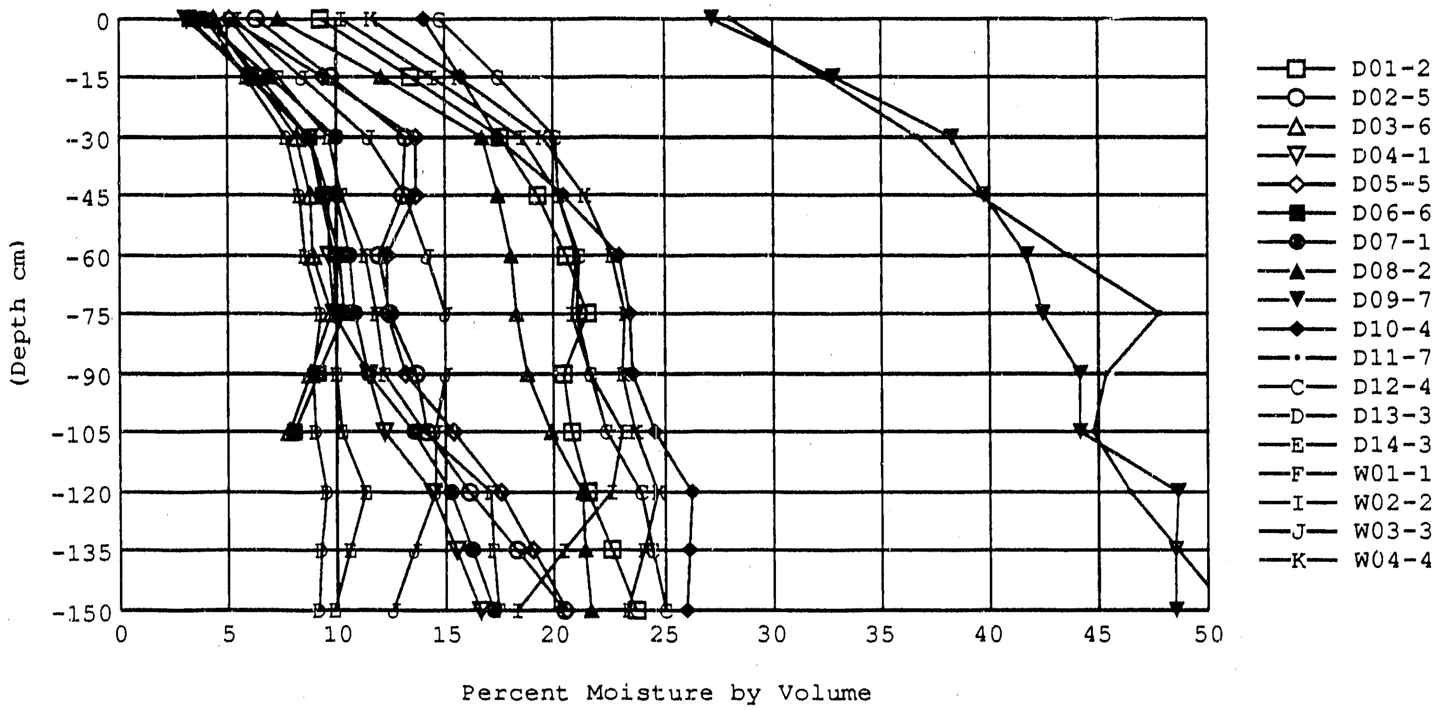
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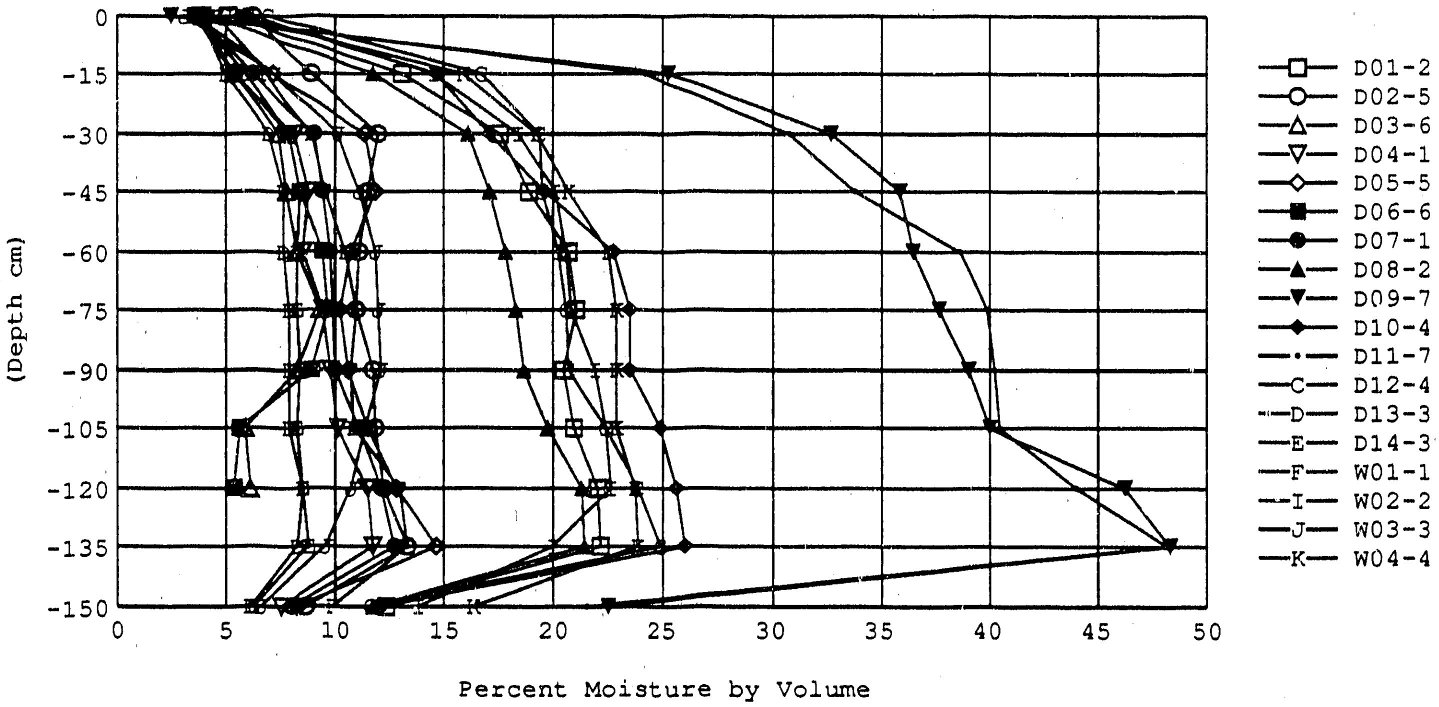

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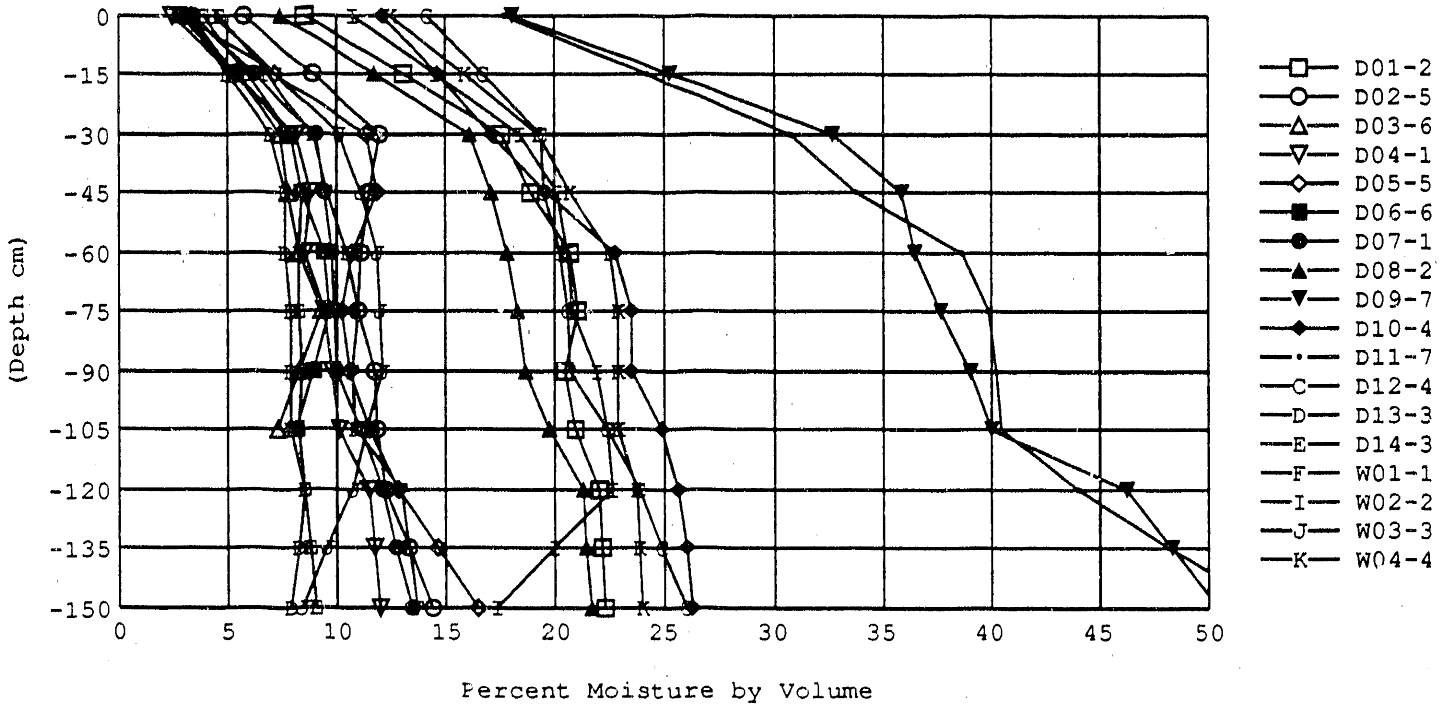

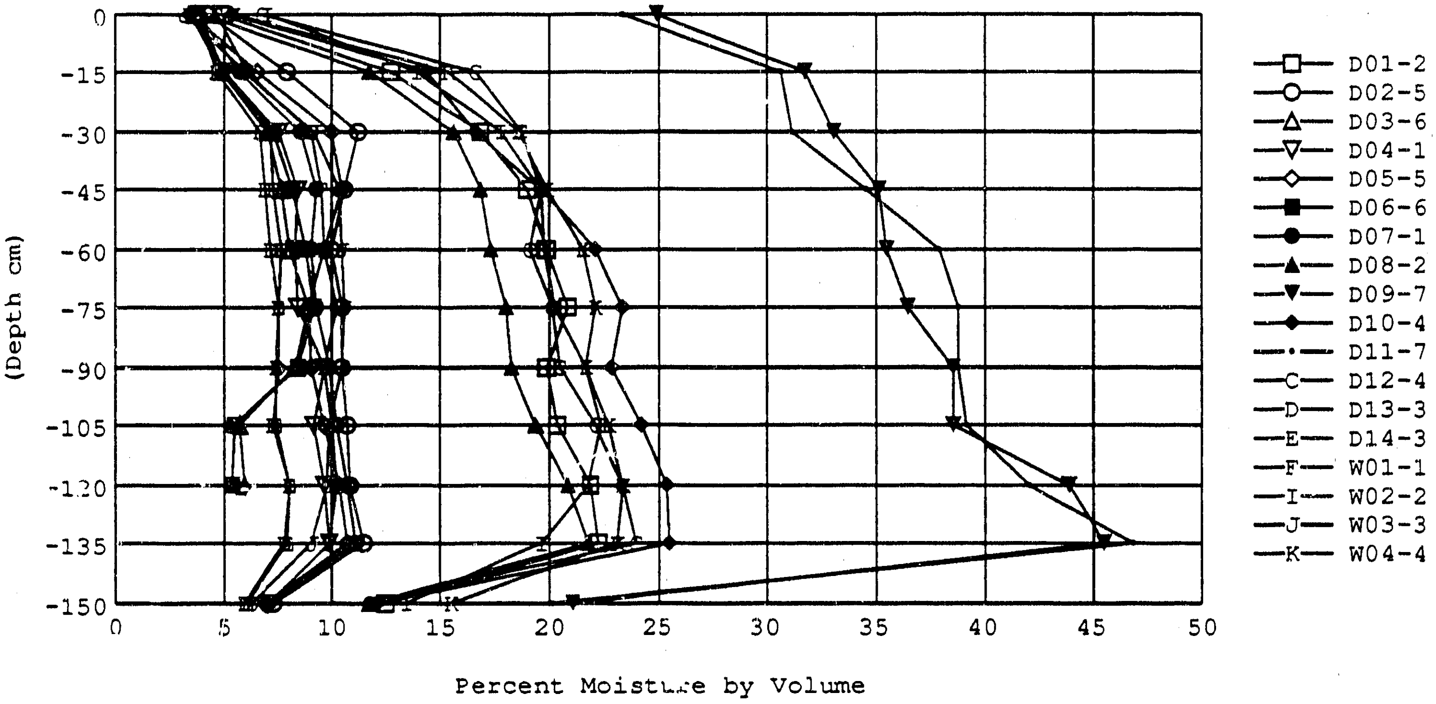

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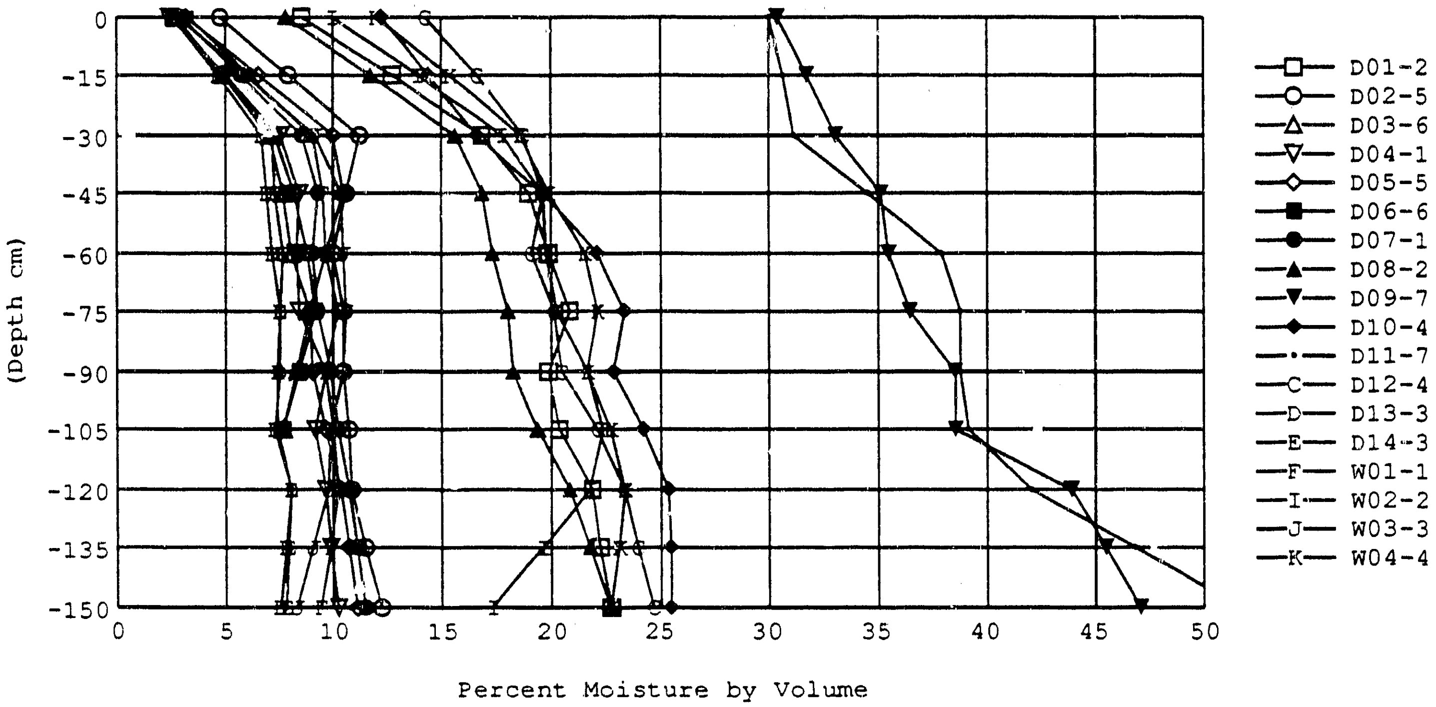

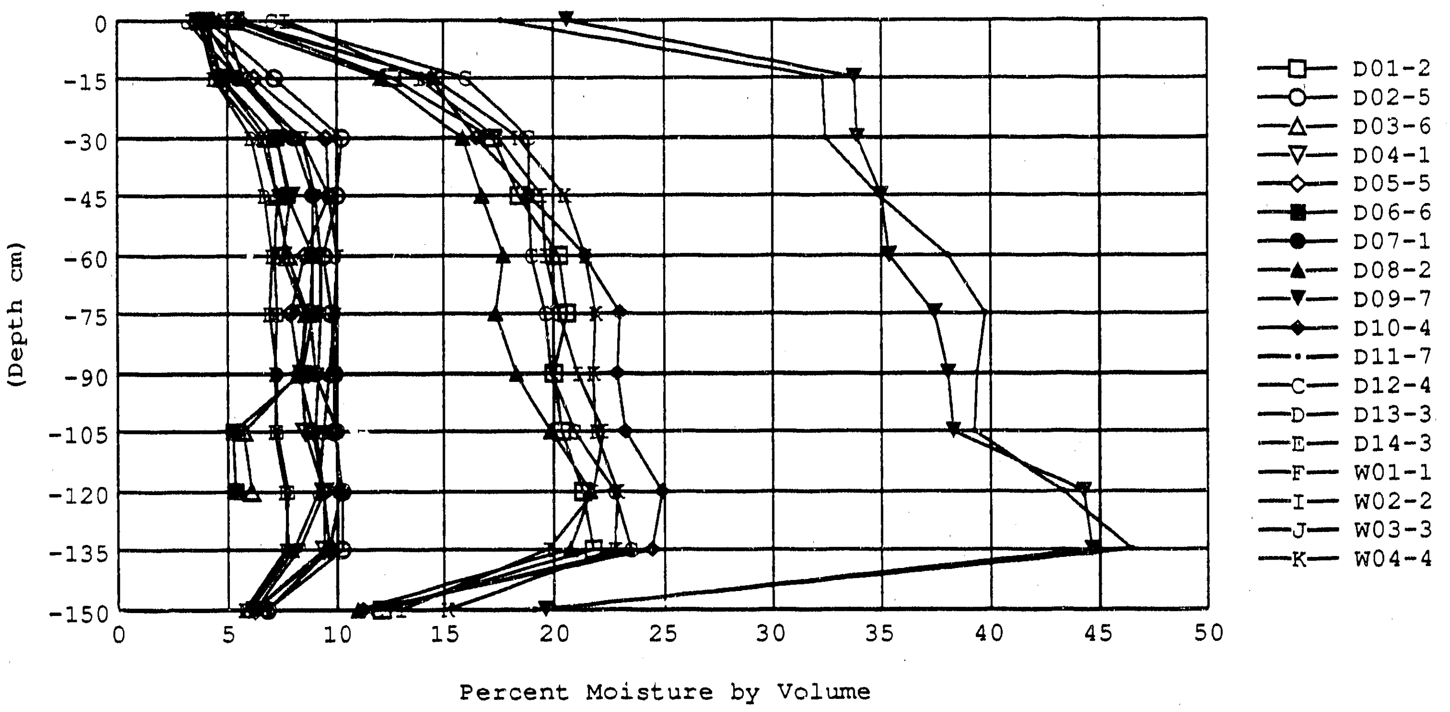

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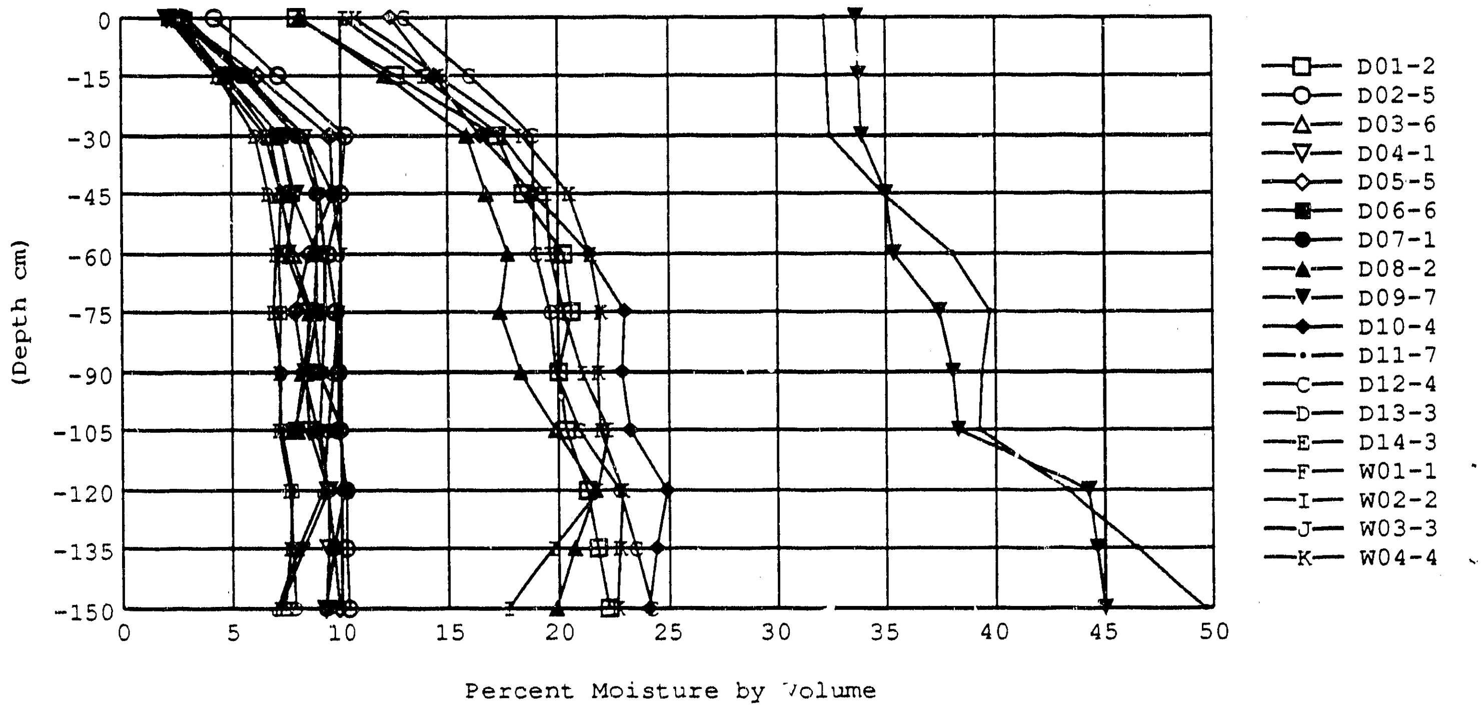

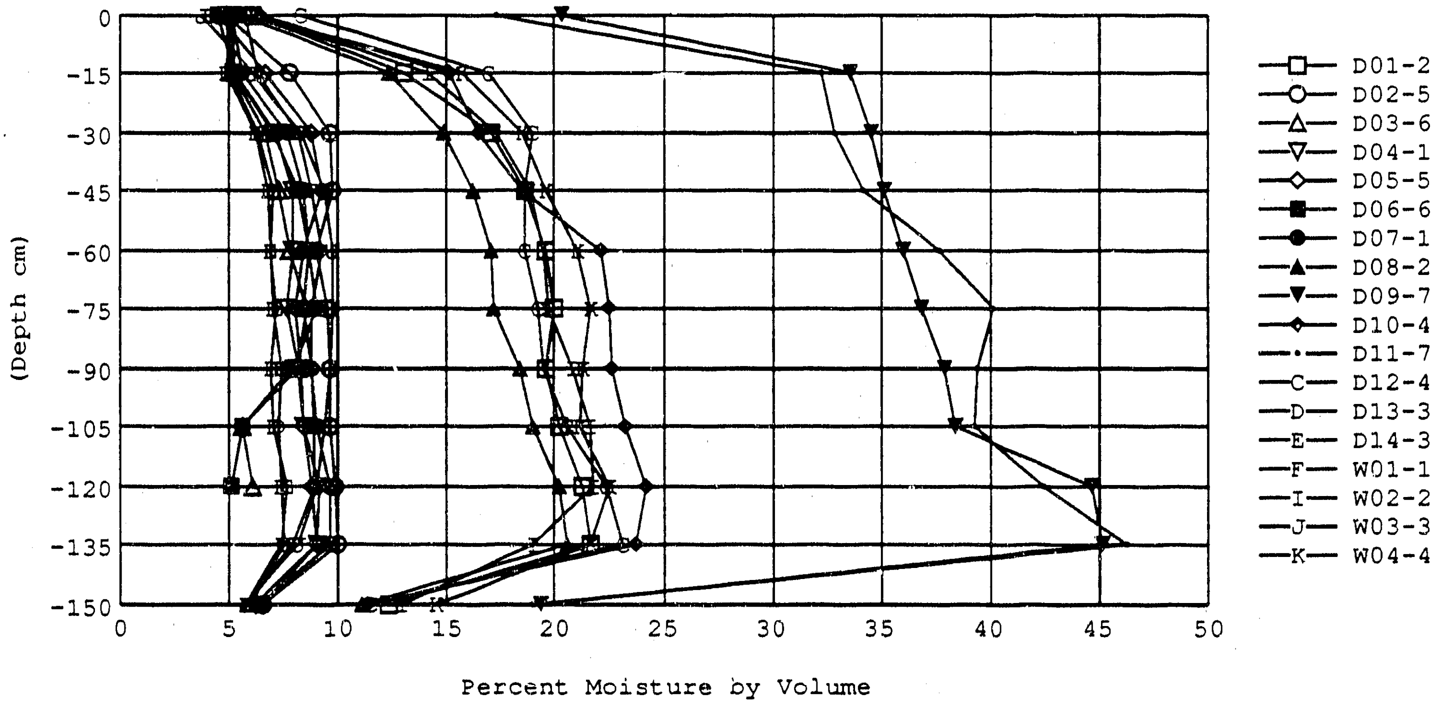

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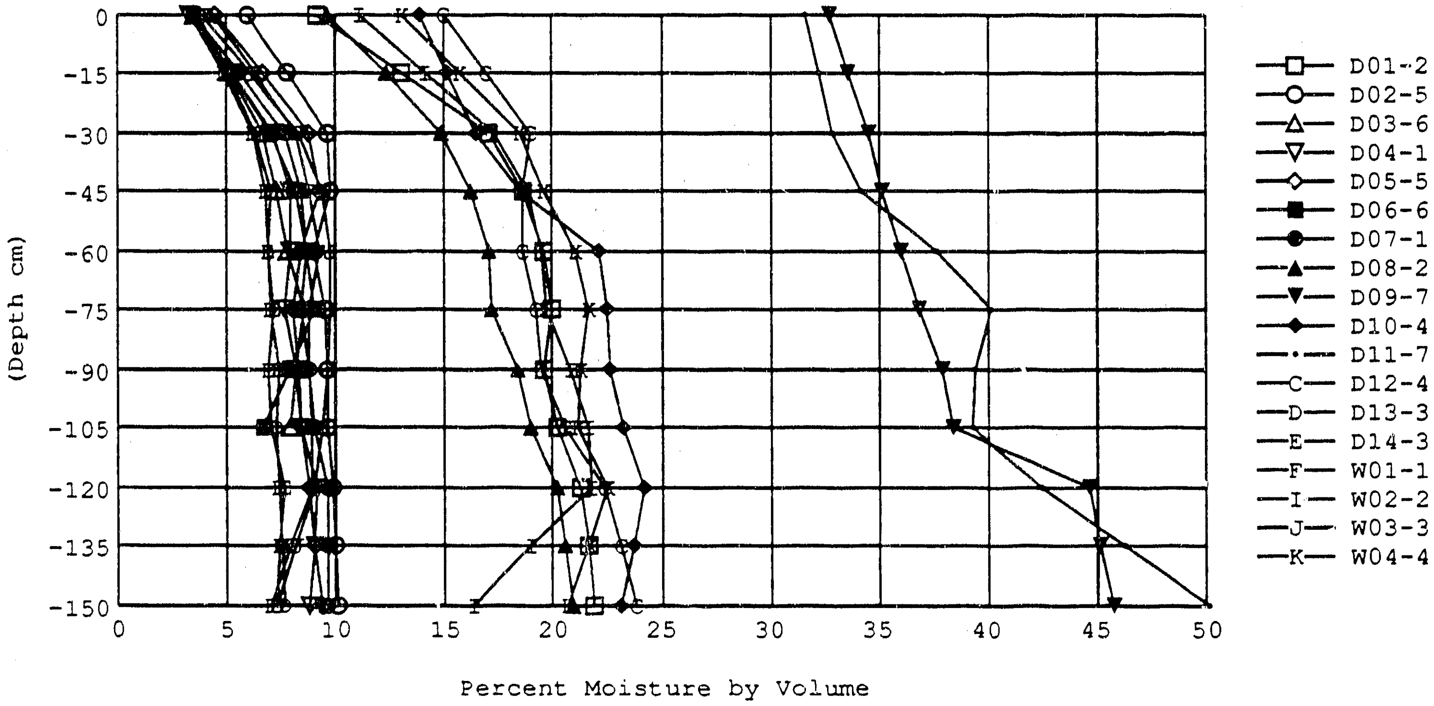

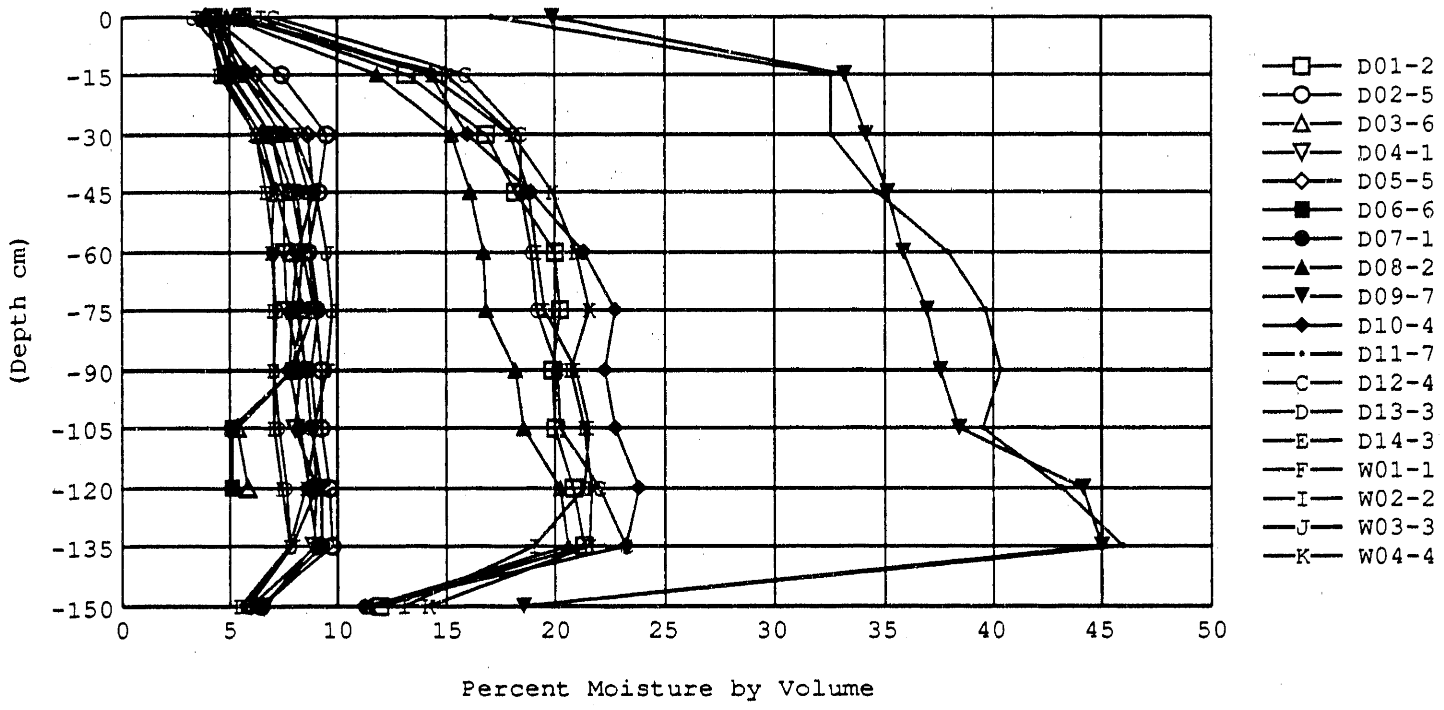

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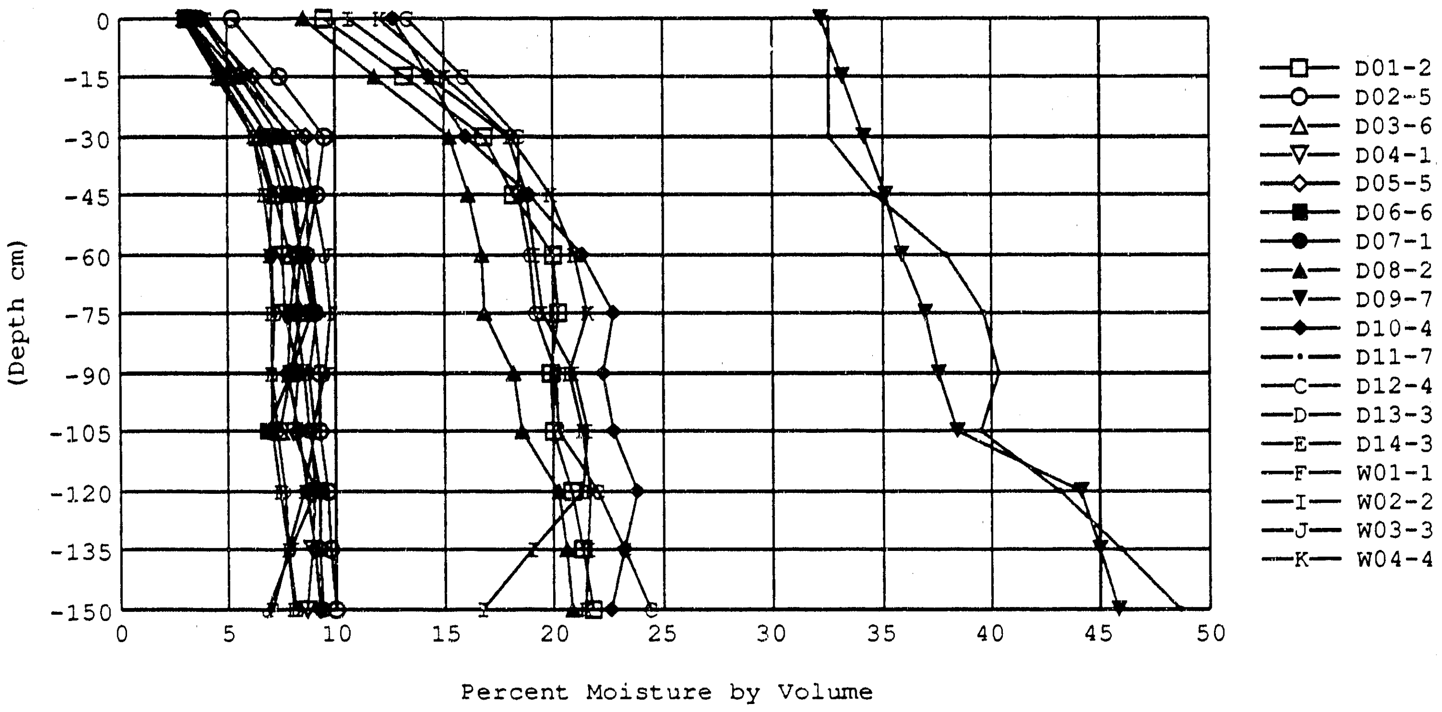
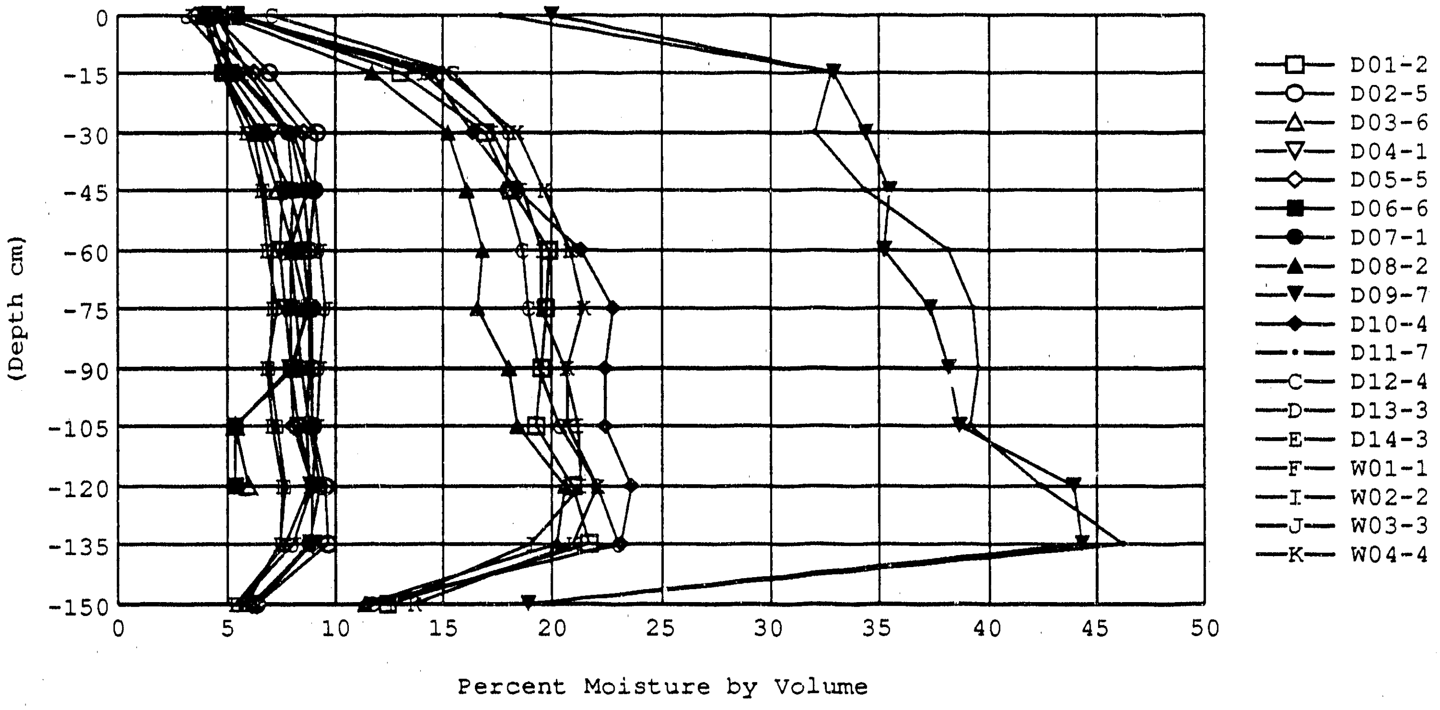
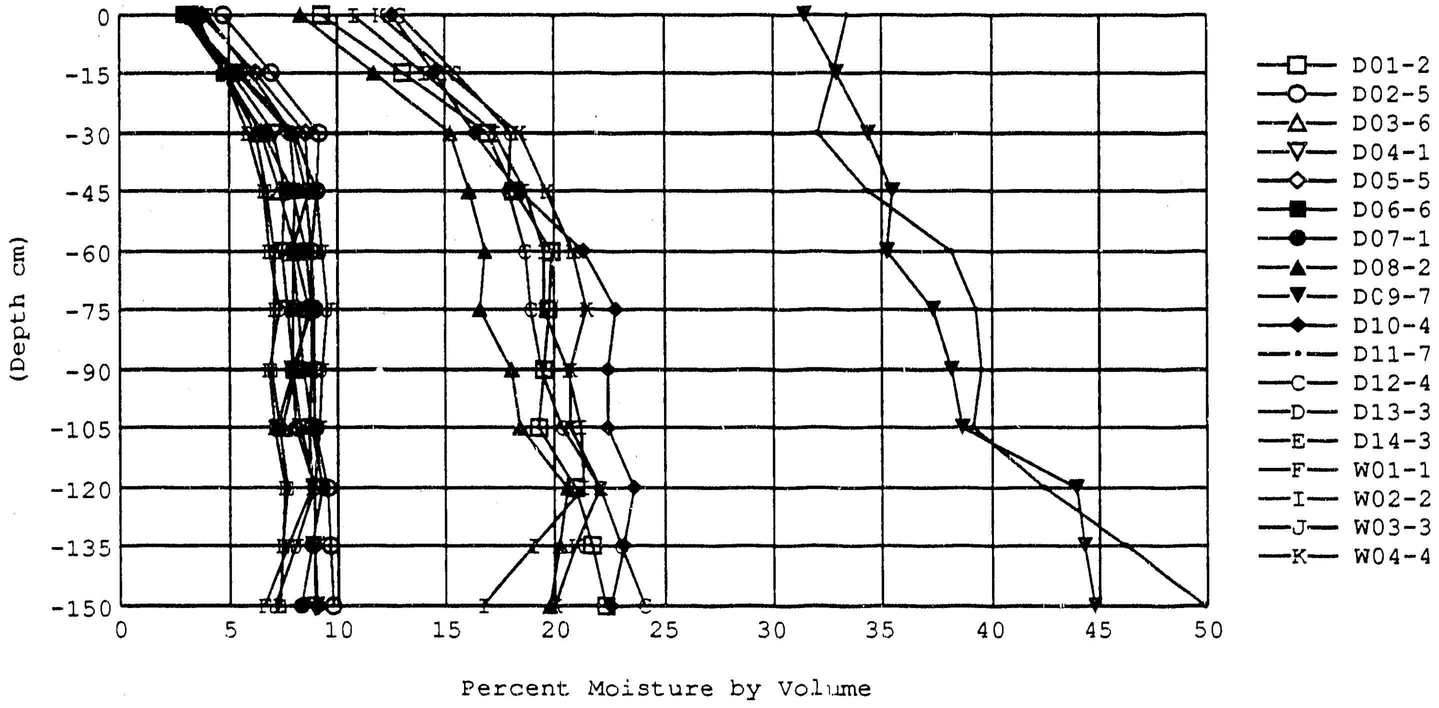
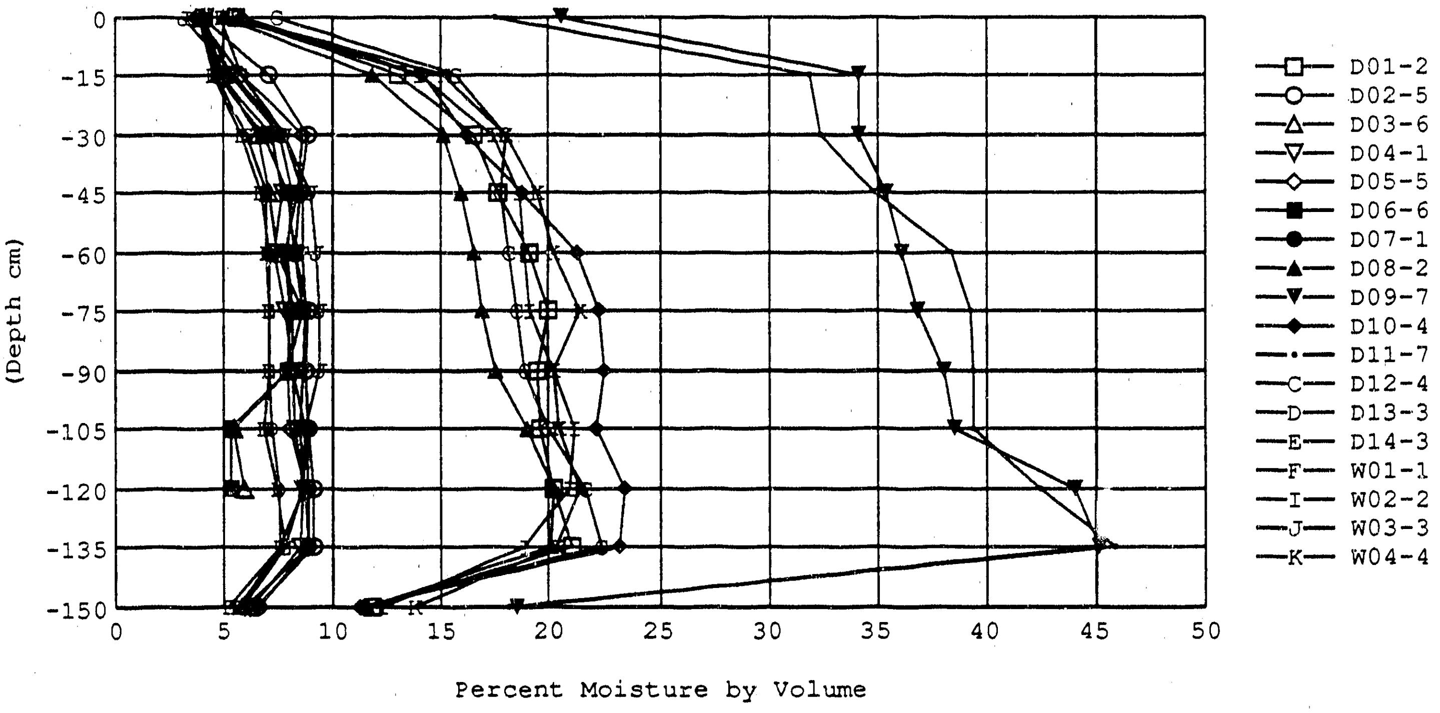


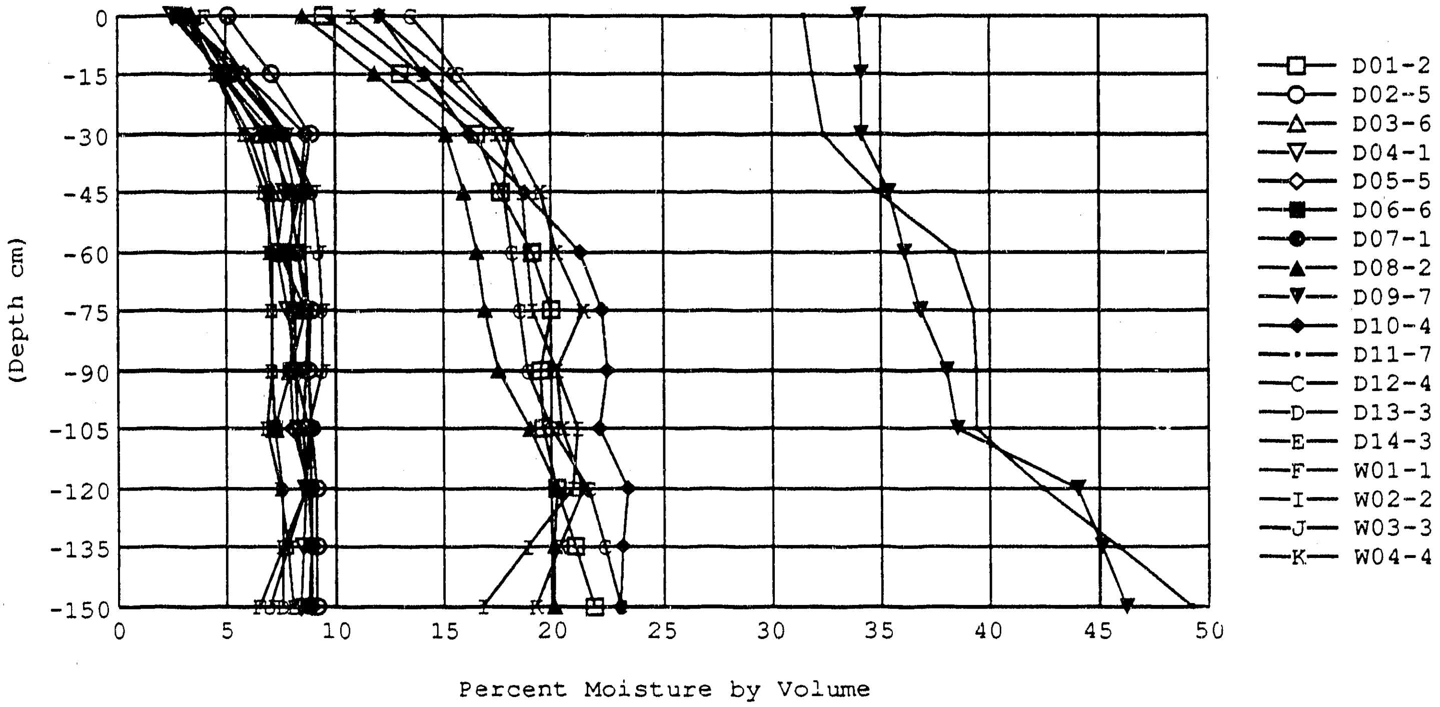


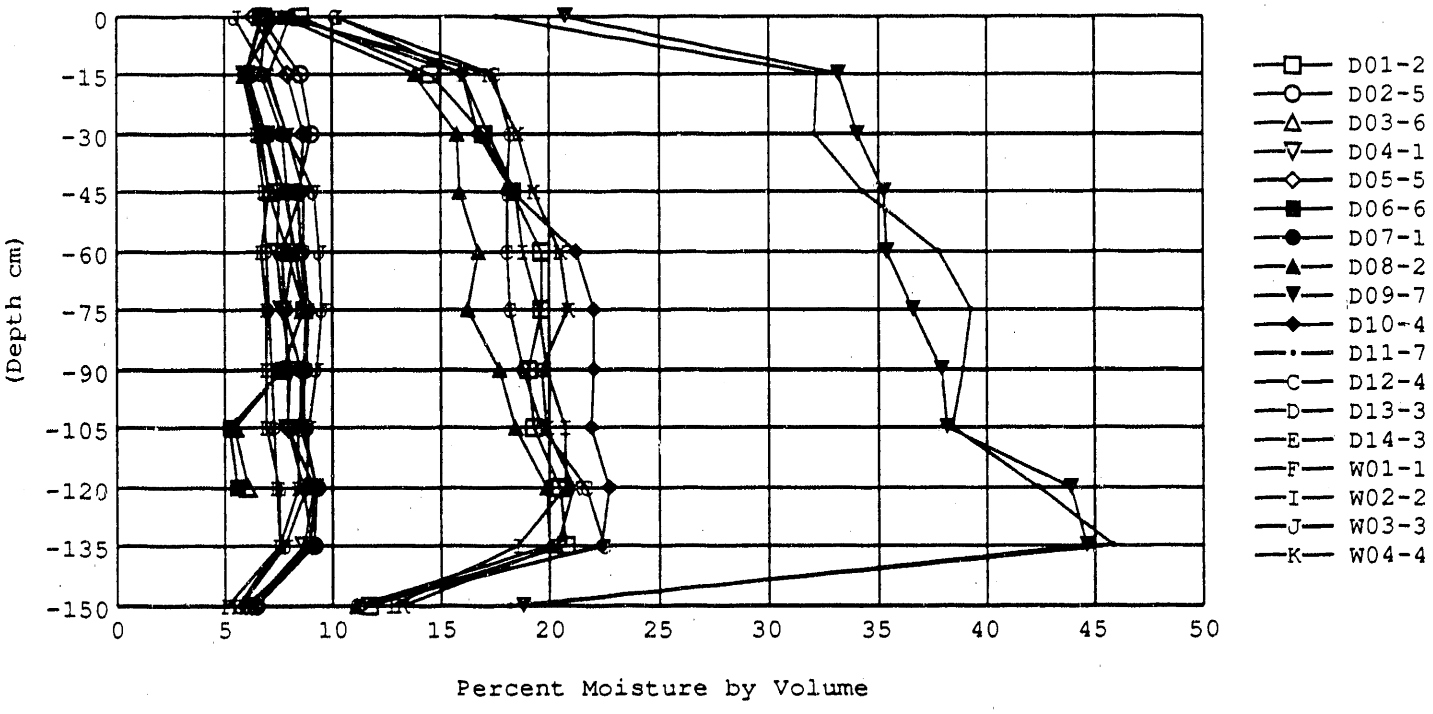
17 October 1988



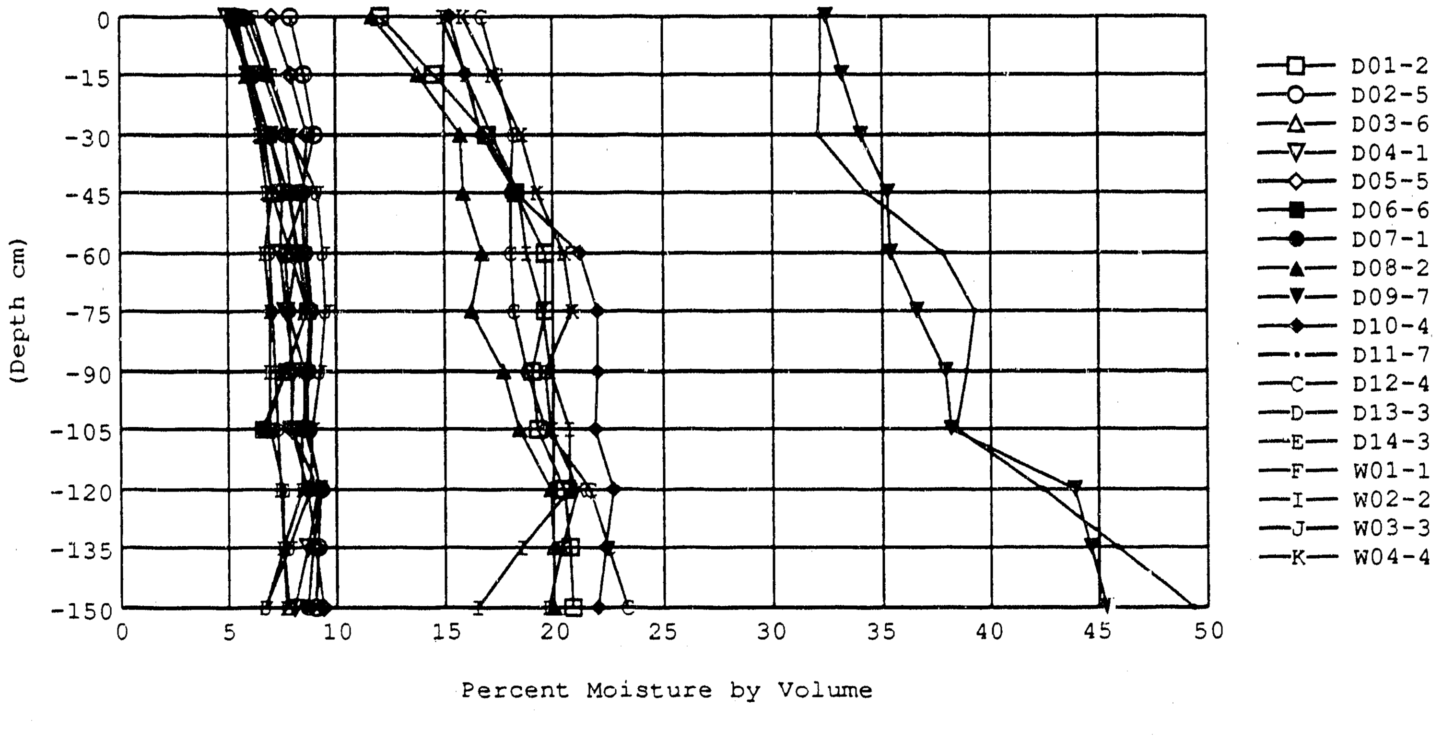


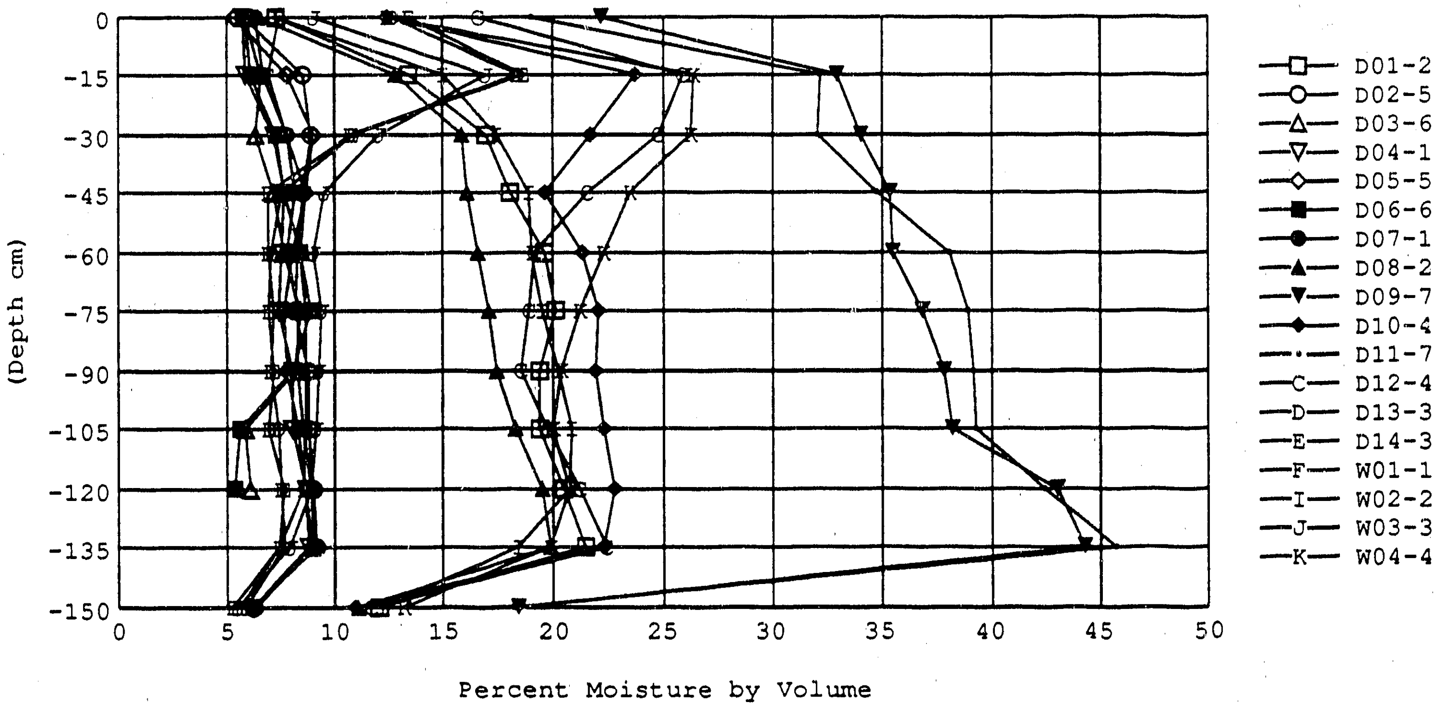
2 November 1988



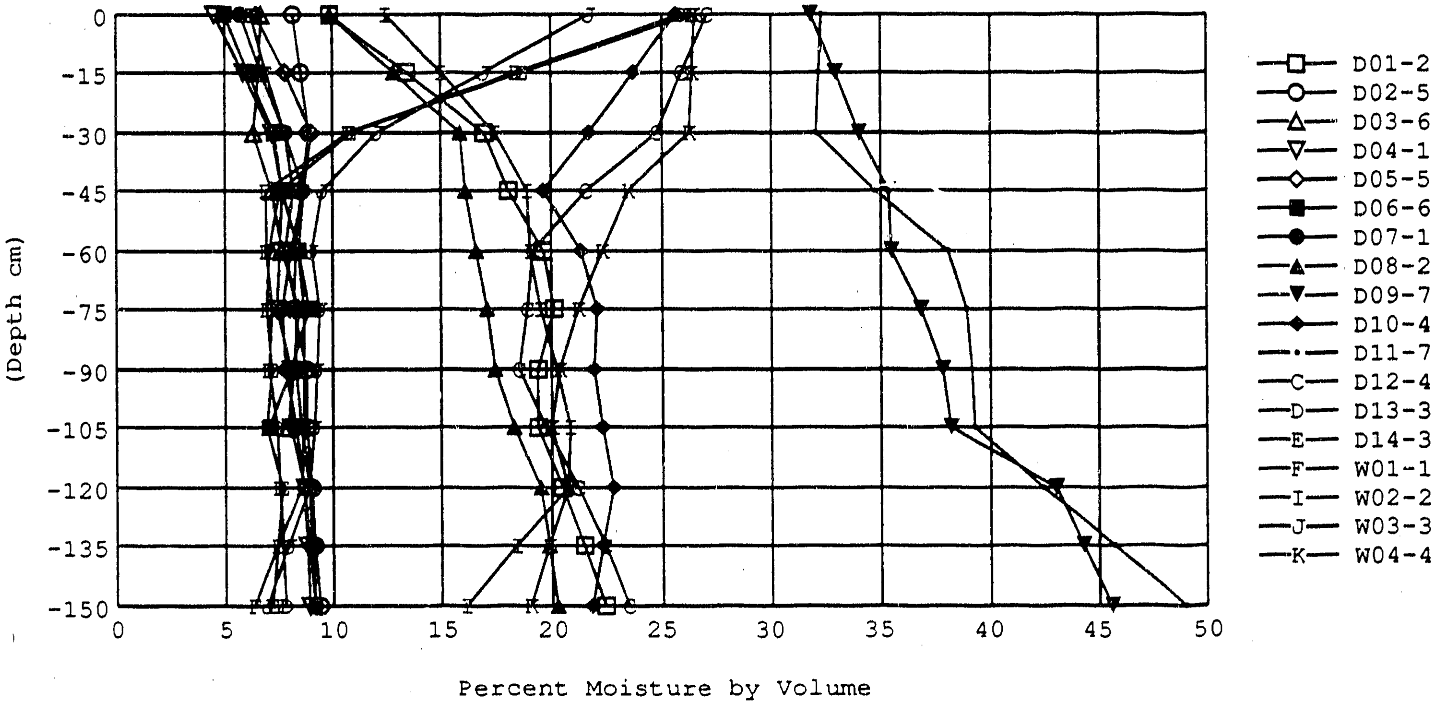


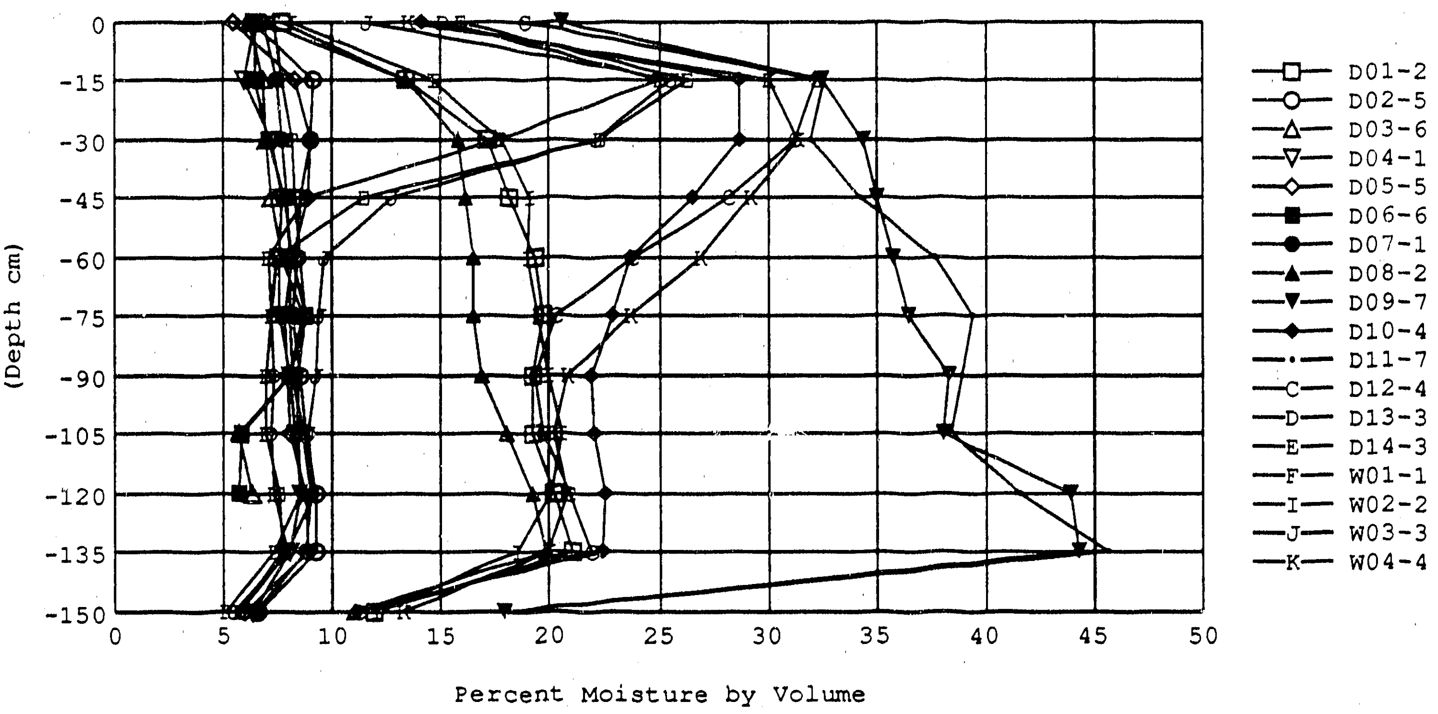
16 November 1988



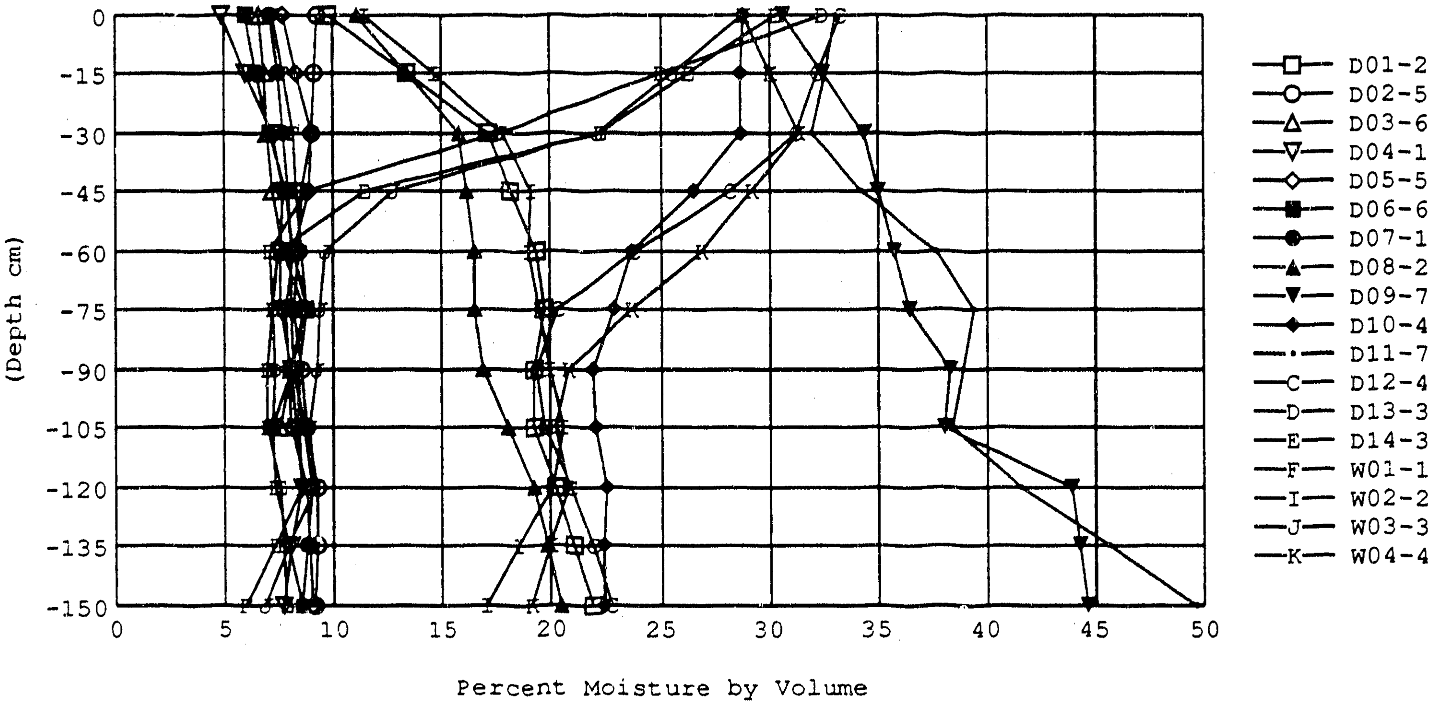


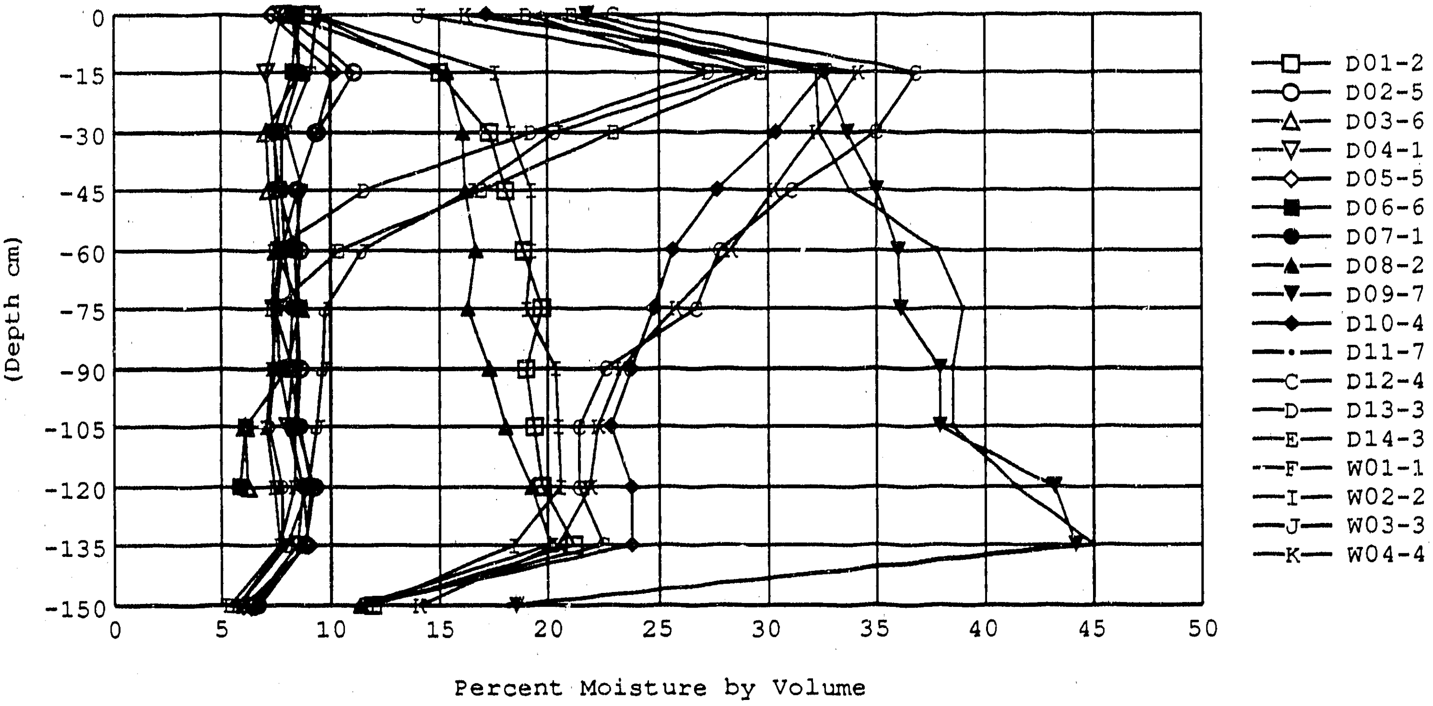
1 December 1988



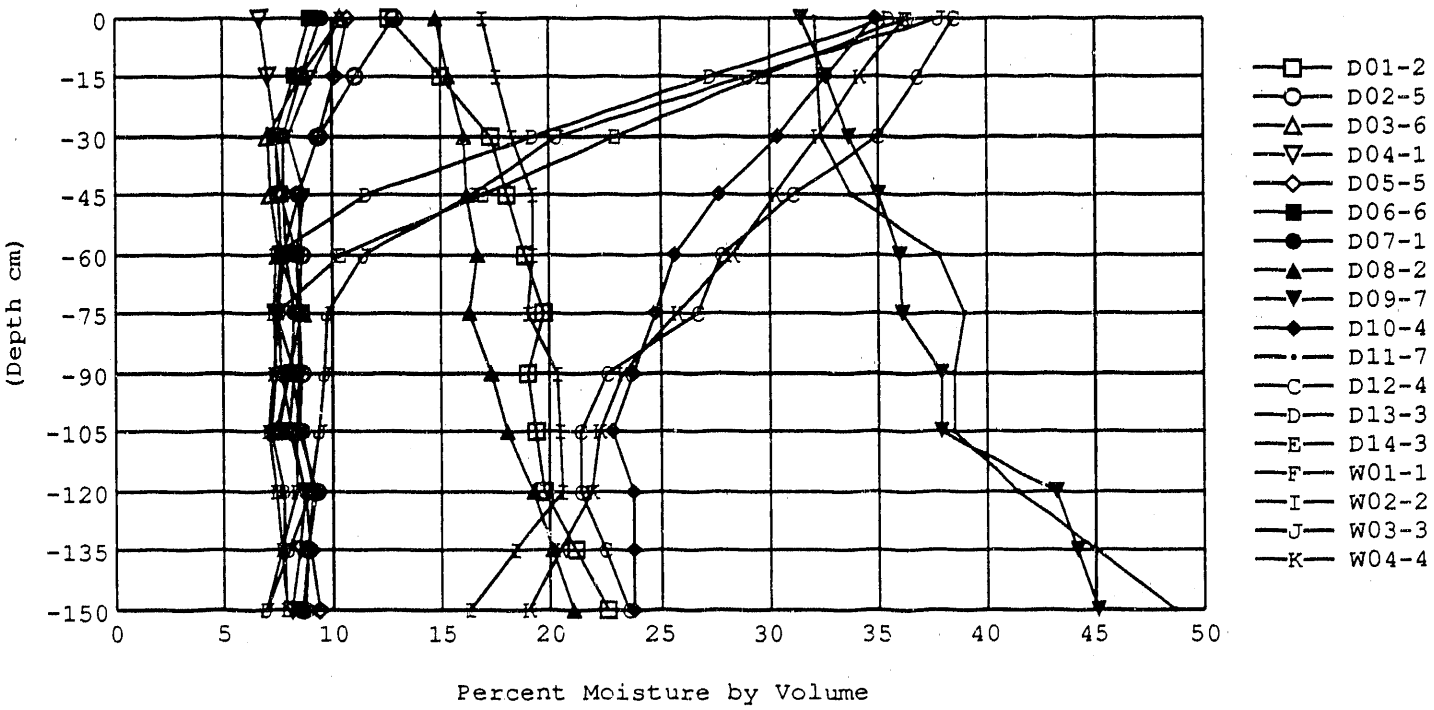


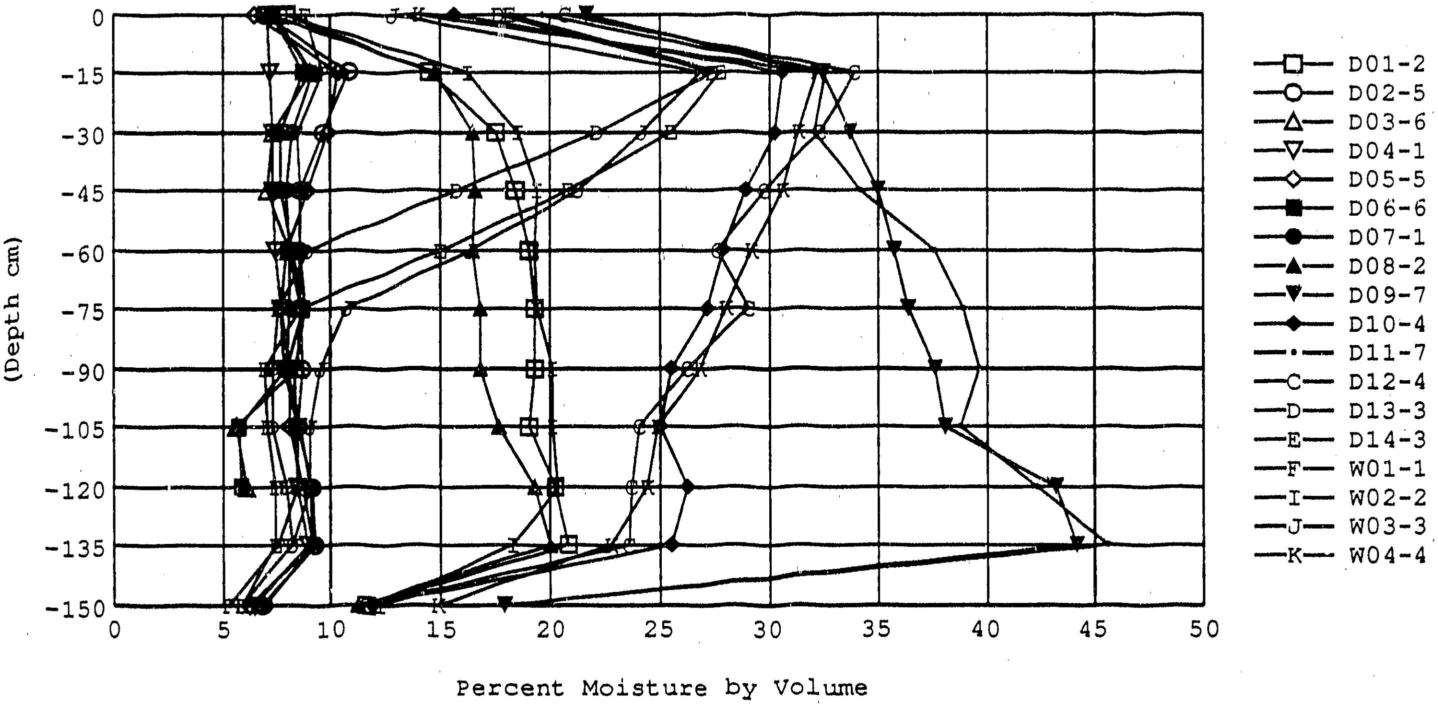
14 December 1988





4 January 1989





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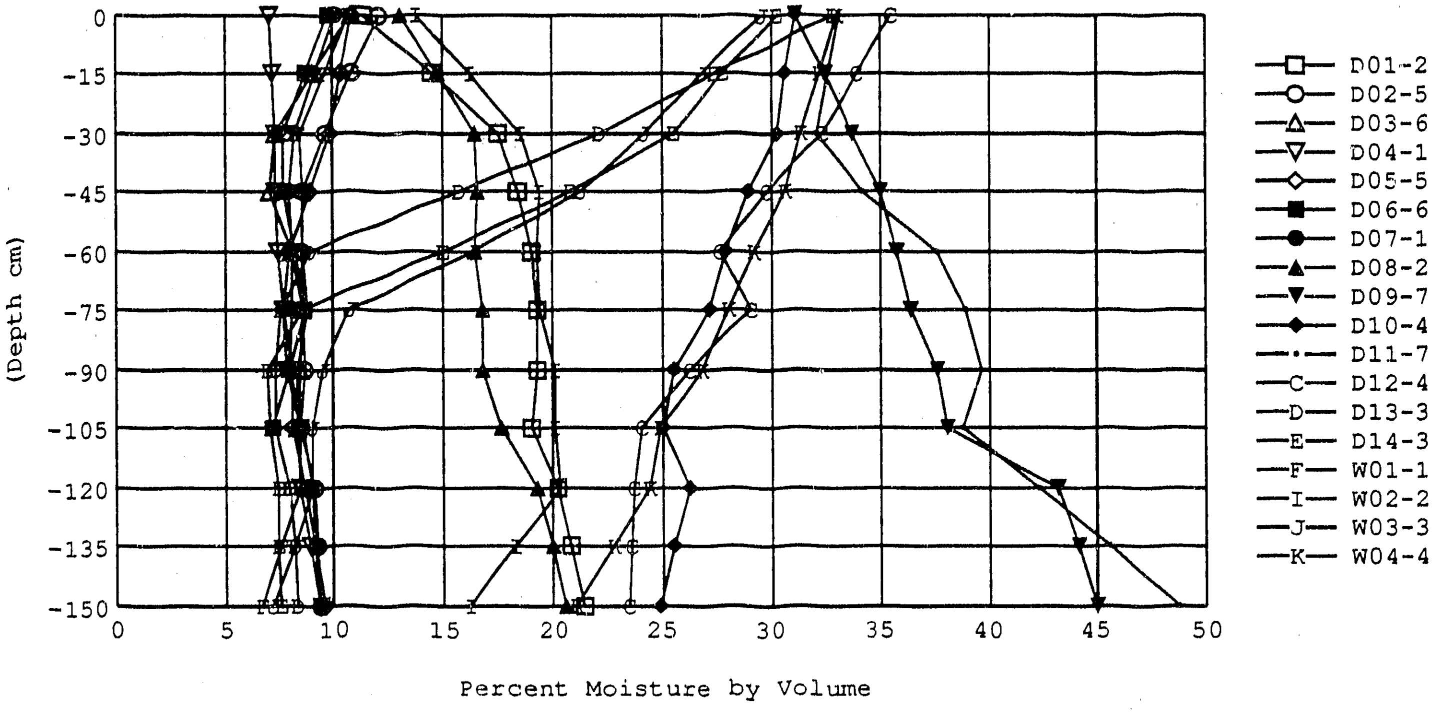
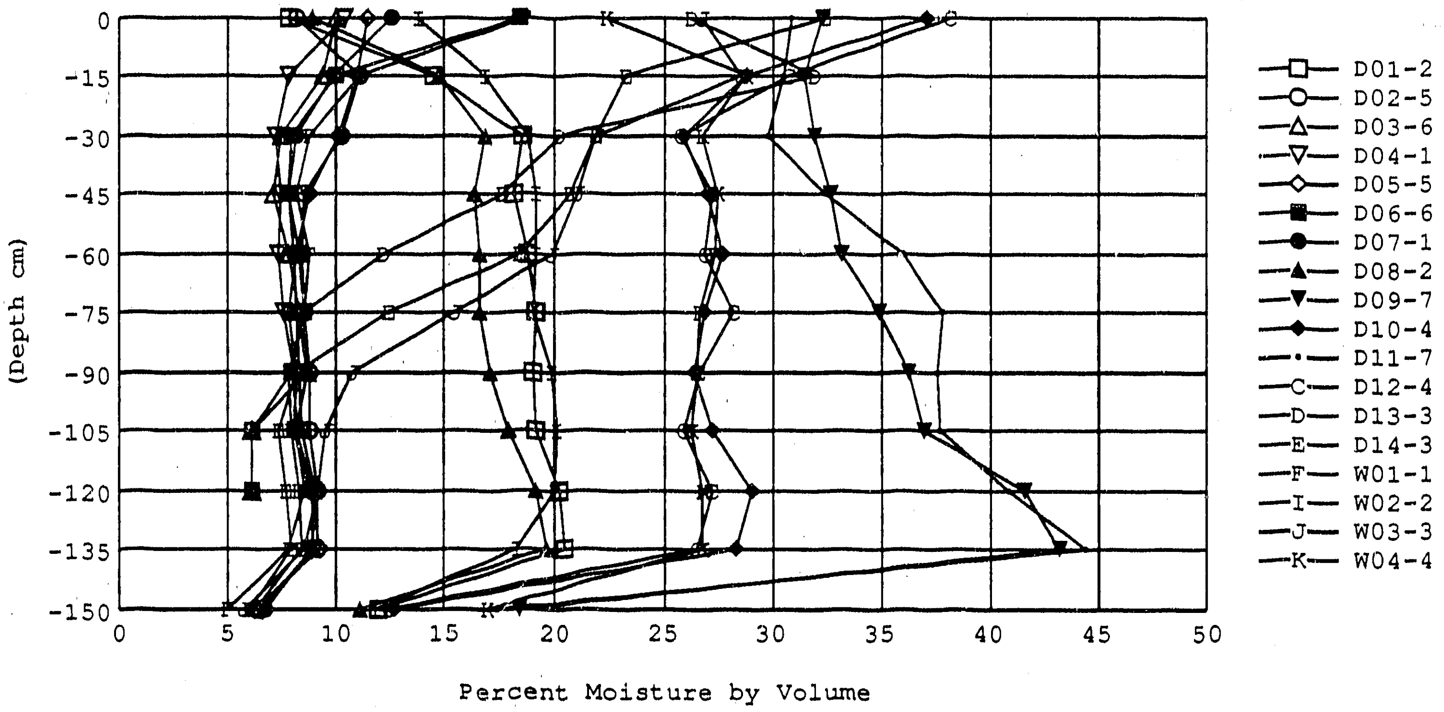
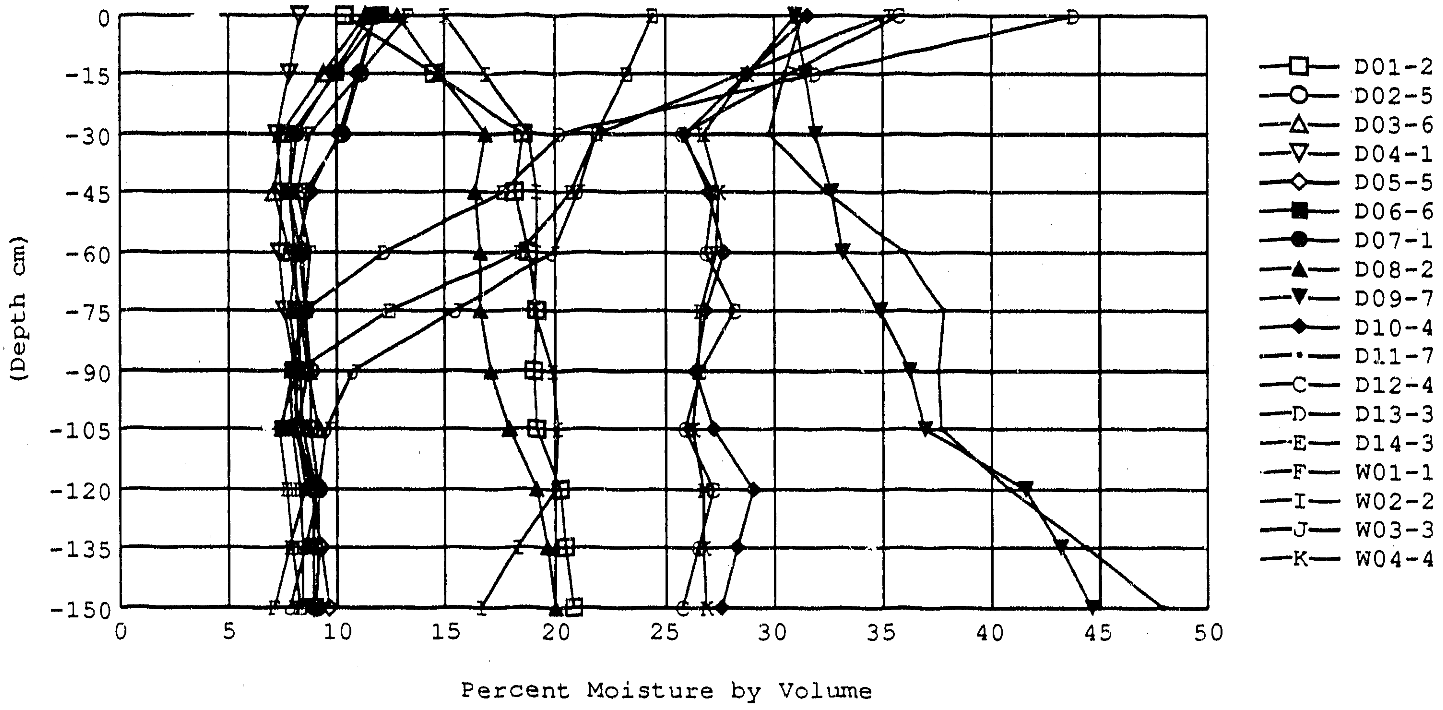
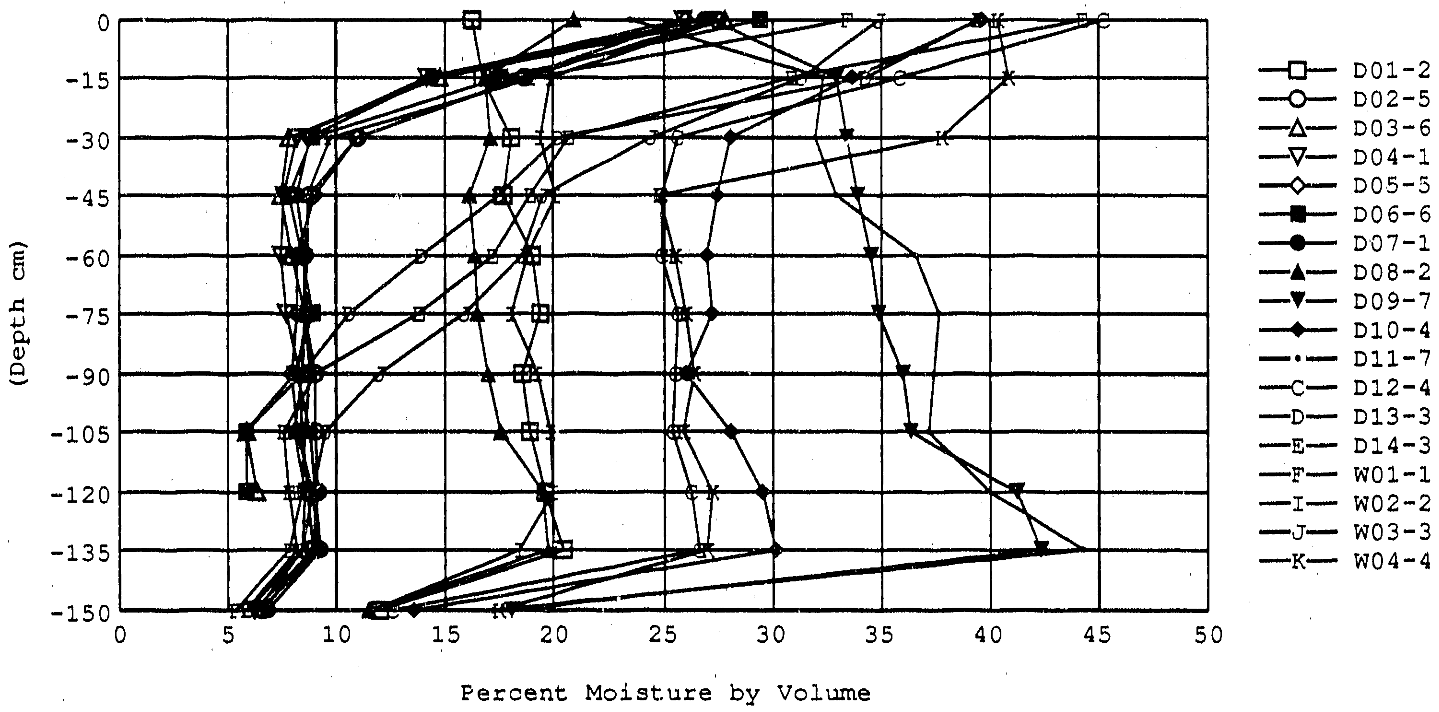


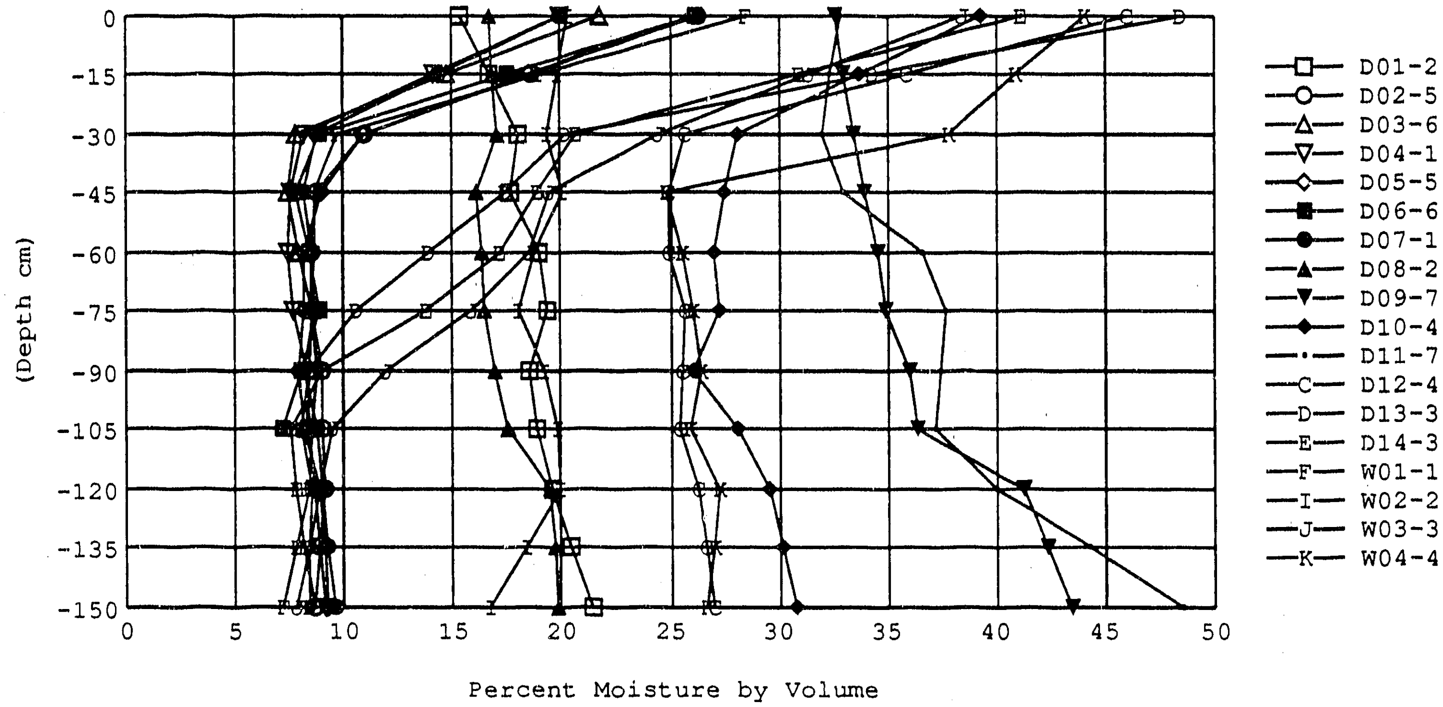


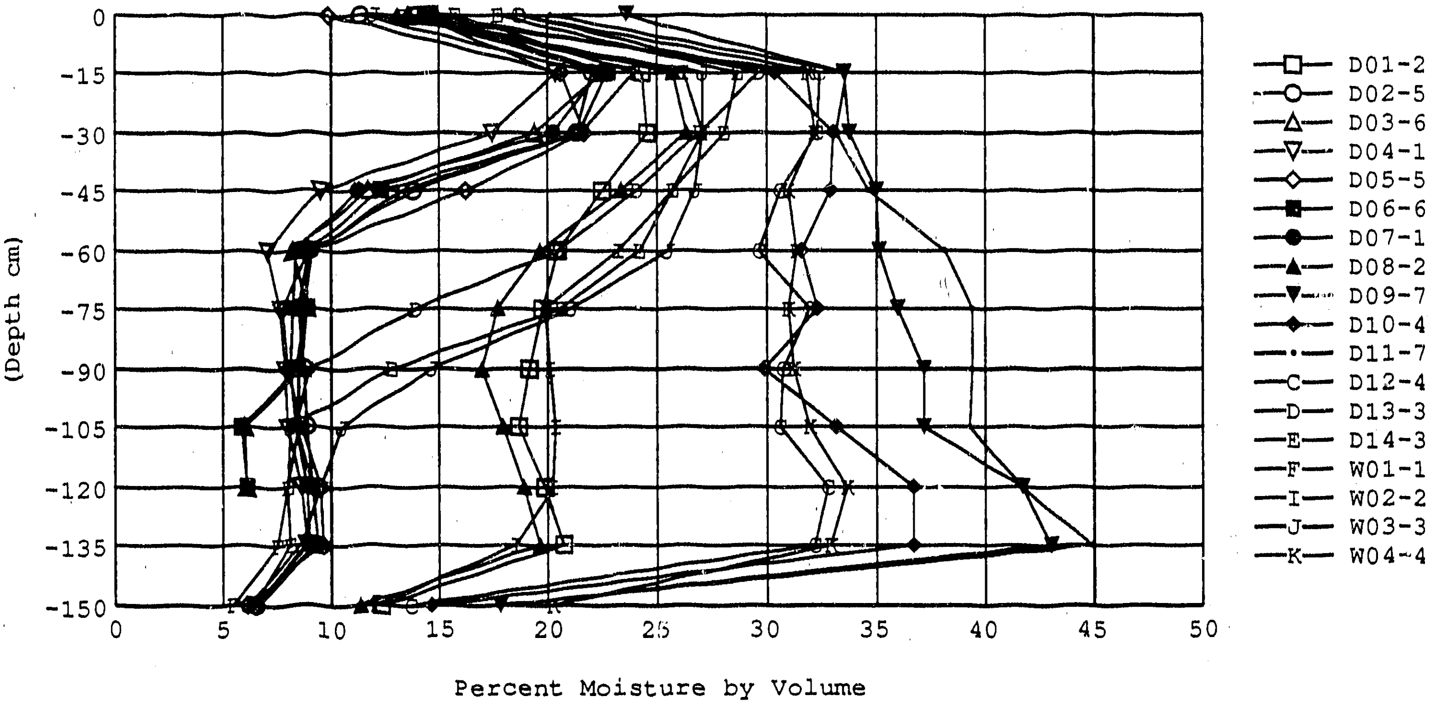
8 February 1989



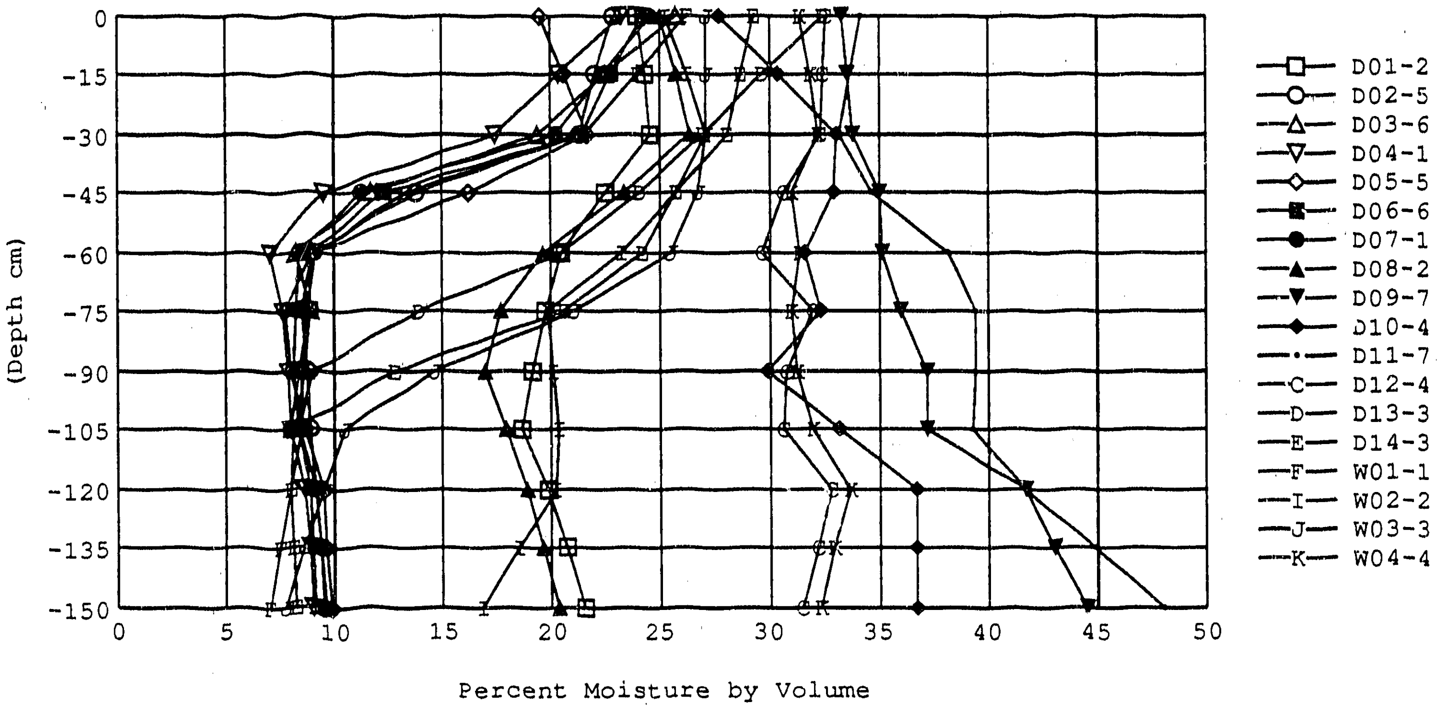


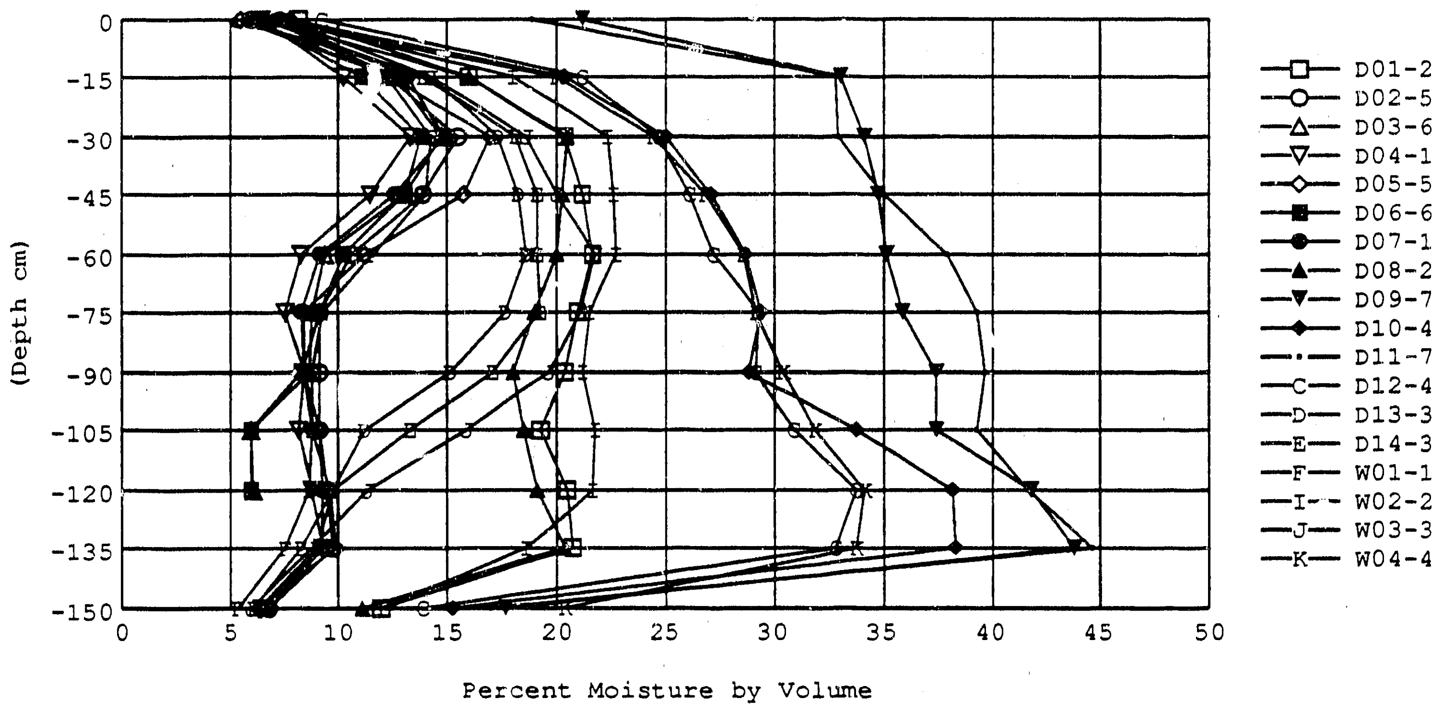
23 February 1989



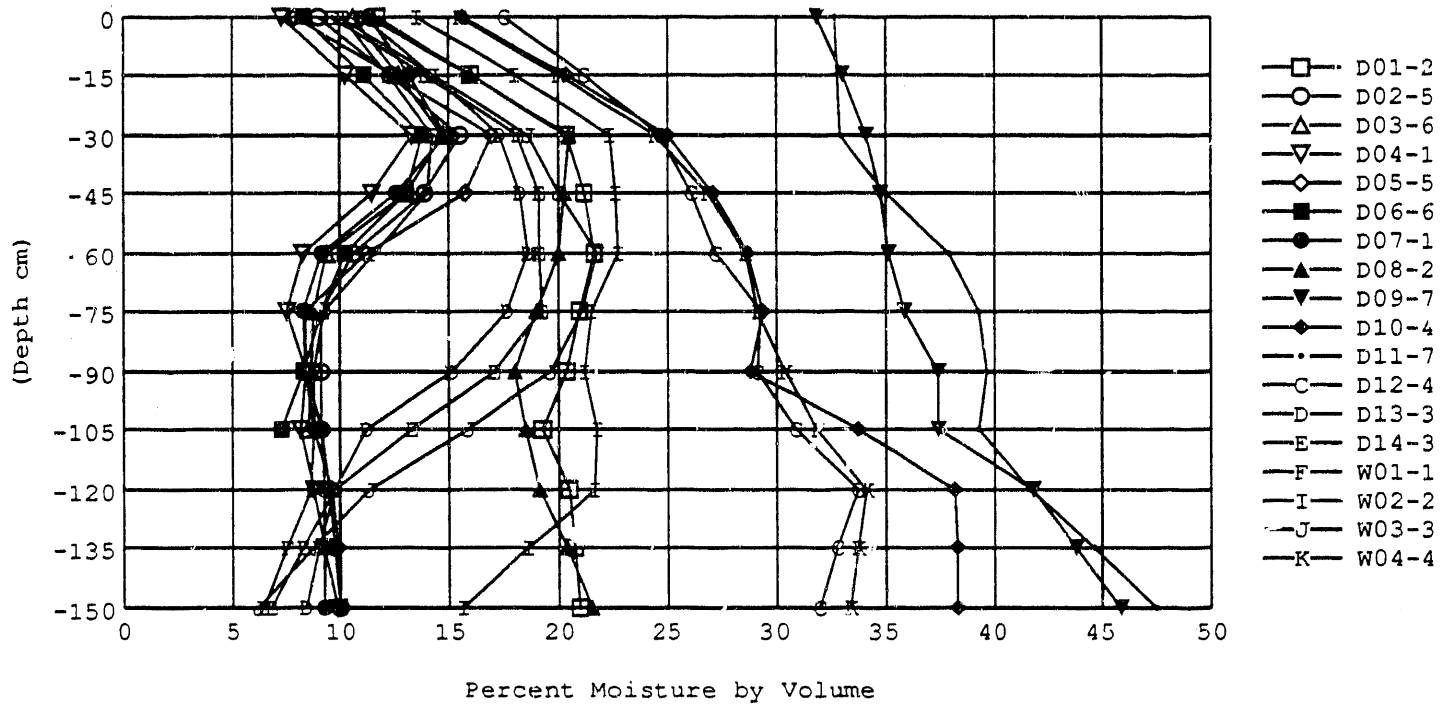


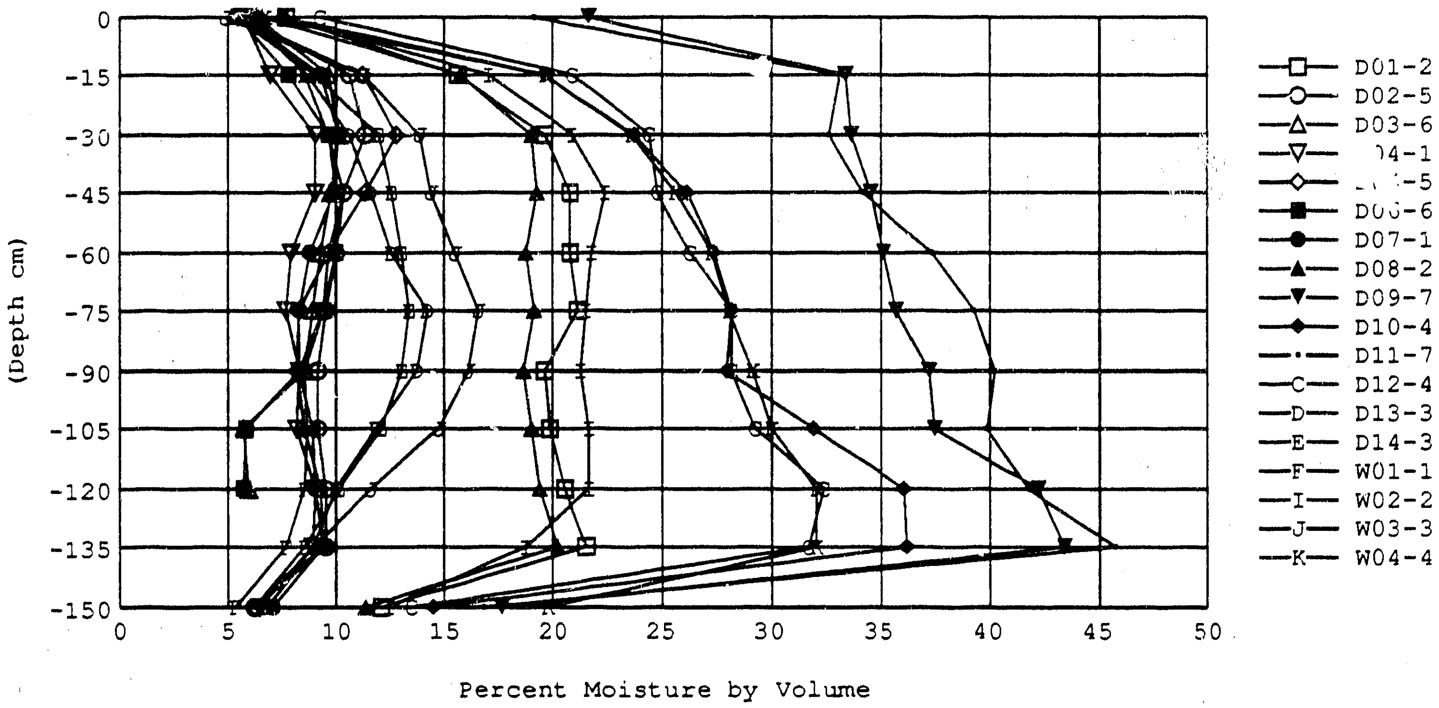
14 March 1989





14 April 1989





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Percent Moisture by Volume
D01-2
D02-5
D03-6
D04-1
D05-5
D06-6
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D08-2
D09-7
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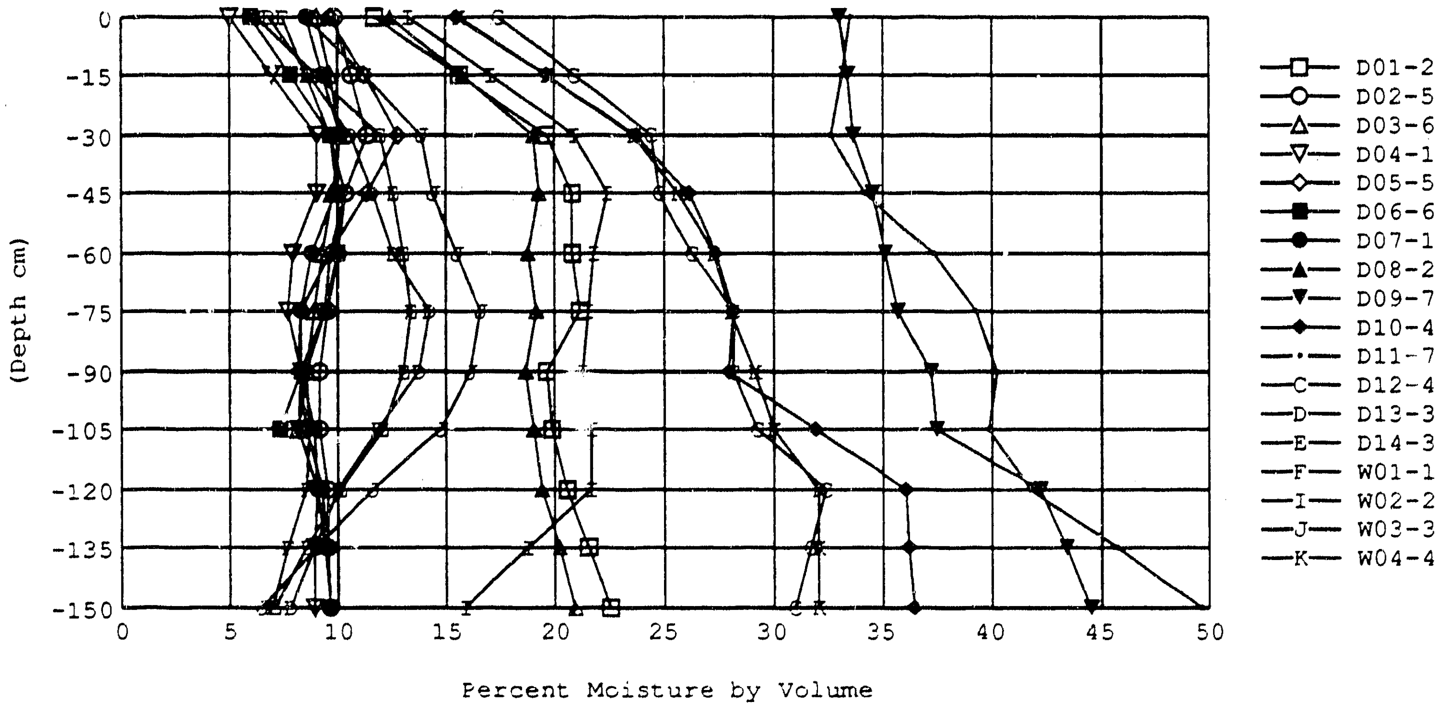
5 May 1989



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Percent Moisture by Volume
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D02-5
D03-6
D04-1
D05-5
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D07-1
D08-2
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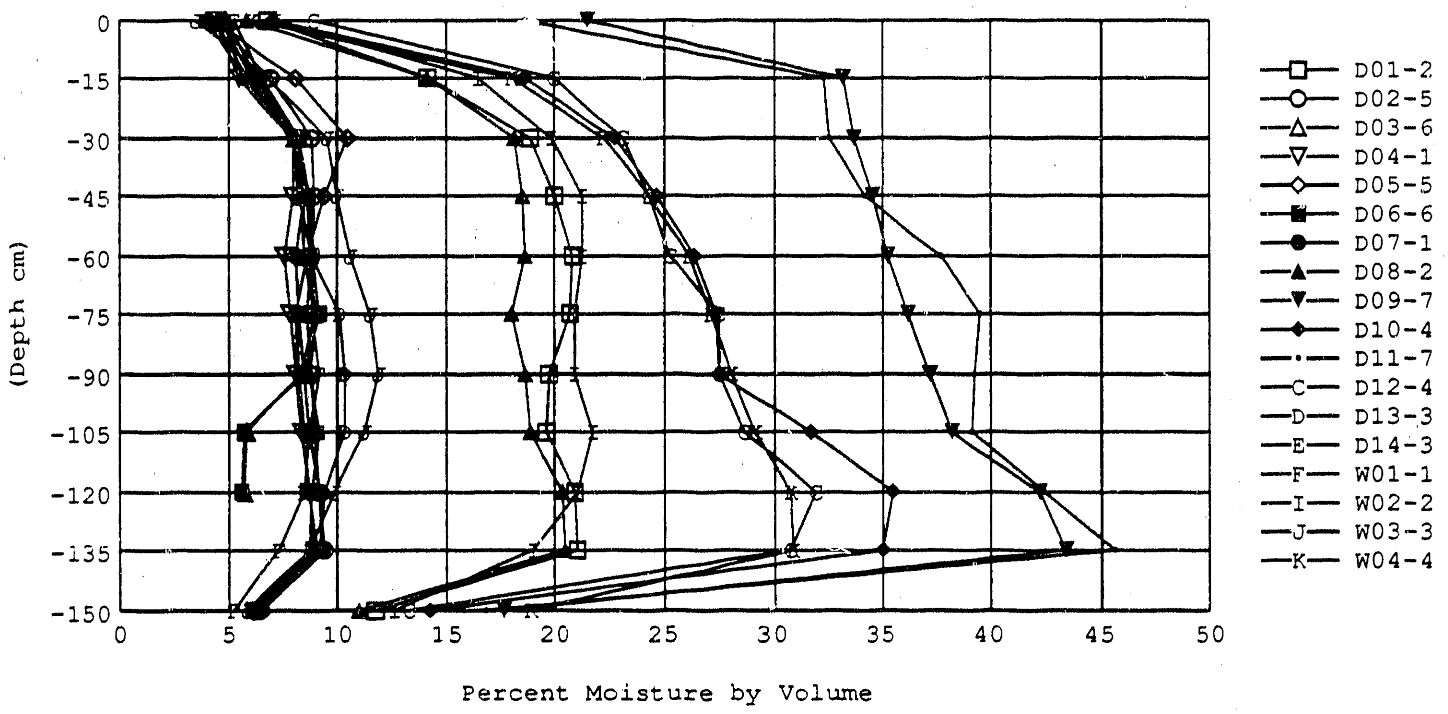
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Percent Moisture by Volume
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D02-5
D03-6
D04-1
D05-5
D06-6
D07-1
D08-2
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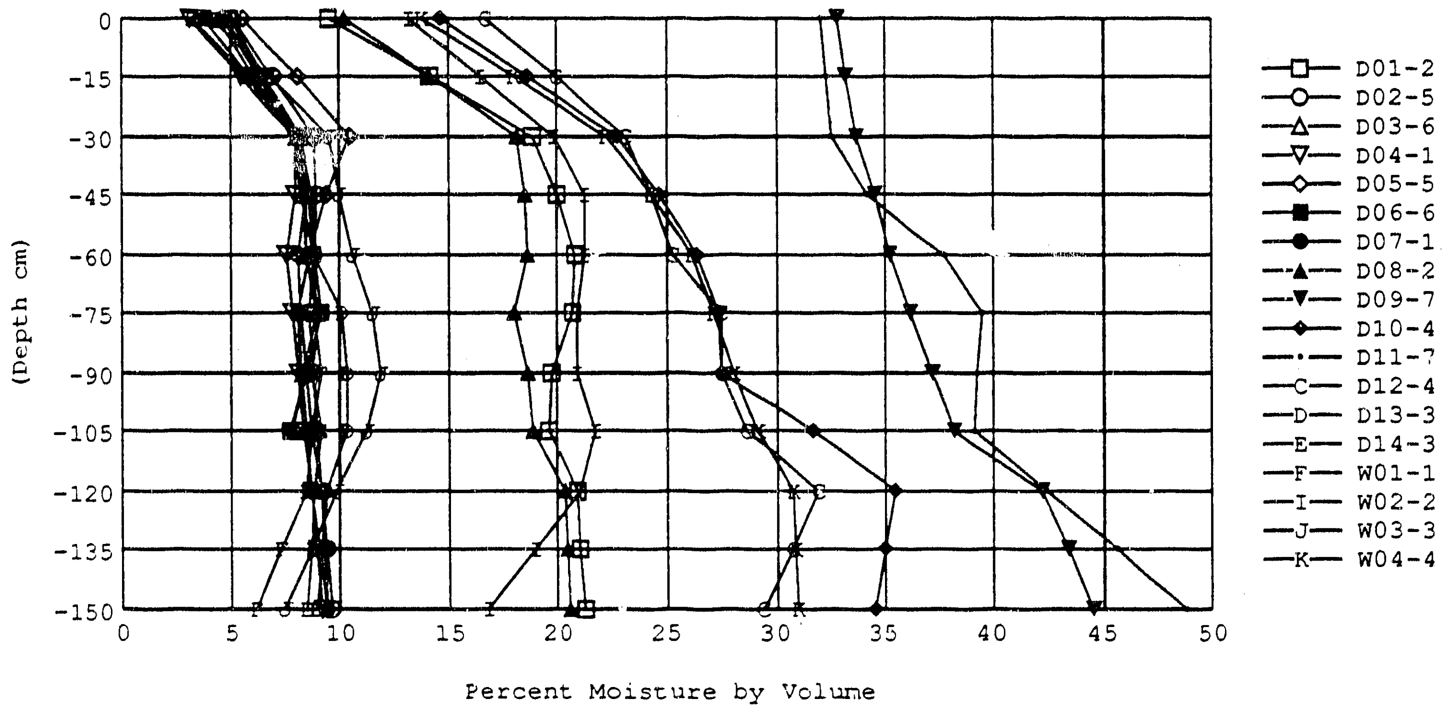
19 May 1989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Percent Moisture by Volume
D01-2
D02-5
D03-6
D04-1
D05-5
D06-6
D07-1
D08-2
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D12-4
D13-3
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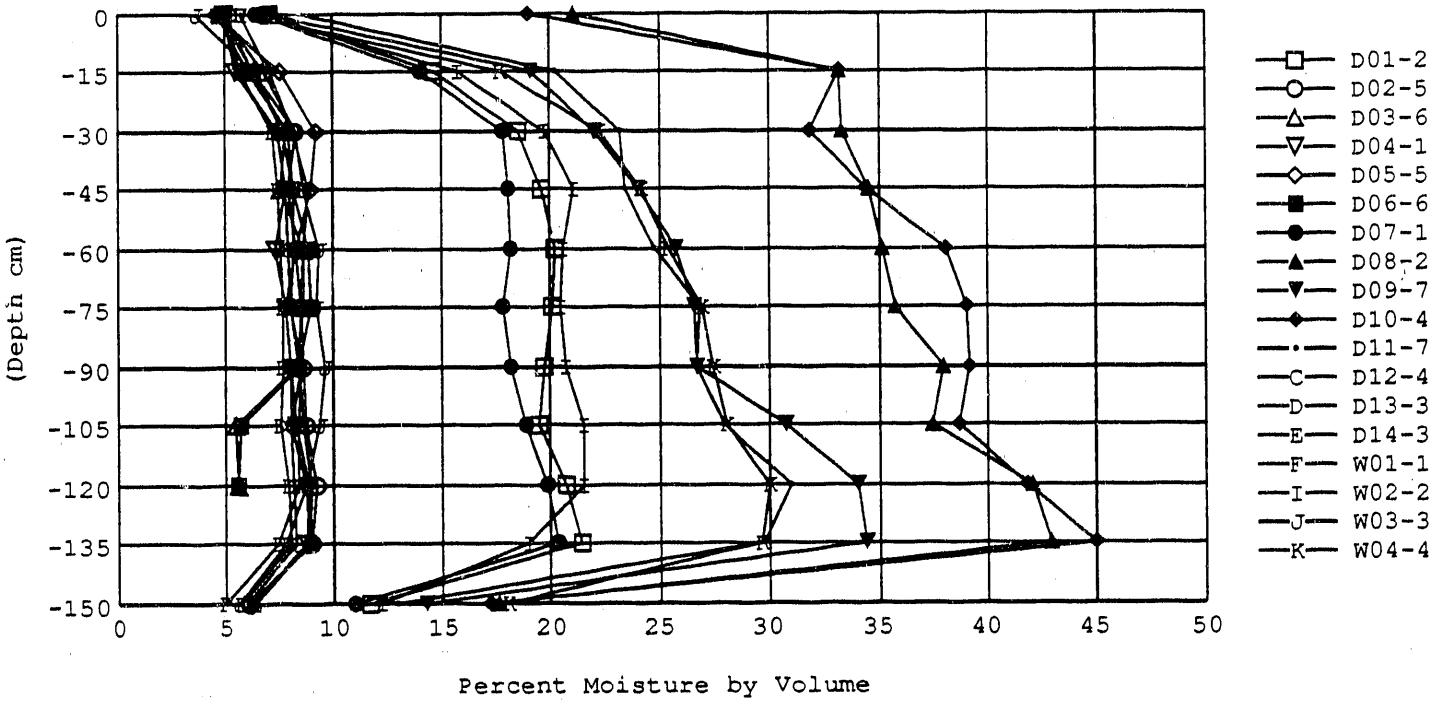
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Percent Moisture by Volume
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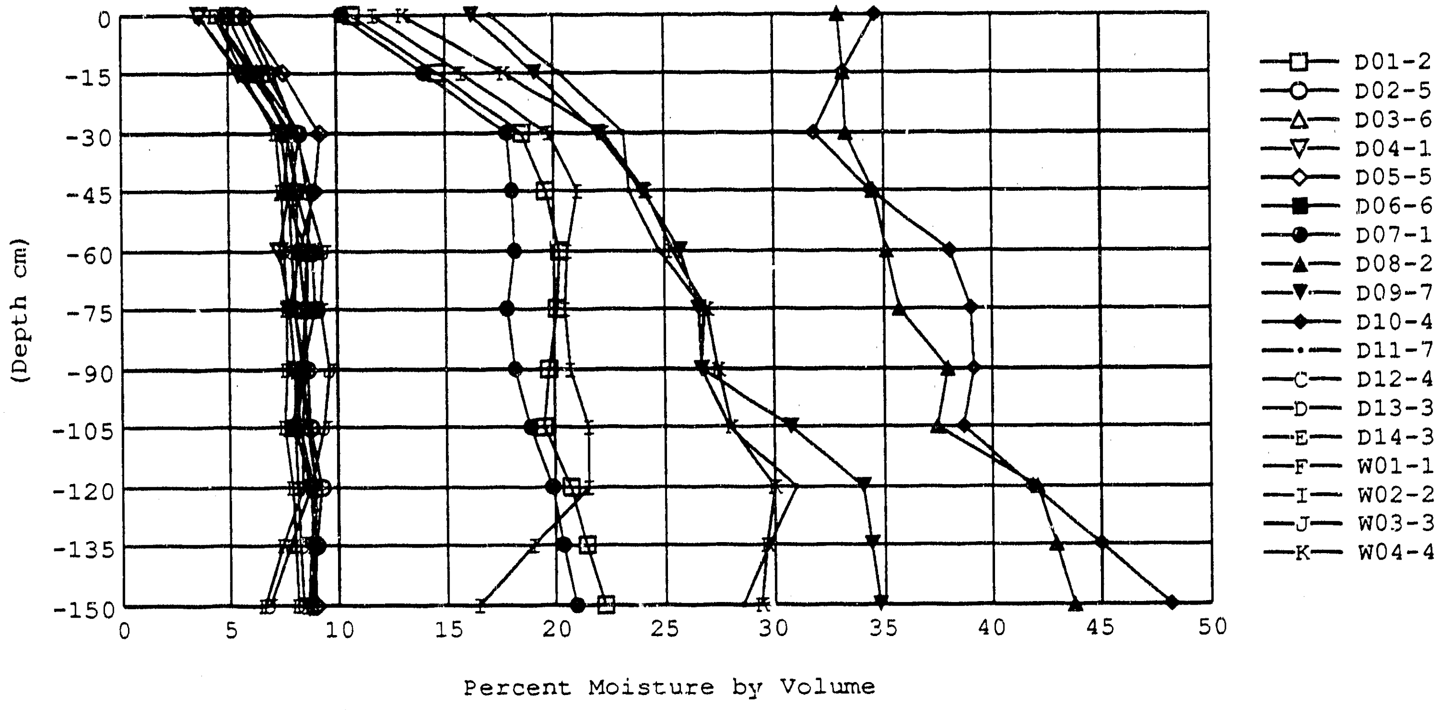
1 June 1989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Percent Moisture by Volume
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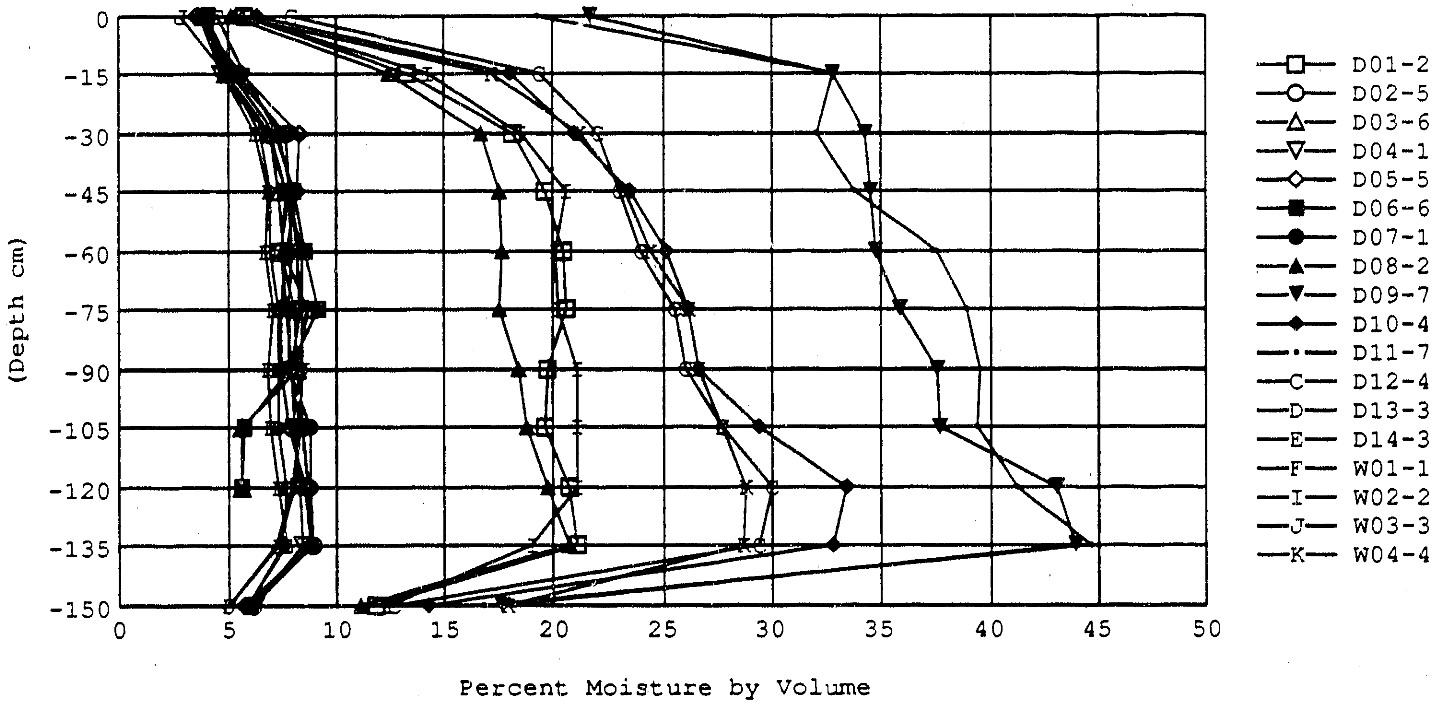
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Percent Moisture by Volume
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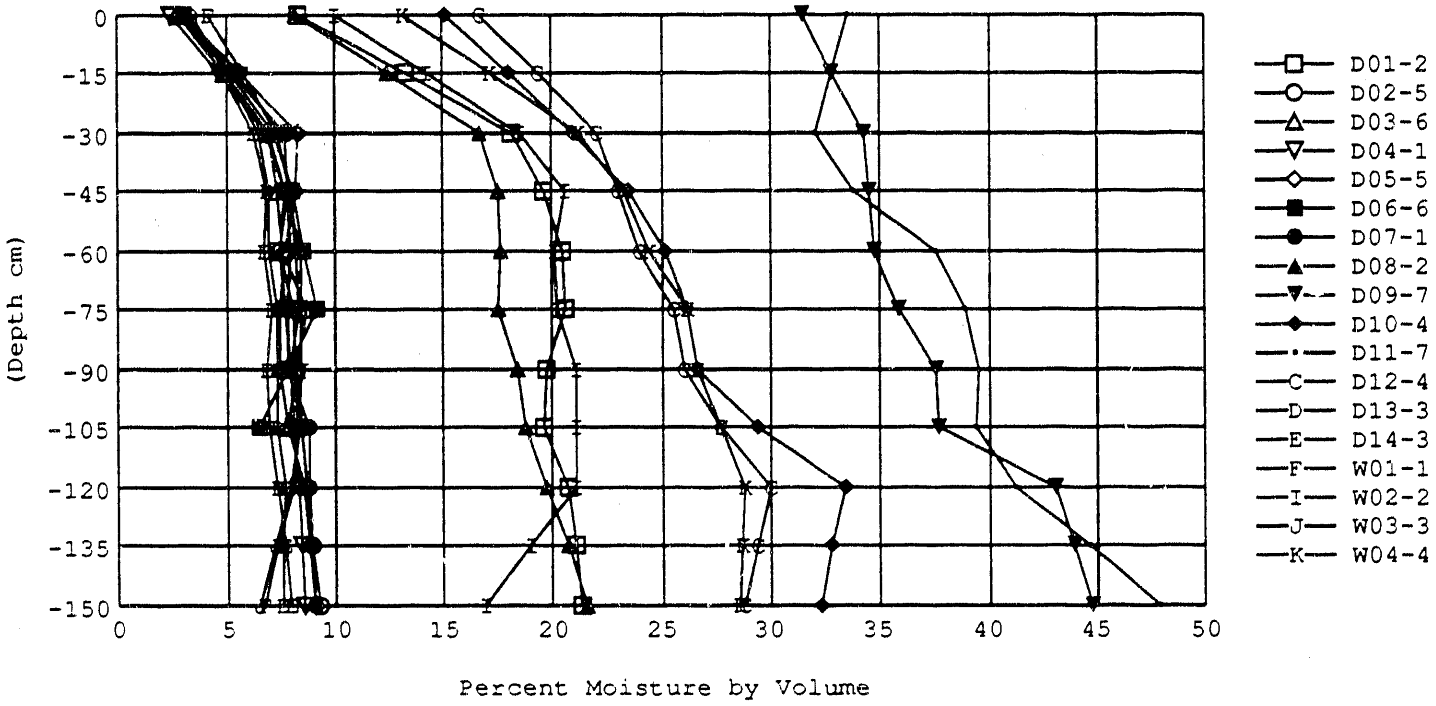
16 June 1989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Percent Moisture by Volume
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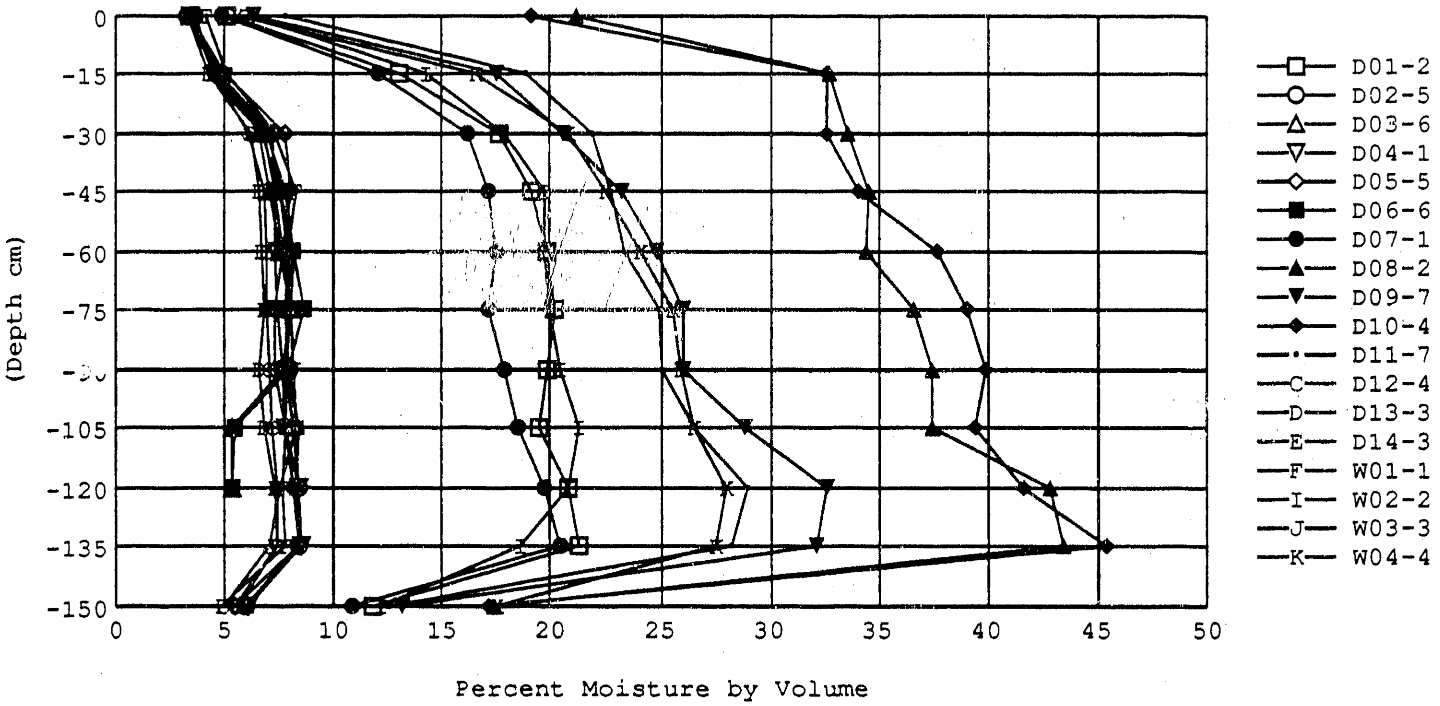
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Percent Moisture by Volume
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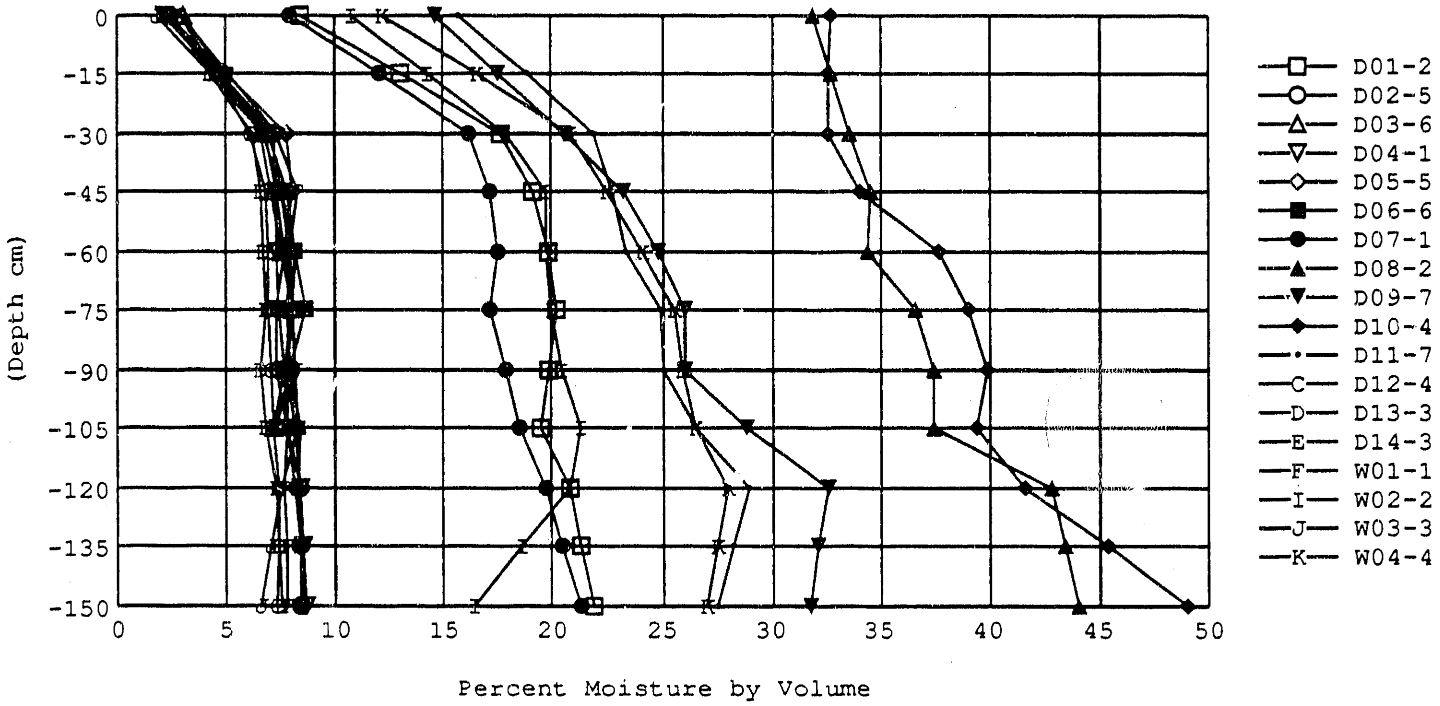
29 June 1989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Percent Moisture by Volume
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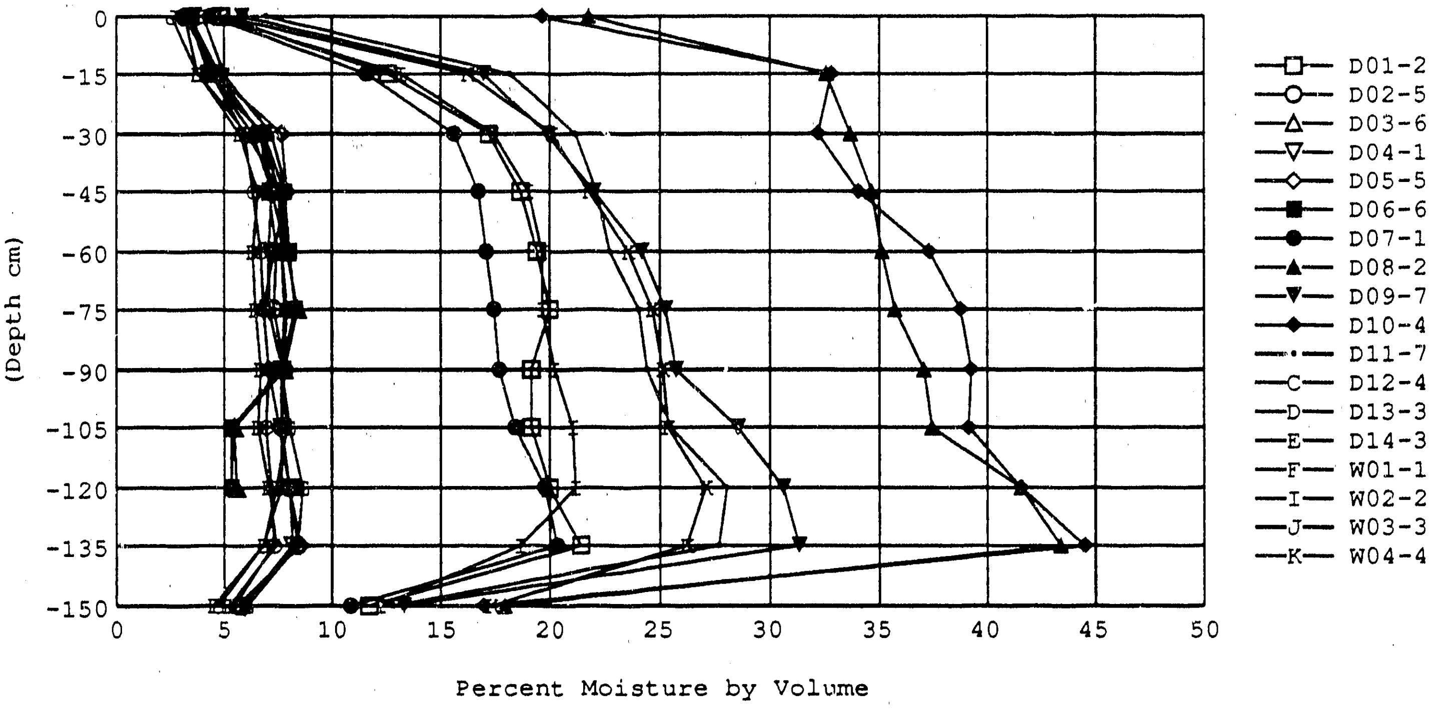
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Percent Moisture by Volume
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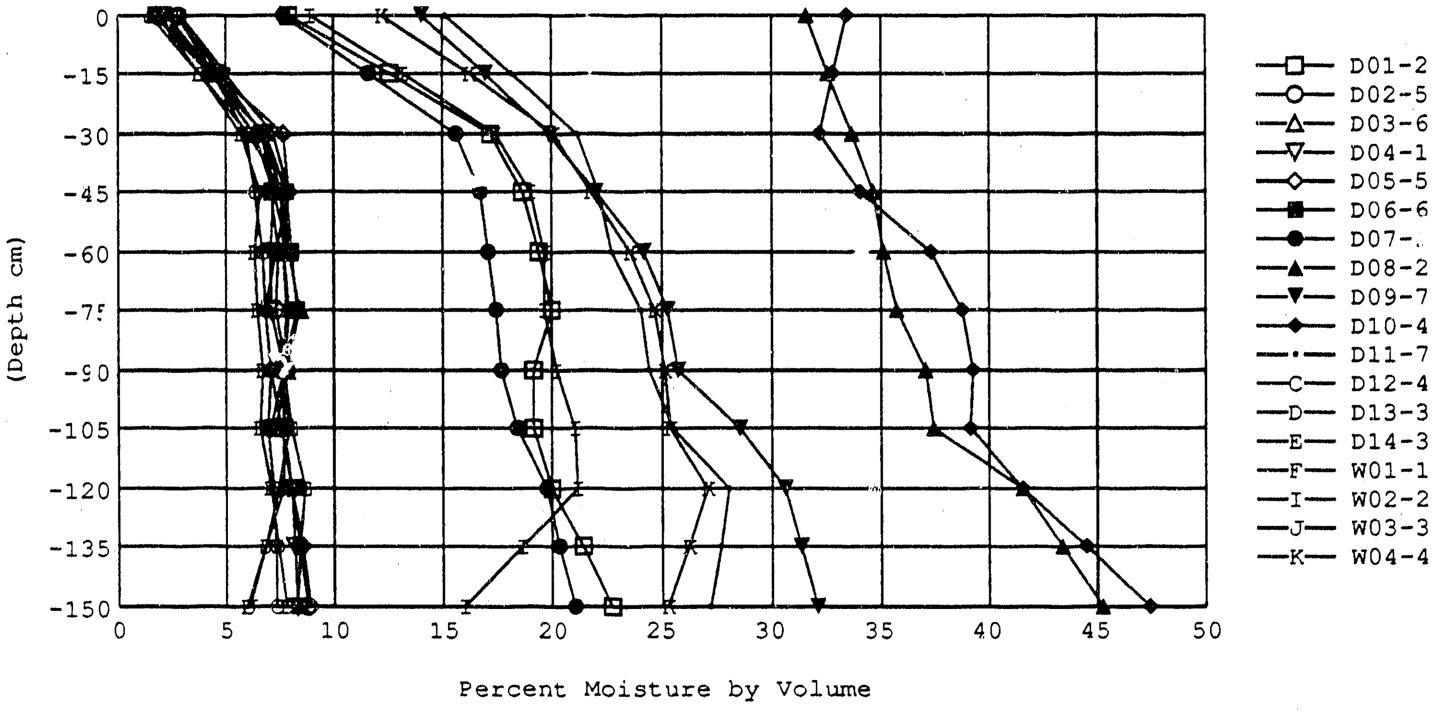
13 July 1989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Percent Moisture by Volume
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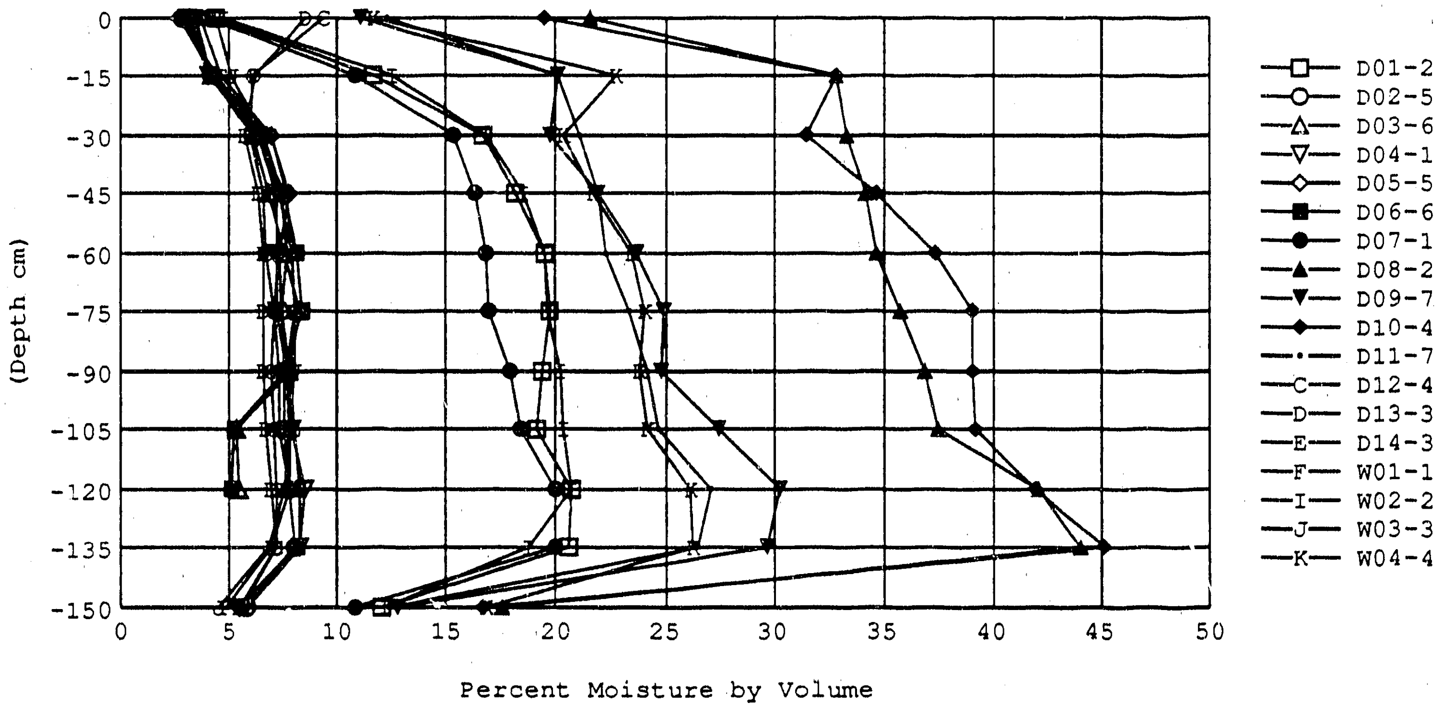

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Percent Moisture by Volume
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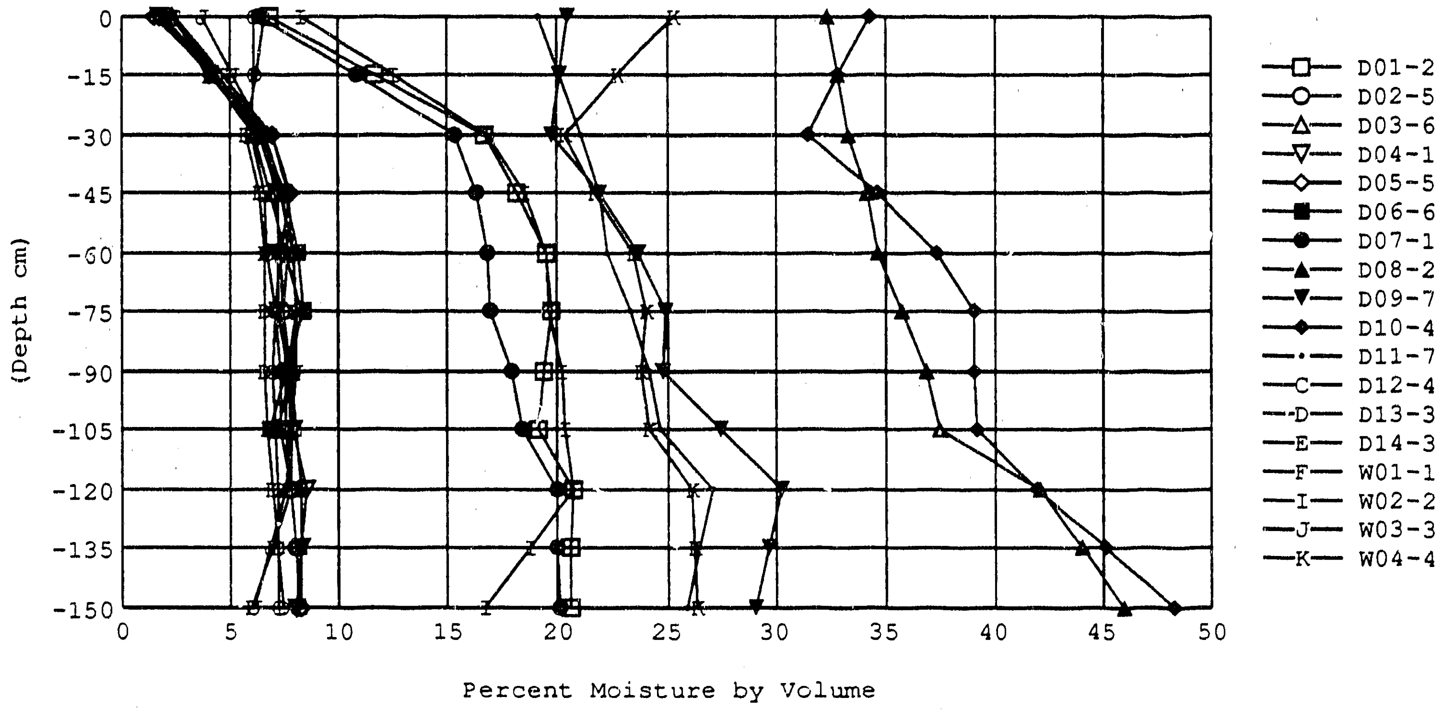
27 July 1989



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Percent Moisture by Volume
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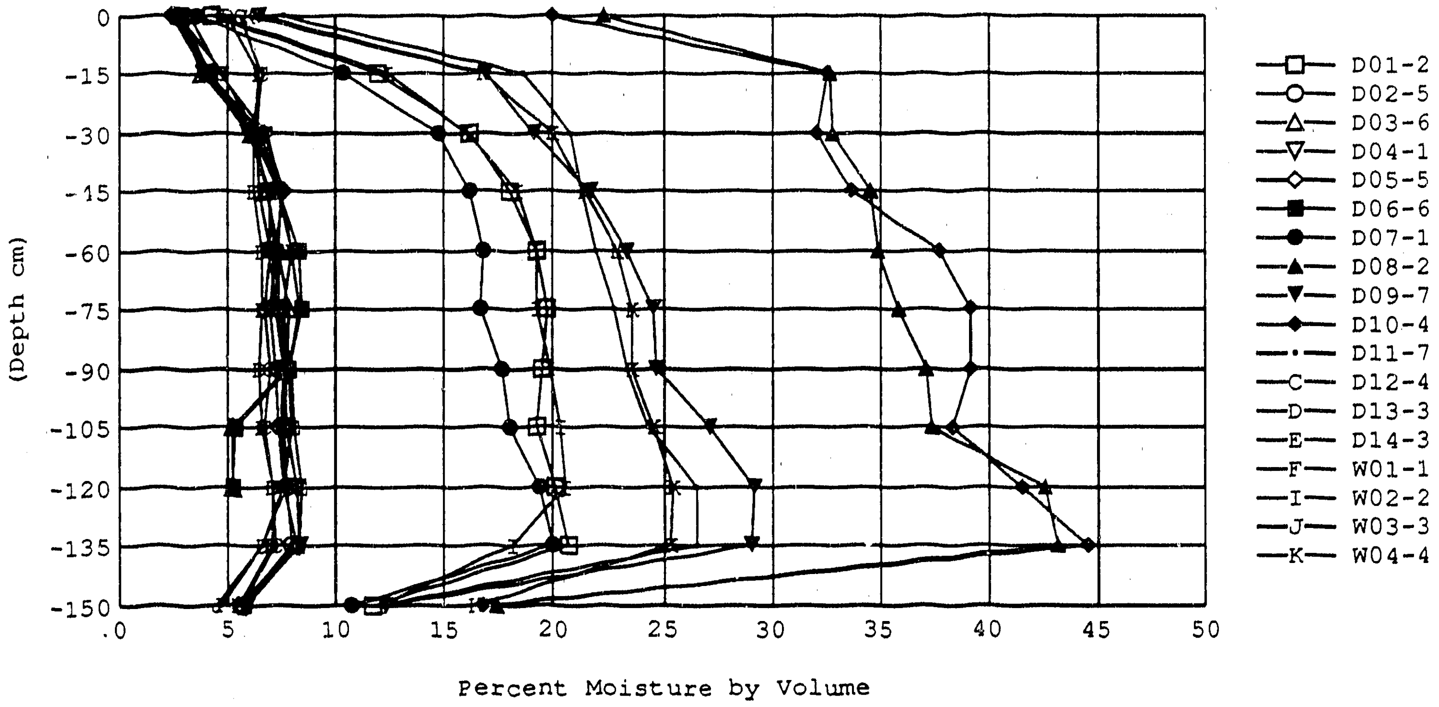
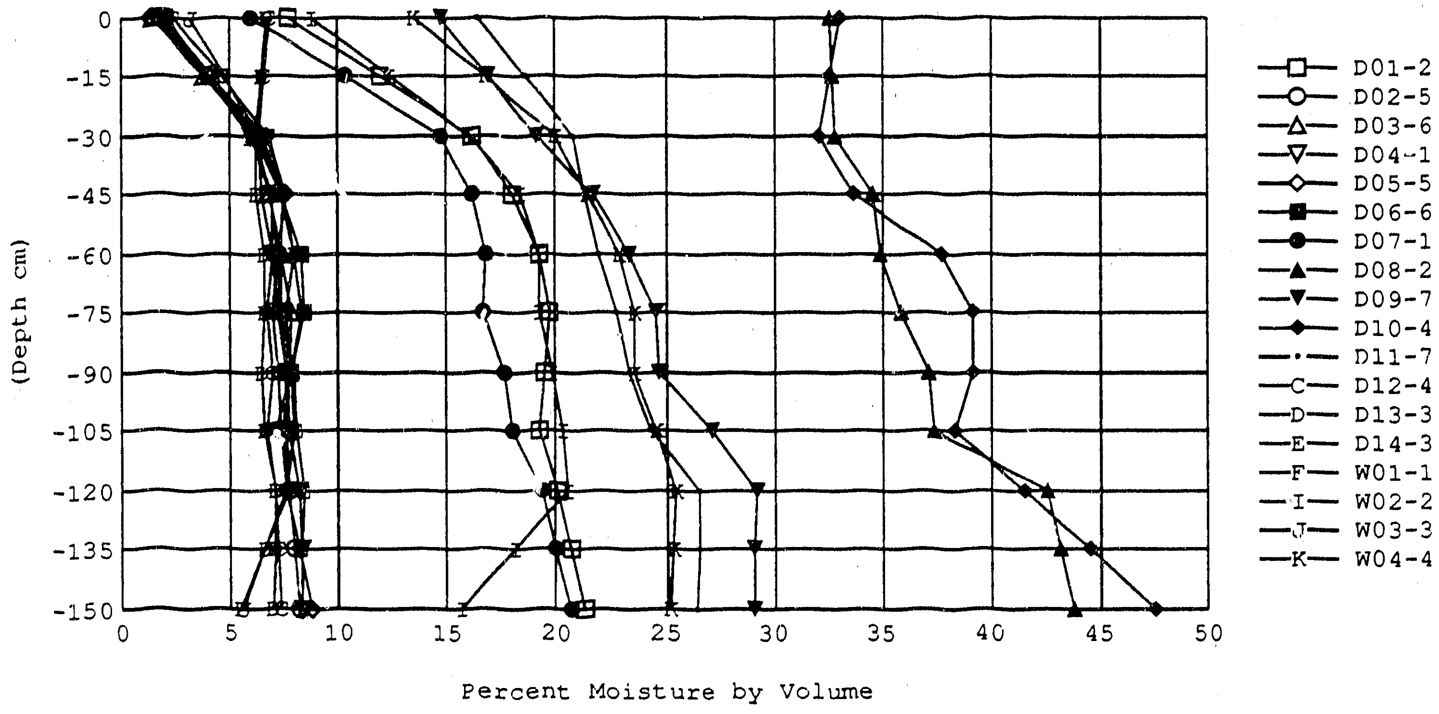
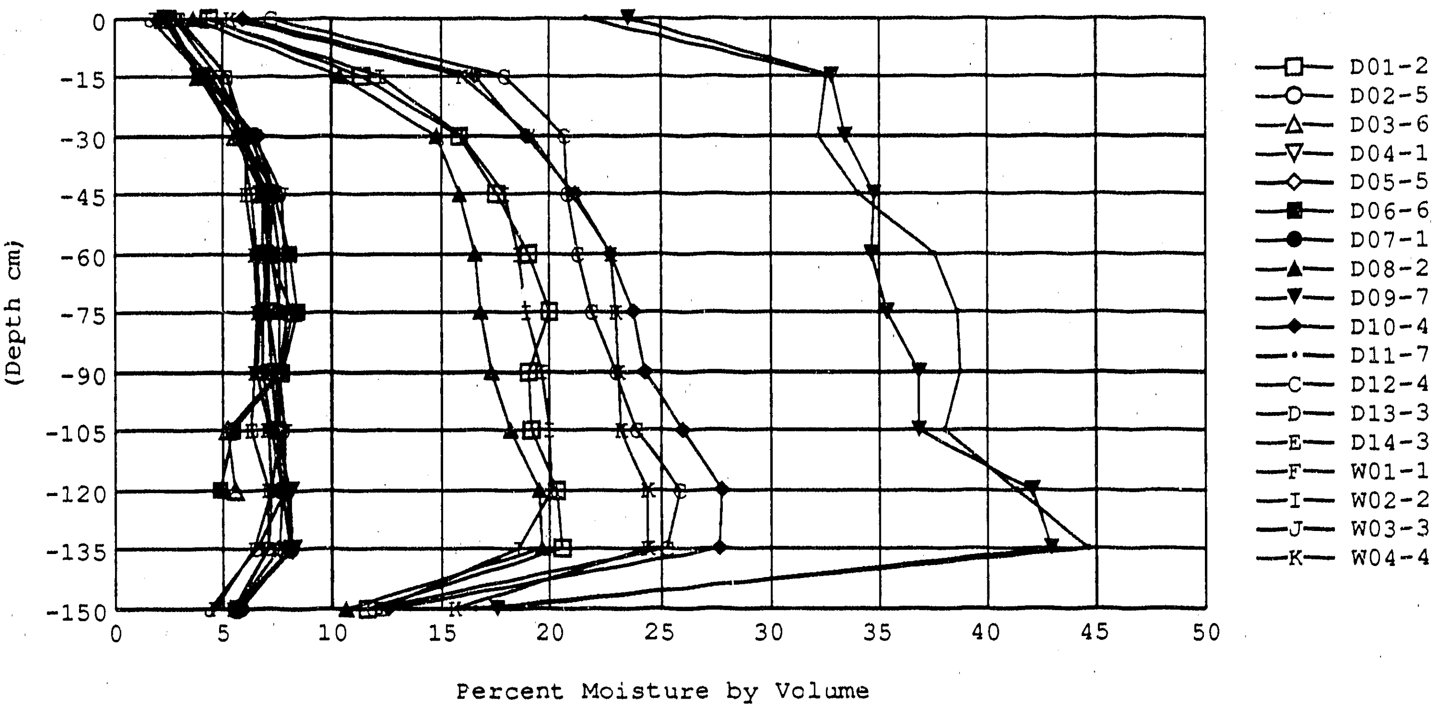
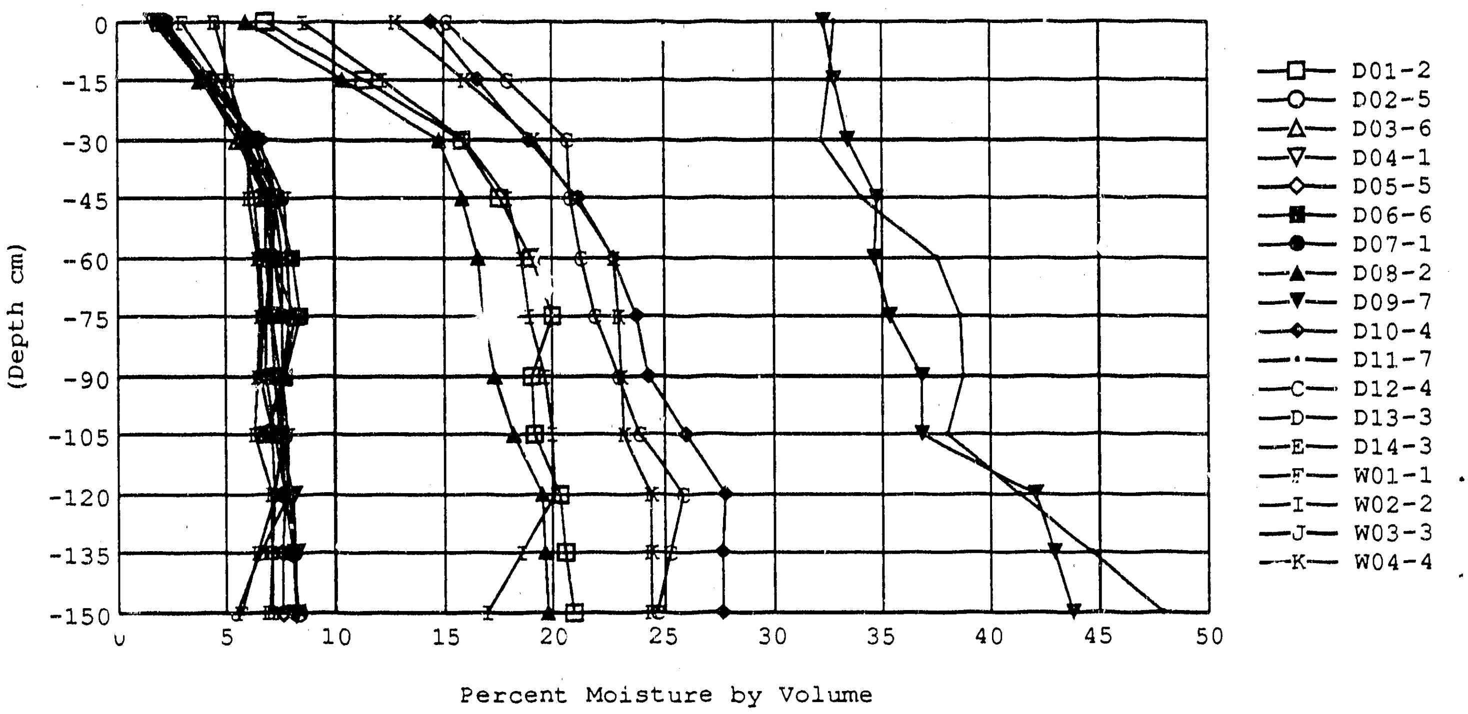


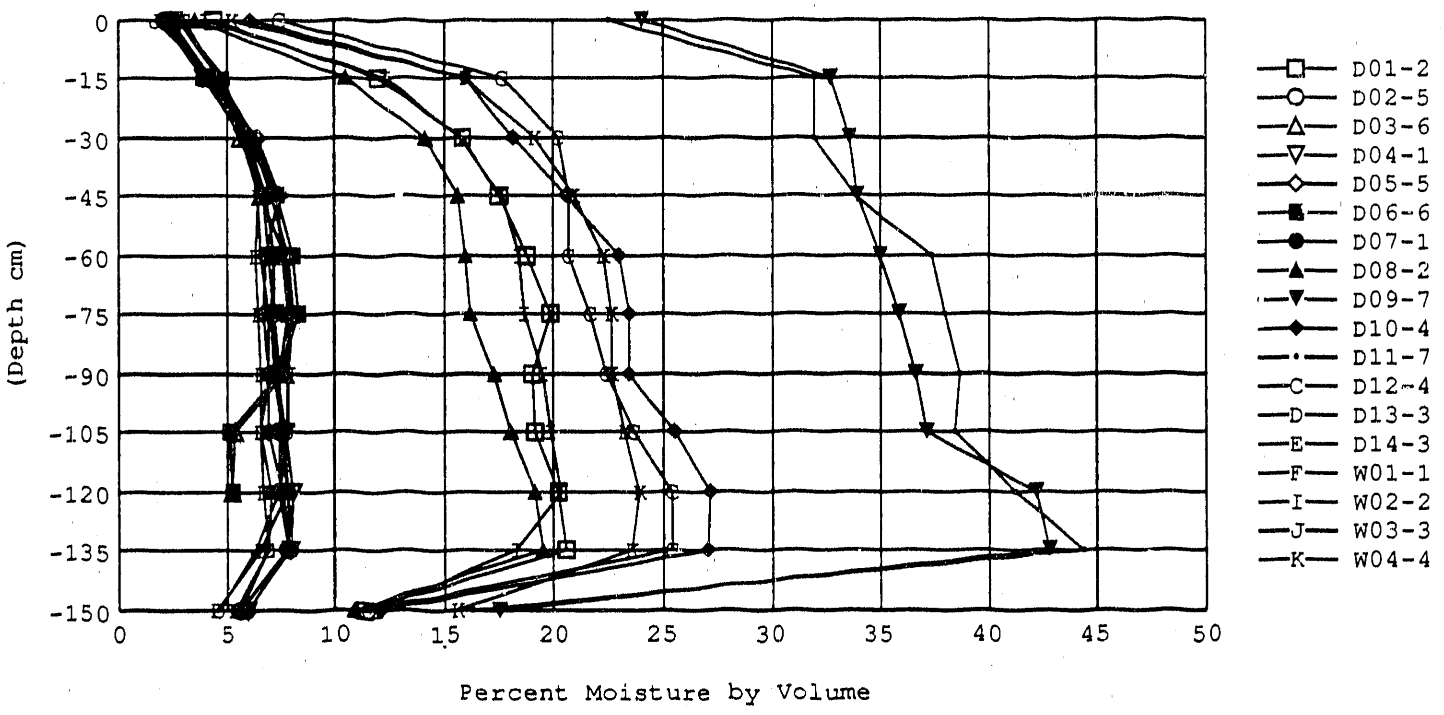
10 August 1989



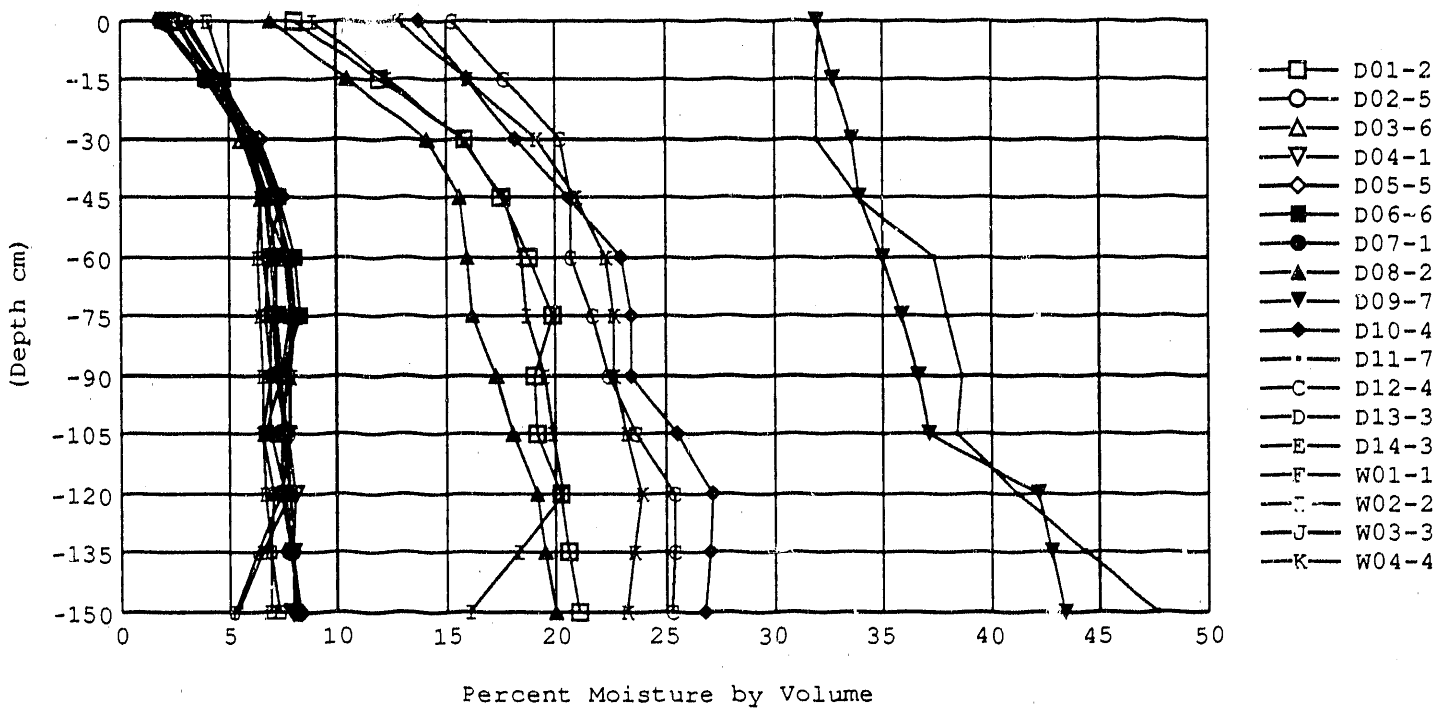


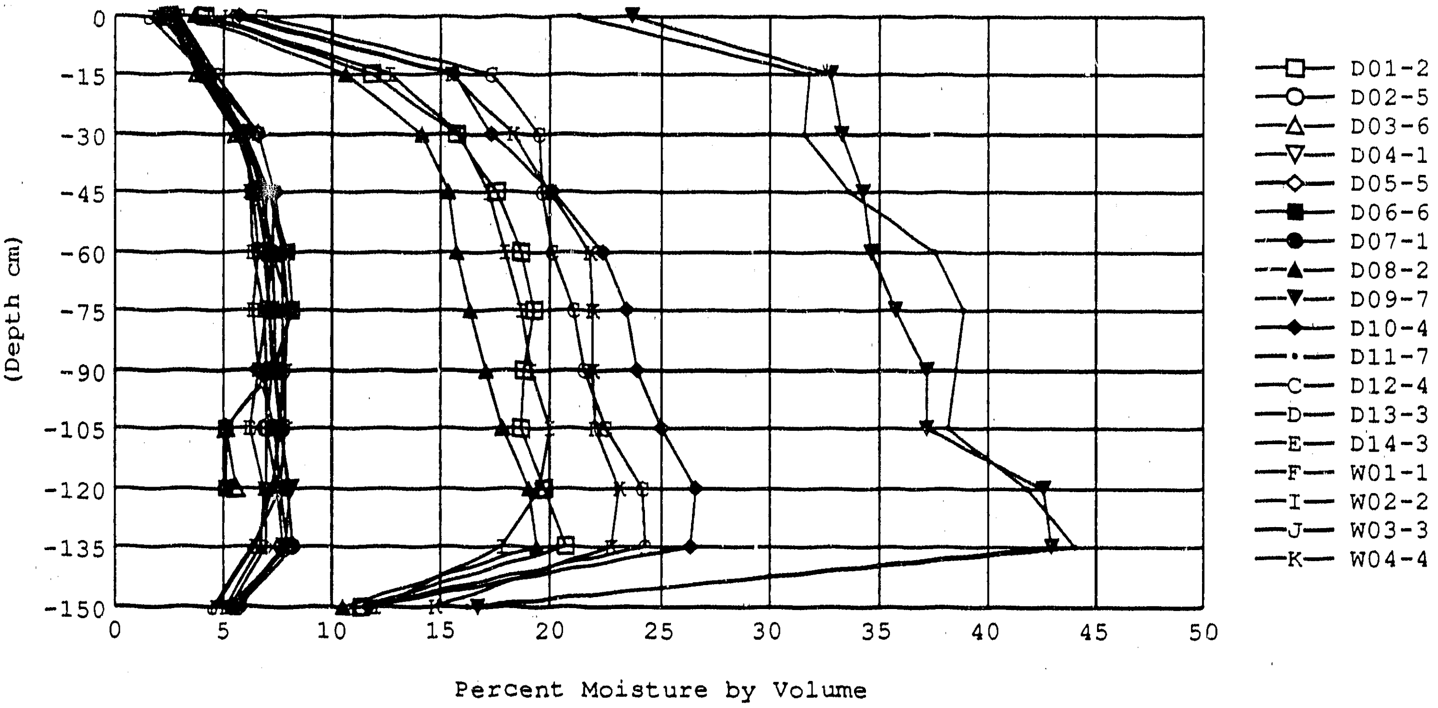
25 August 1989



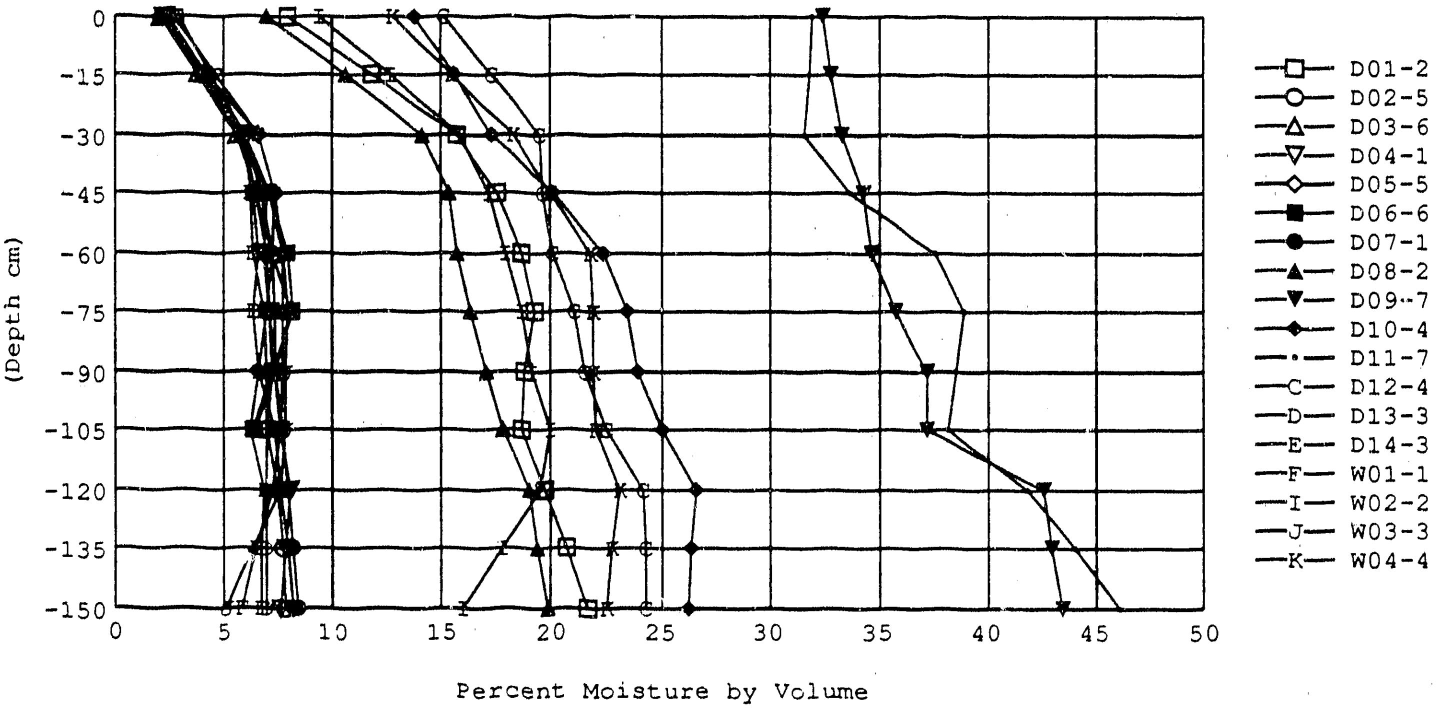


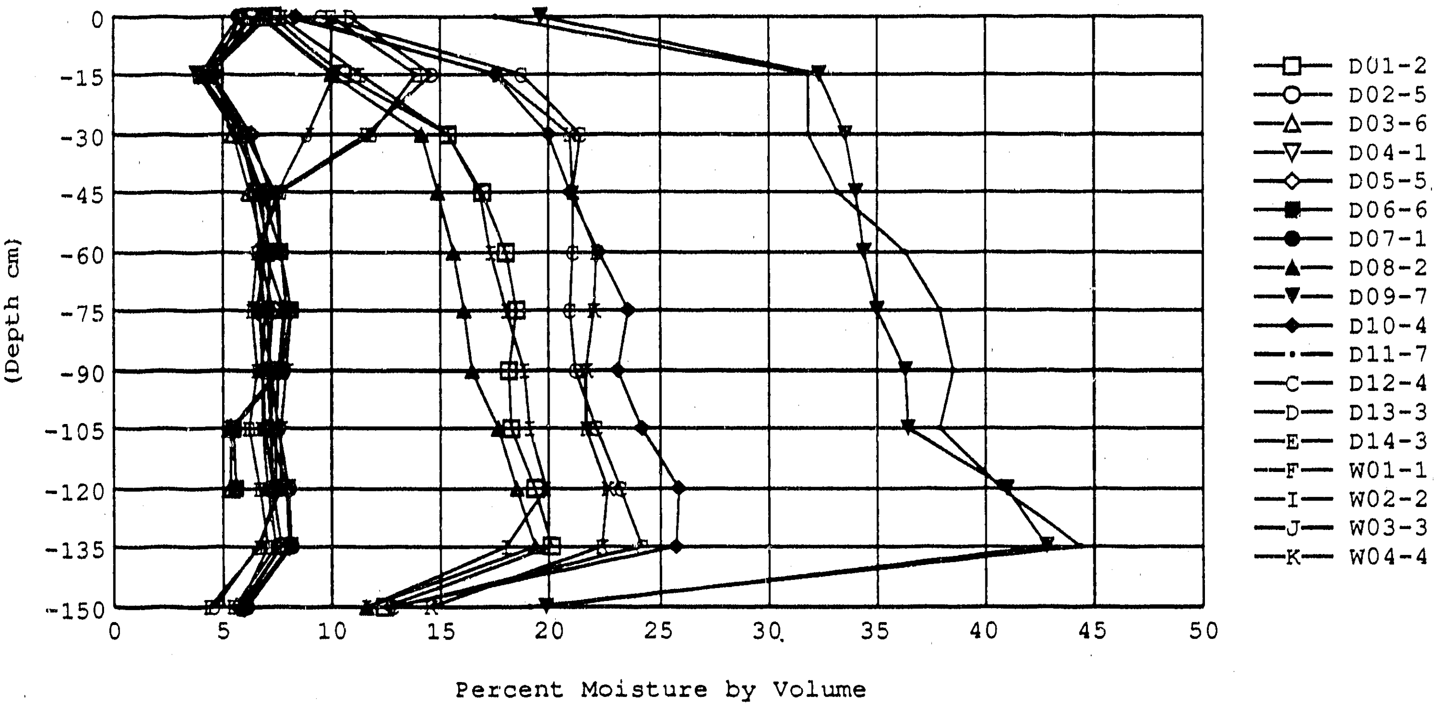
7 September 1989



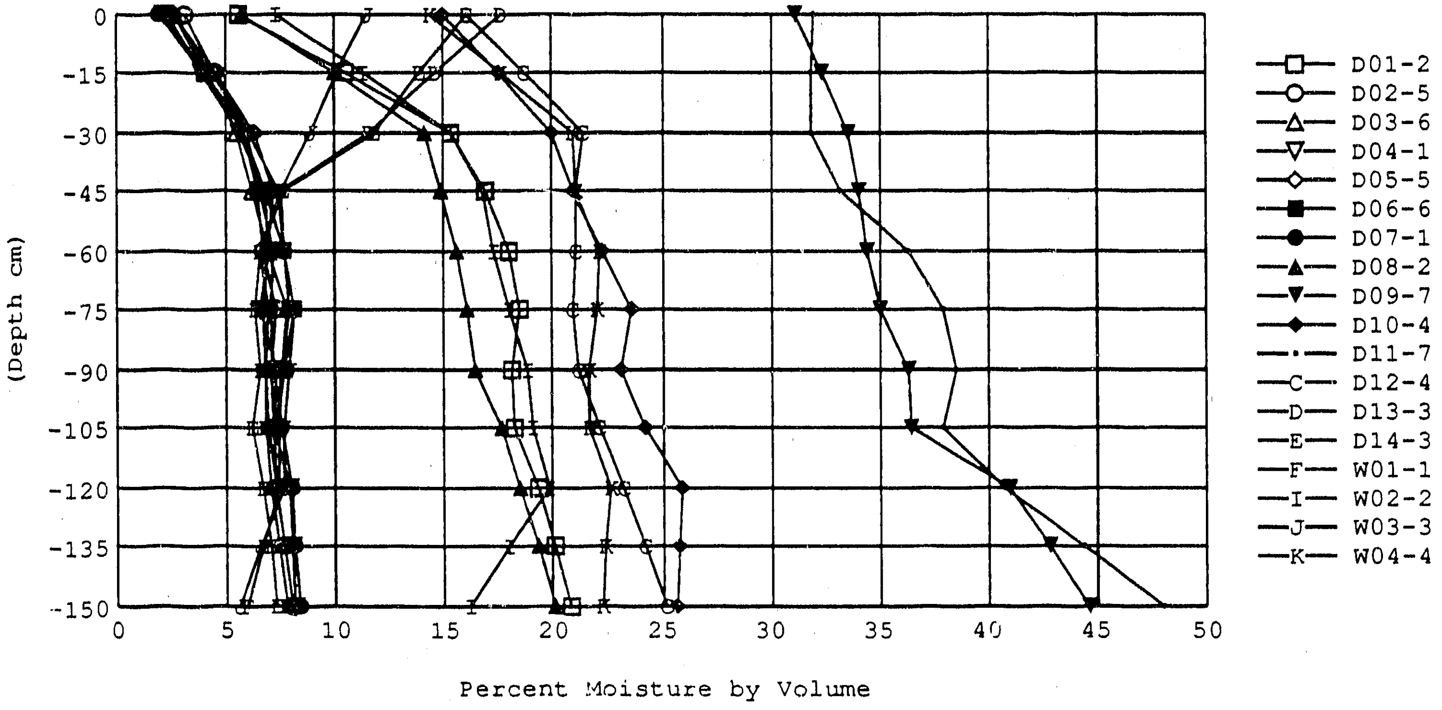


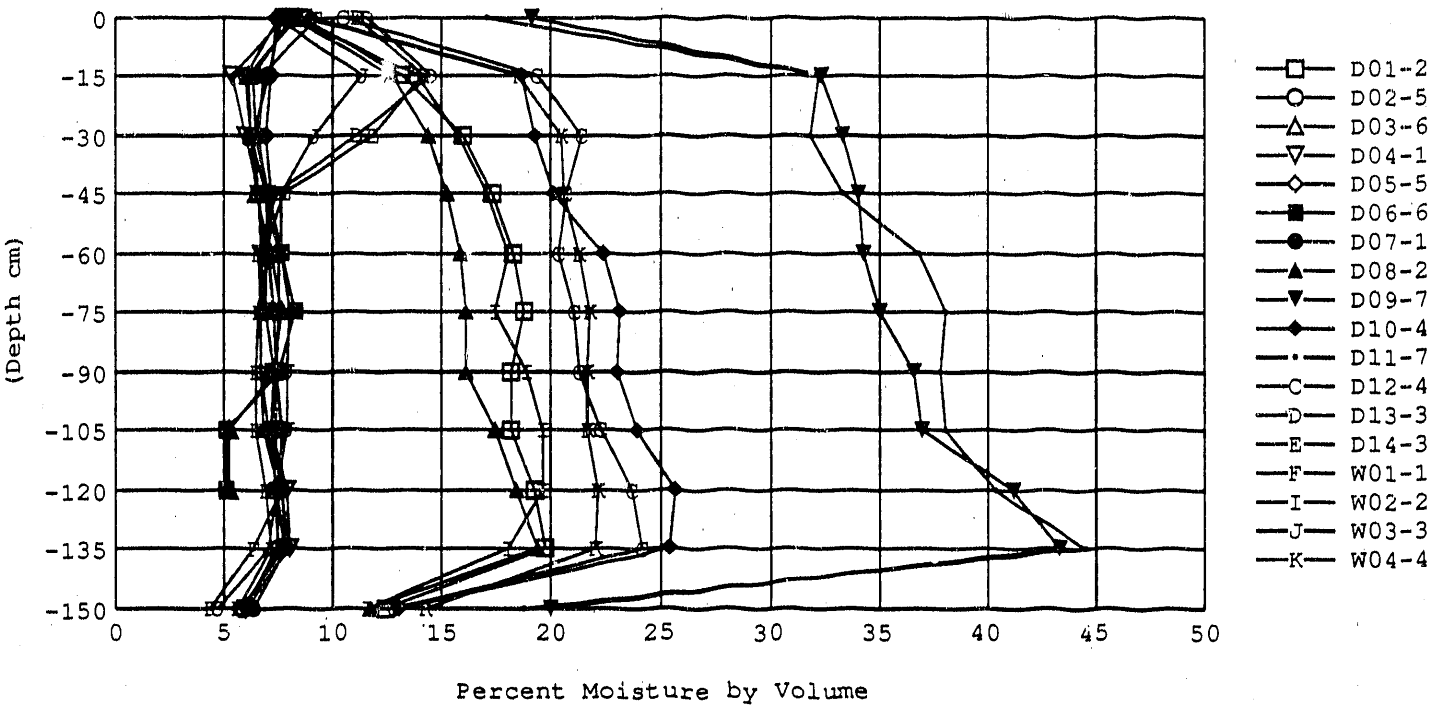
27 September 1989



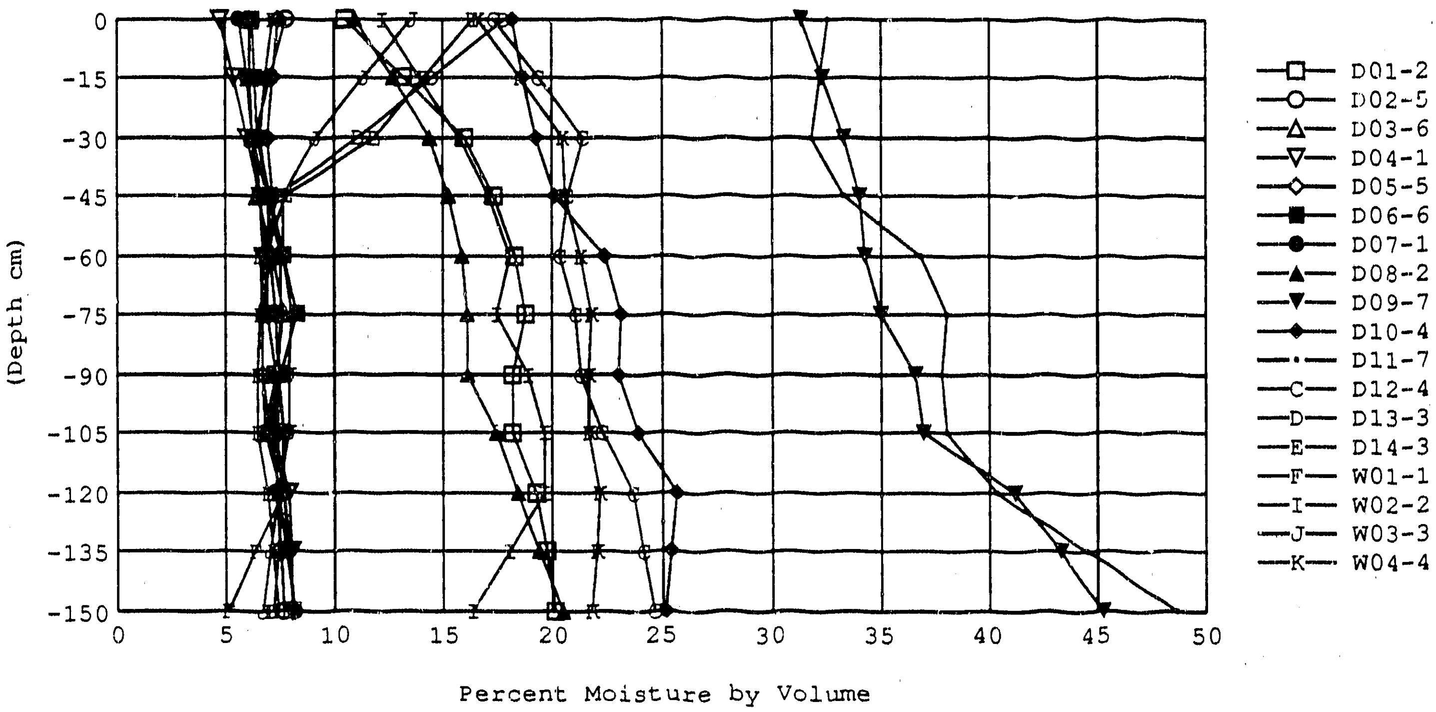


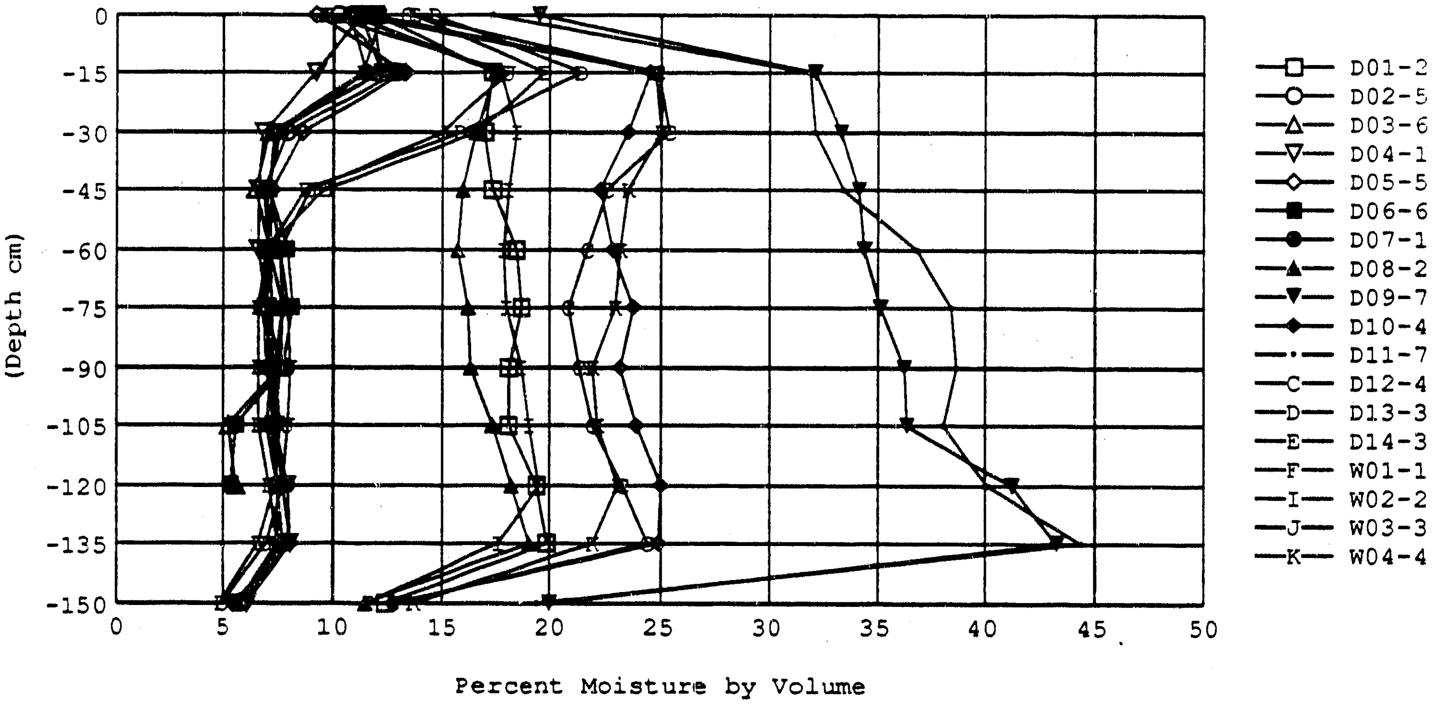
31 October 1989



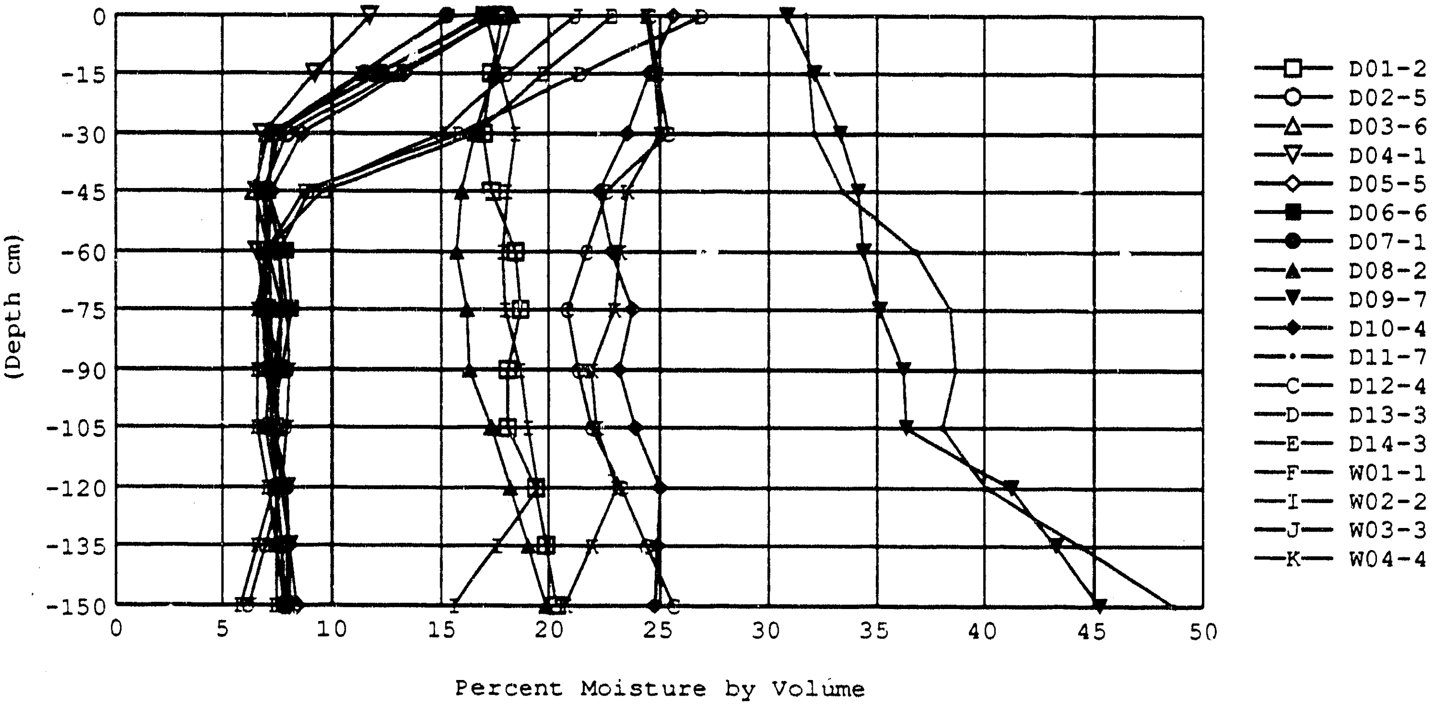


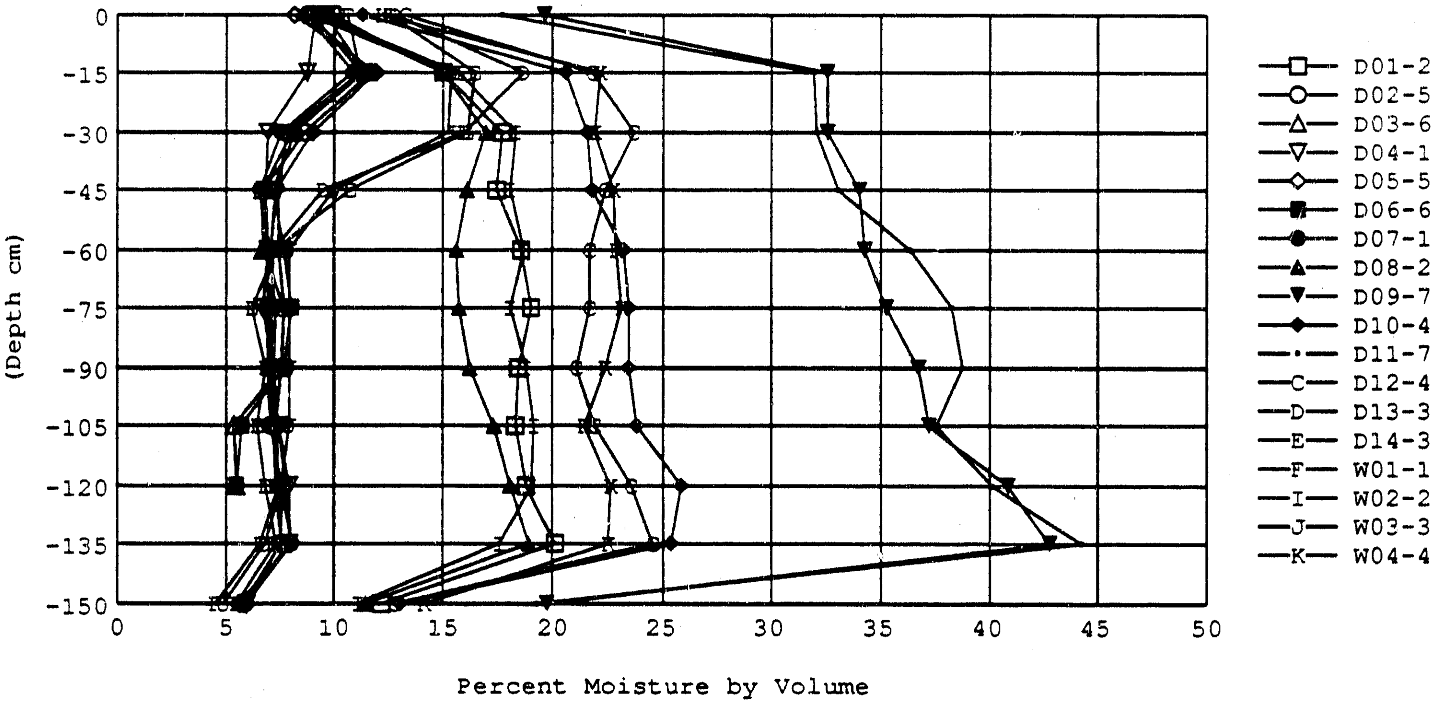
15 November 1989



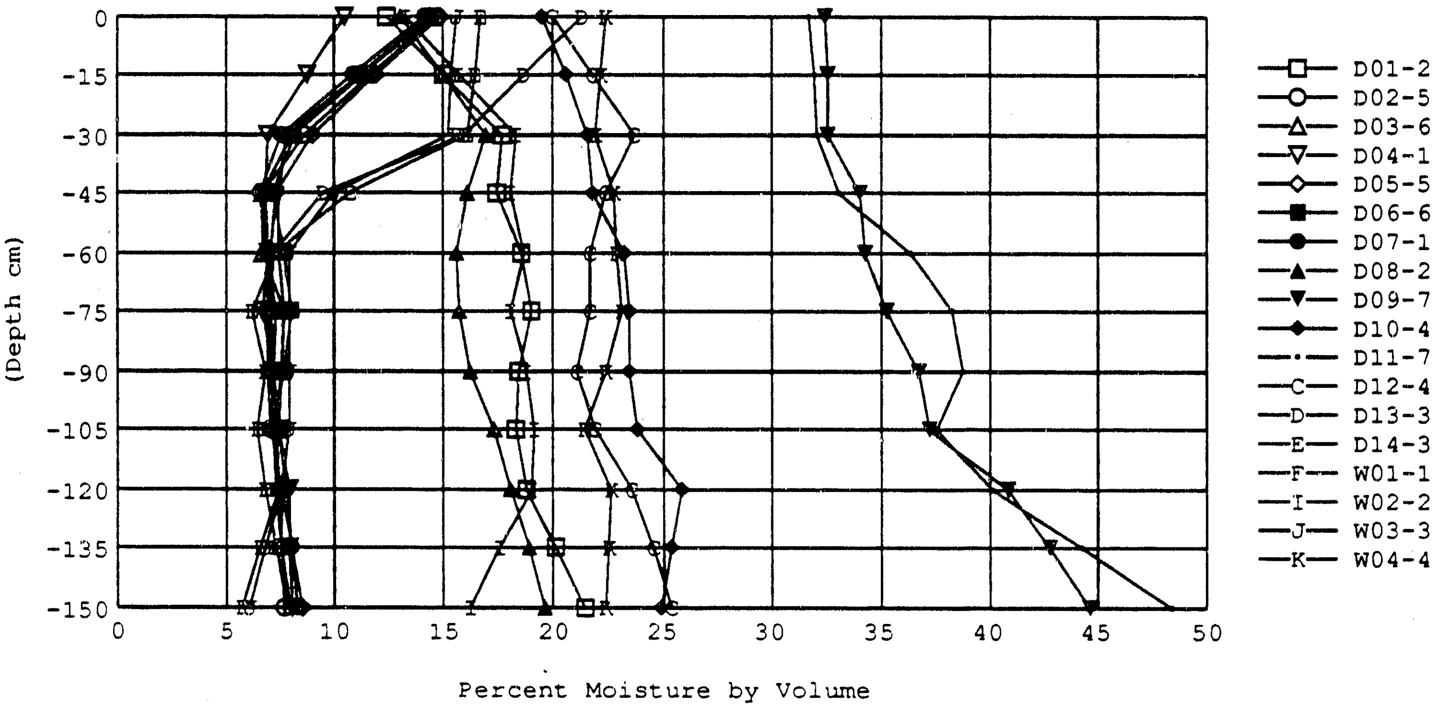


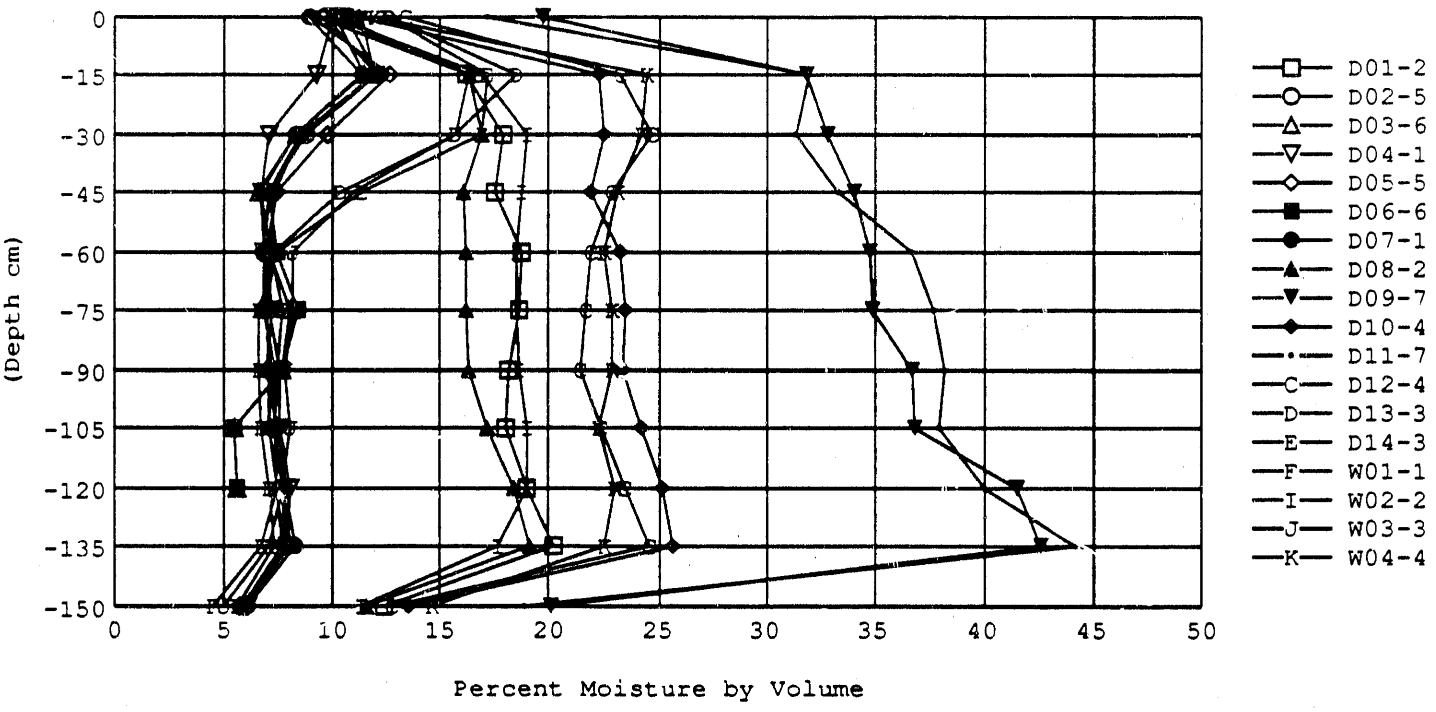
6 December 1989



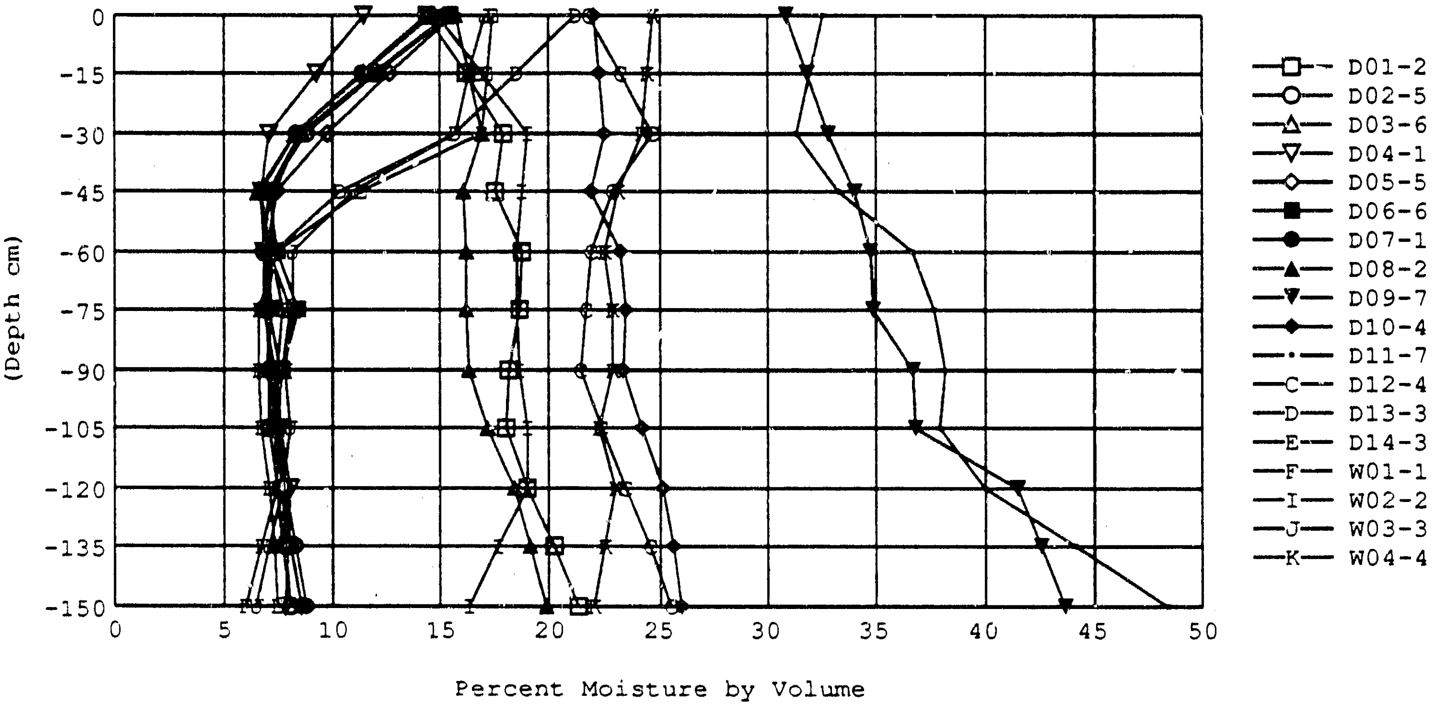


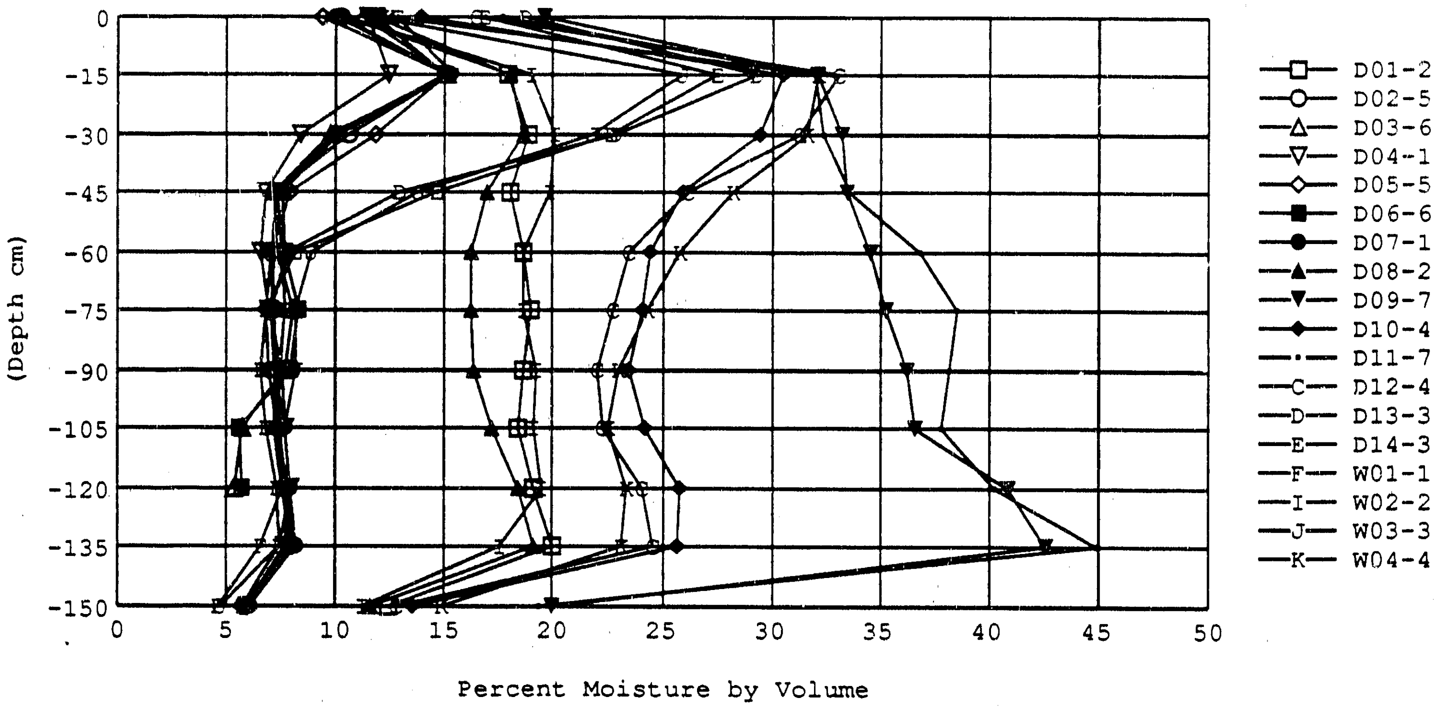
19 December 1989



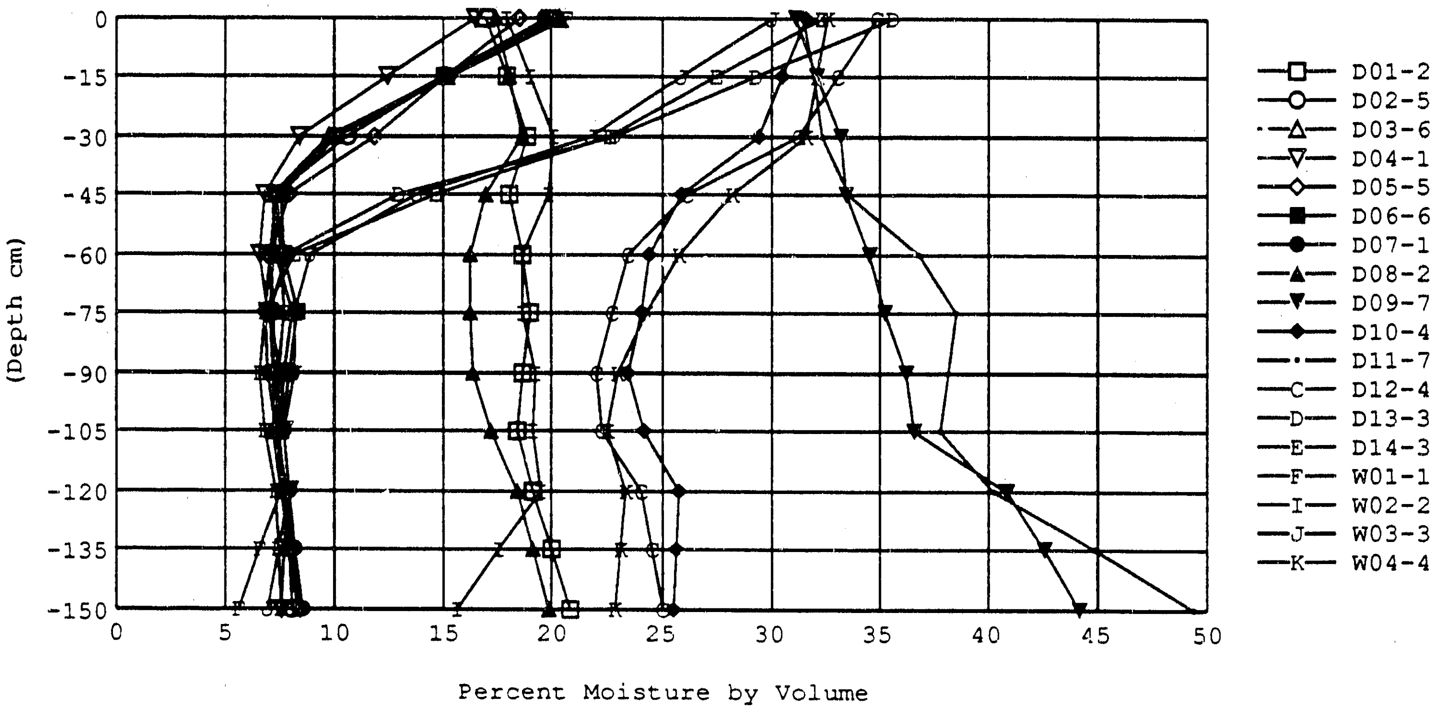


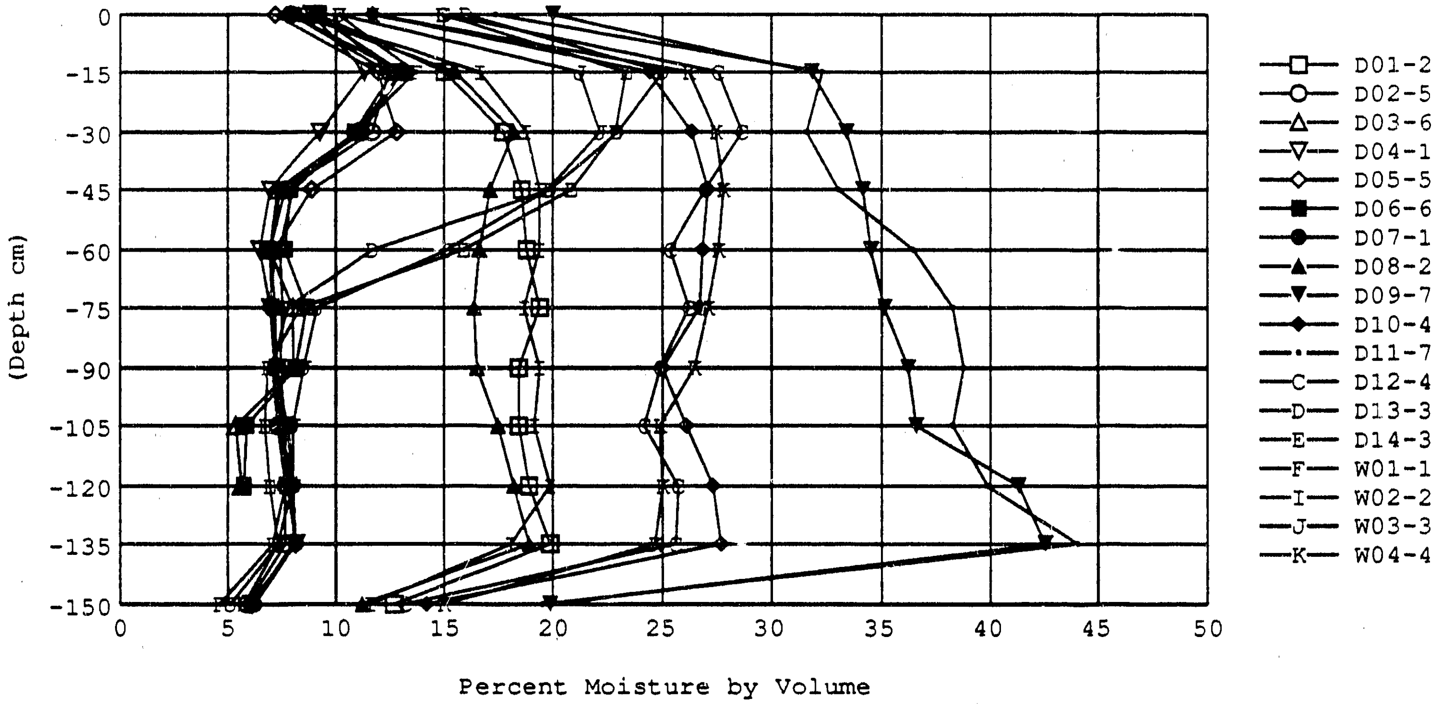
2 January 1990



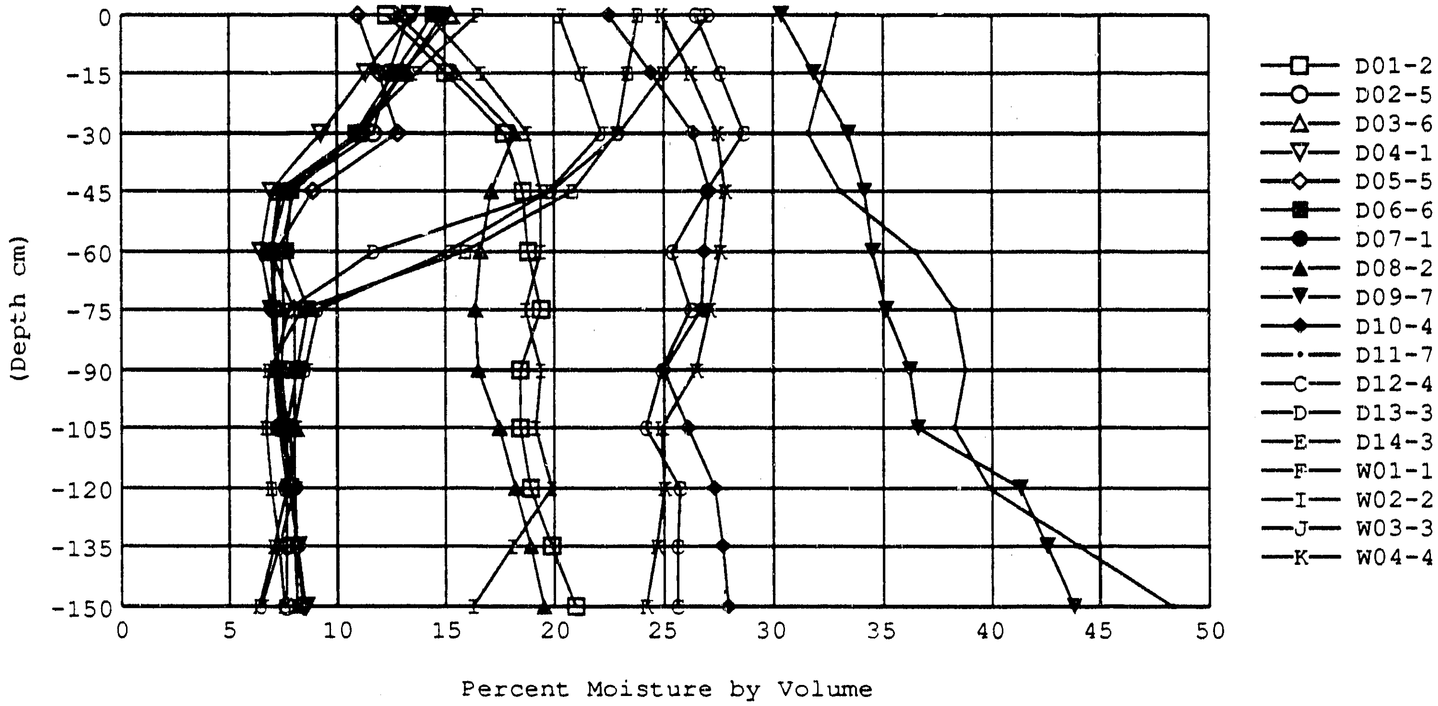


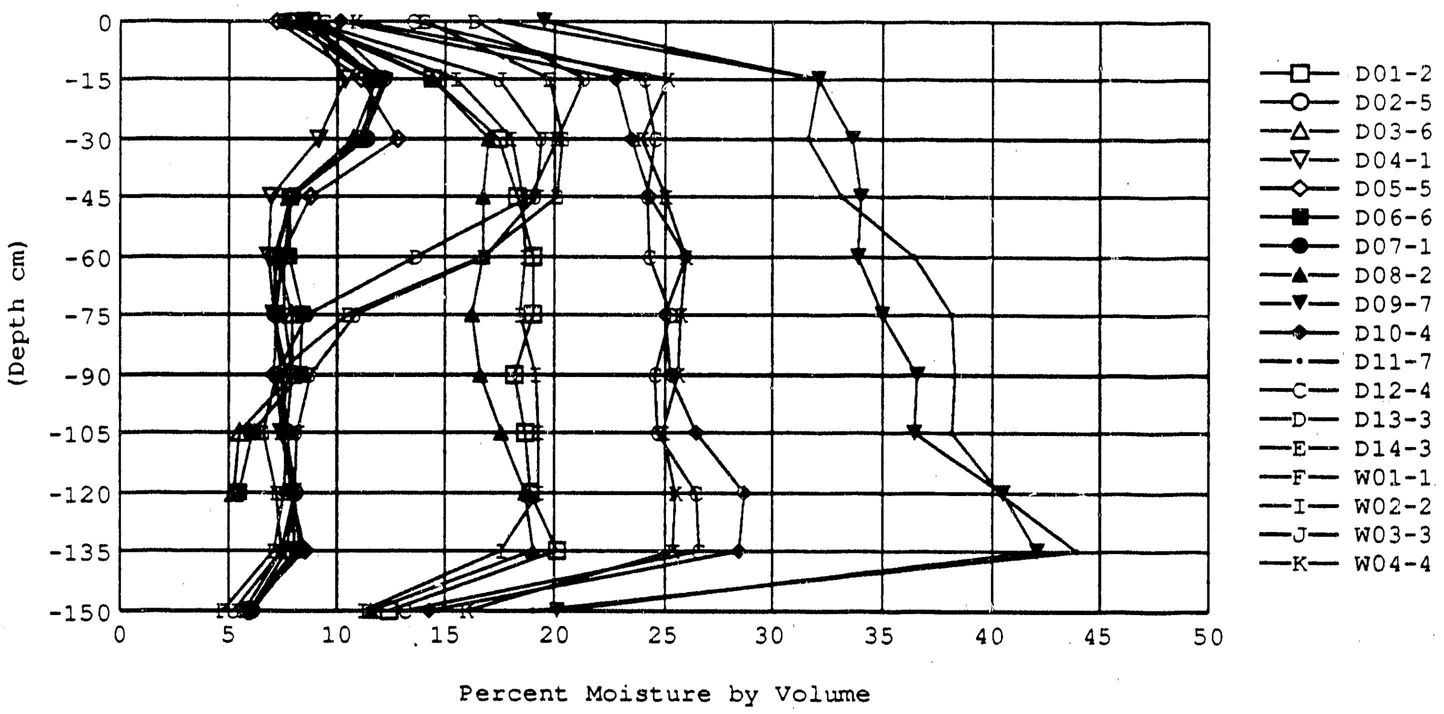
16 January 1990



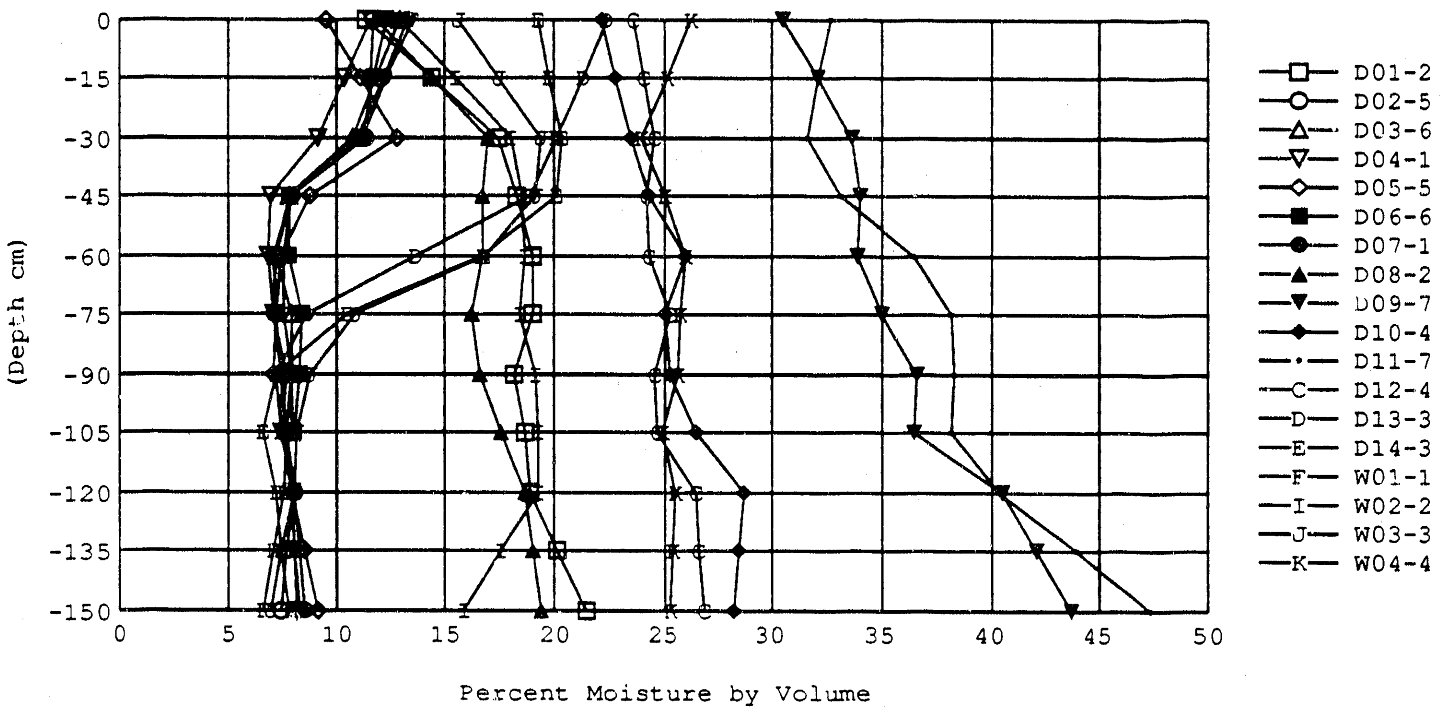


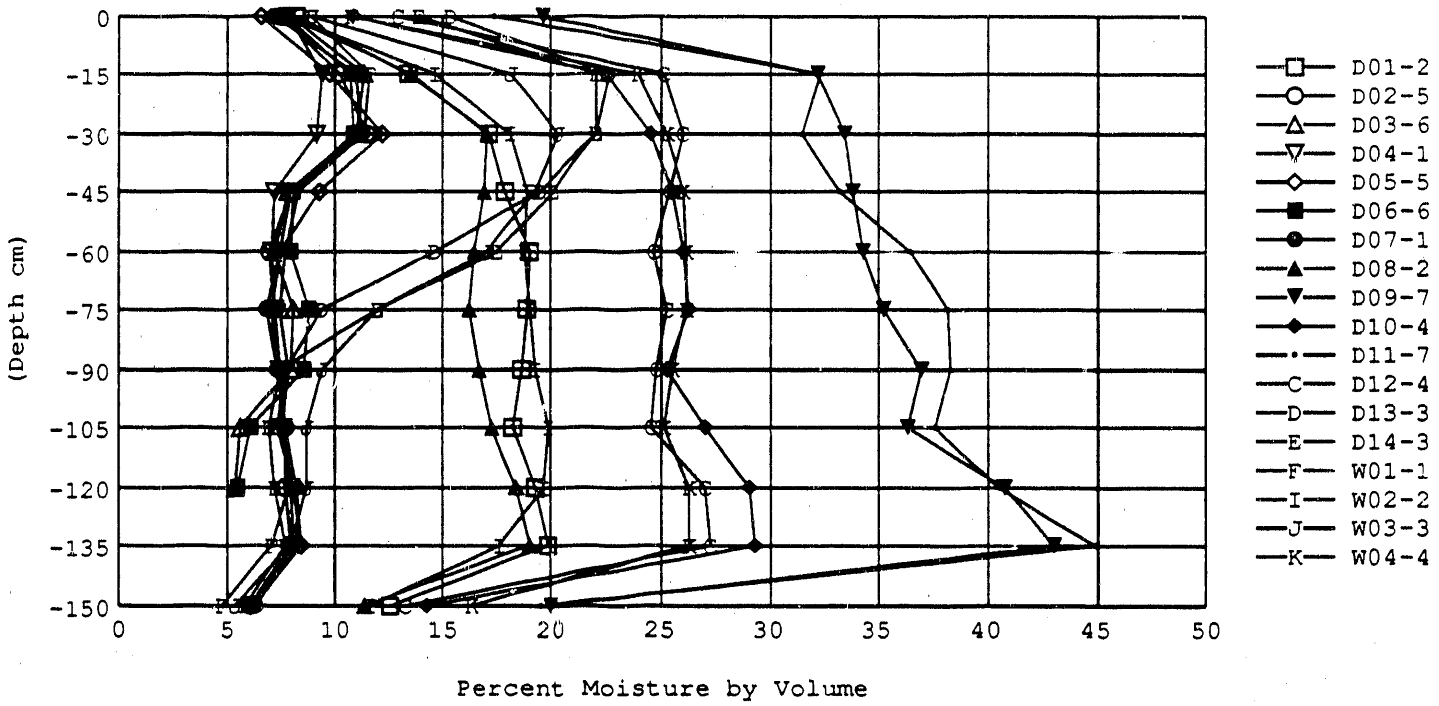
8 February 1990





21 February 1990

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Percent Moisture by Volume
D01-2
D02-5
D03-6
D04-1
D05-5
D06-6
D07-1
D08-2
D09-7
D10-4
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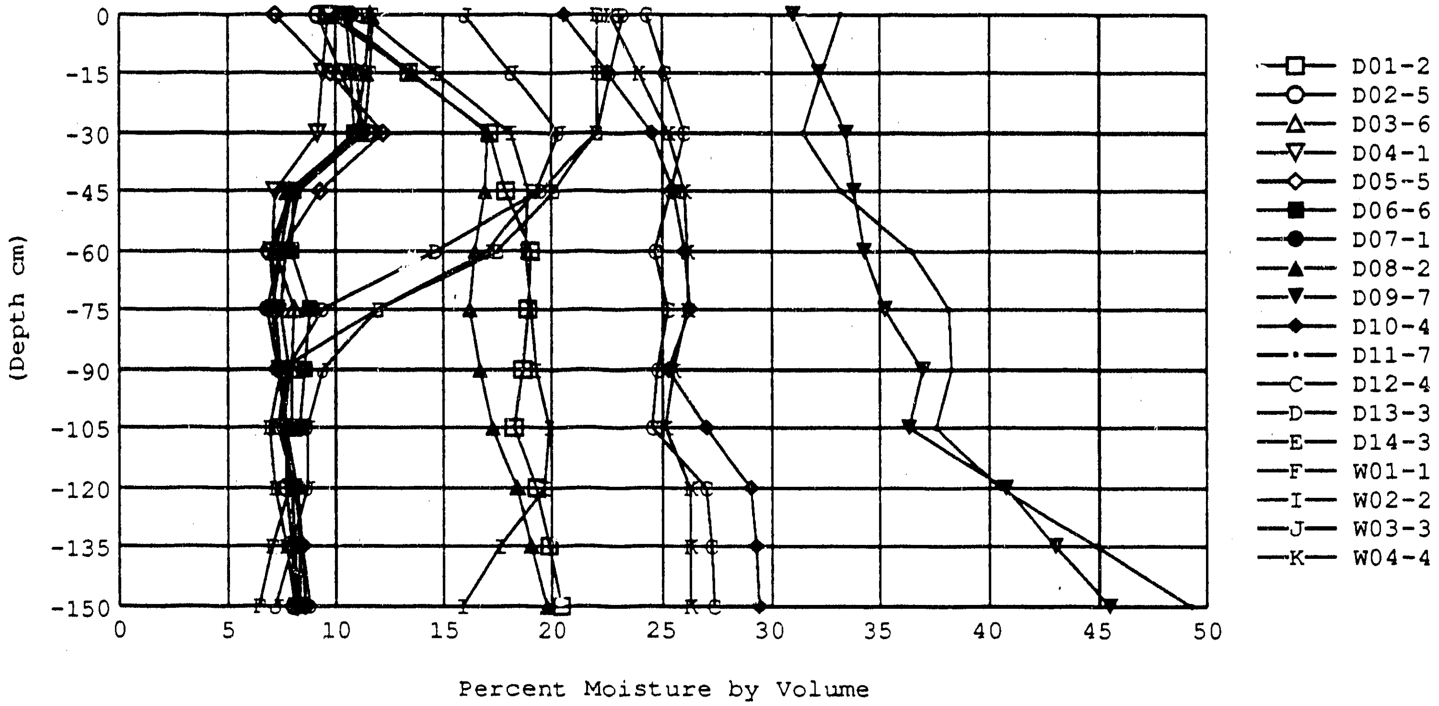
C D12-4
D D13-3
E D14-3
F W01-1
I W02-2
J W03-3
K W04-4

6 March 1990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Percent Moisture by Volume
D01-2
D02-5
D03-6
D04-1
D05-5
D06-6
D07-1
D08-2
D09-7
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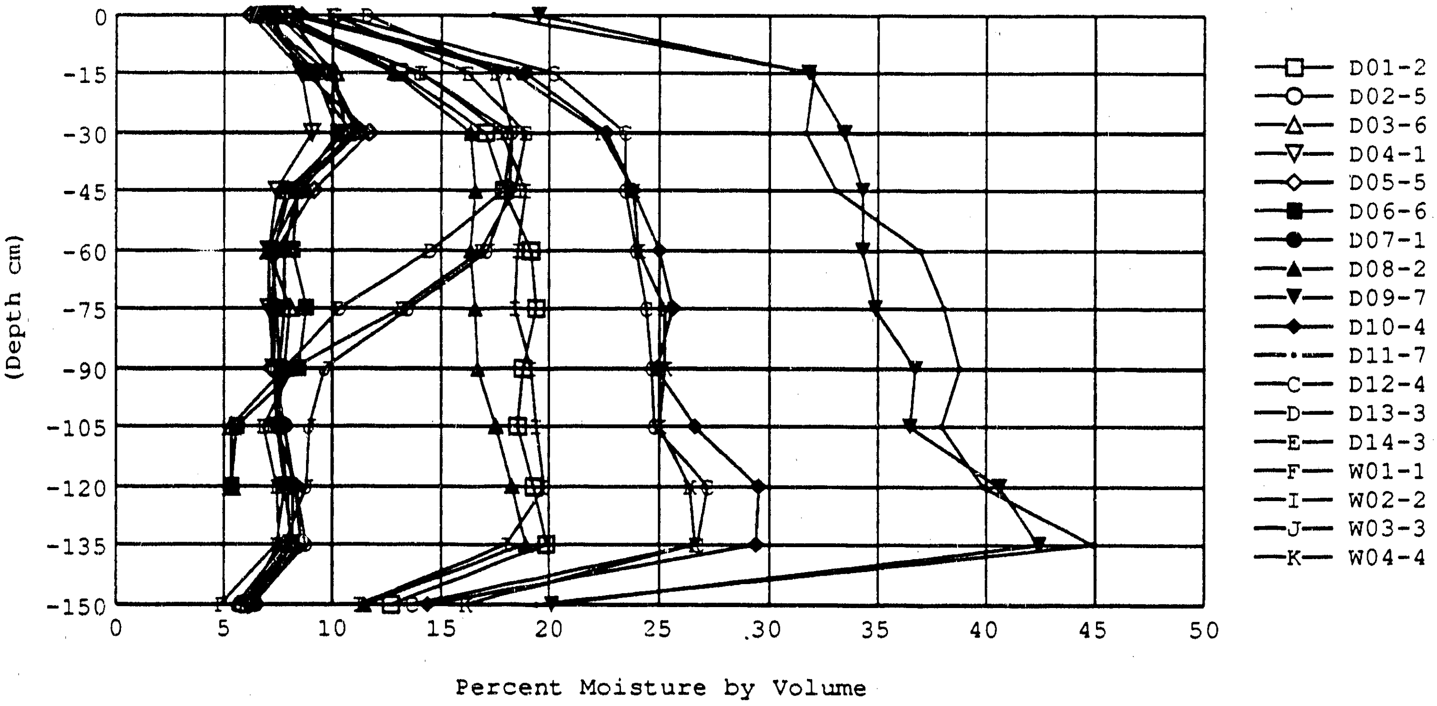
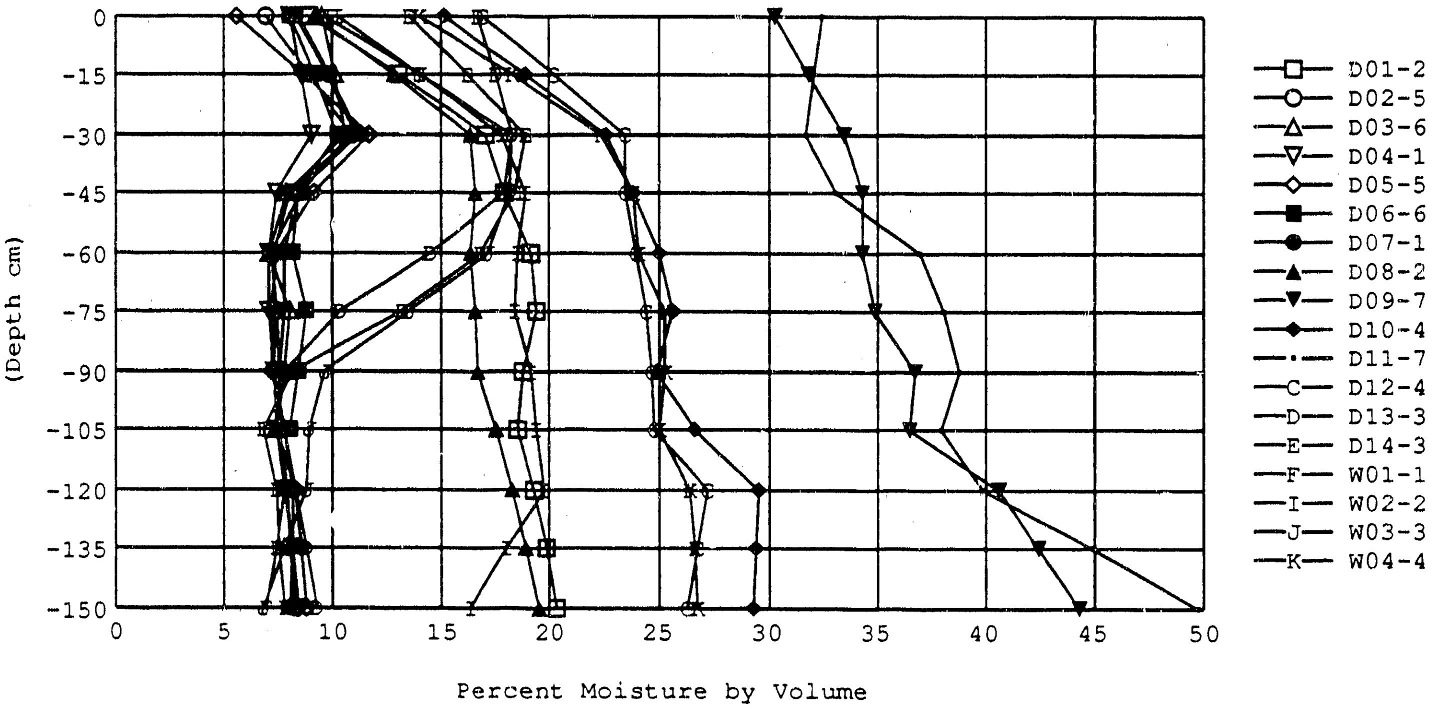
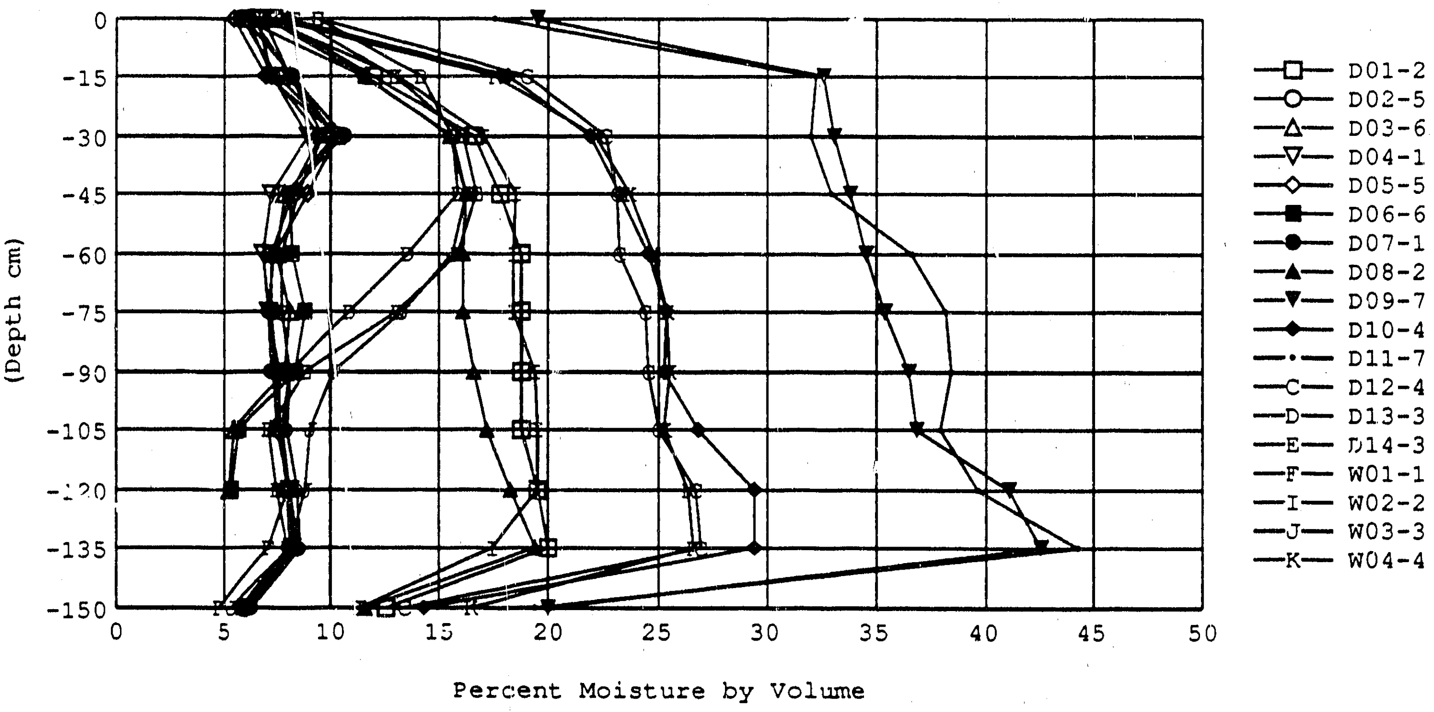
J W03-3
K W04-4



20 March 1990

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Percent Moisture by Volume
D01-2
D02-5
D03-6
D04-1
D05-5
D06-6
D07-1
D08-2
D09-7
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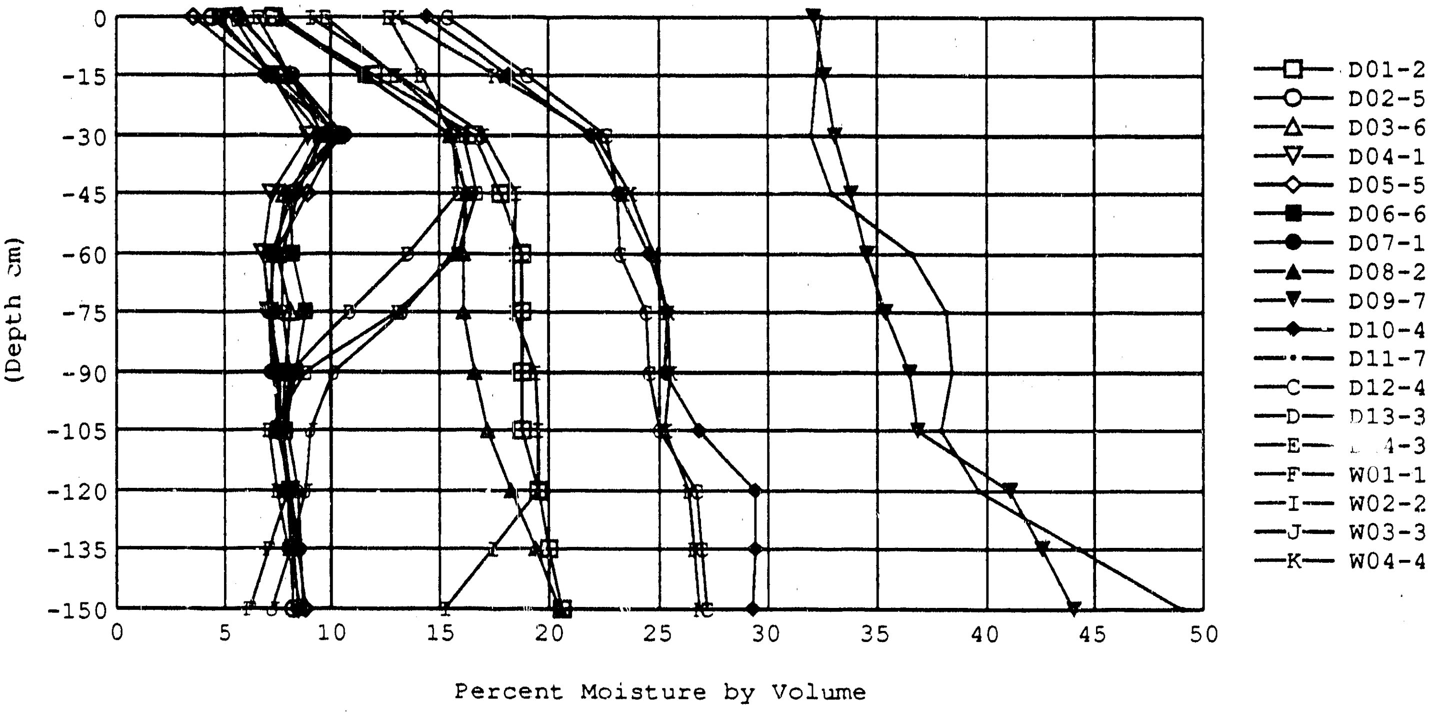
D13-3
D14-3
W01-1
W02-2
W03-3
W04-4

3 April 1990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Percent Moisture by Volume
D01-2
D02-5
D03-6
D04-1
D05-5
D06-6
D07-1
D08-2
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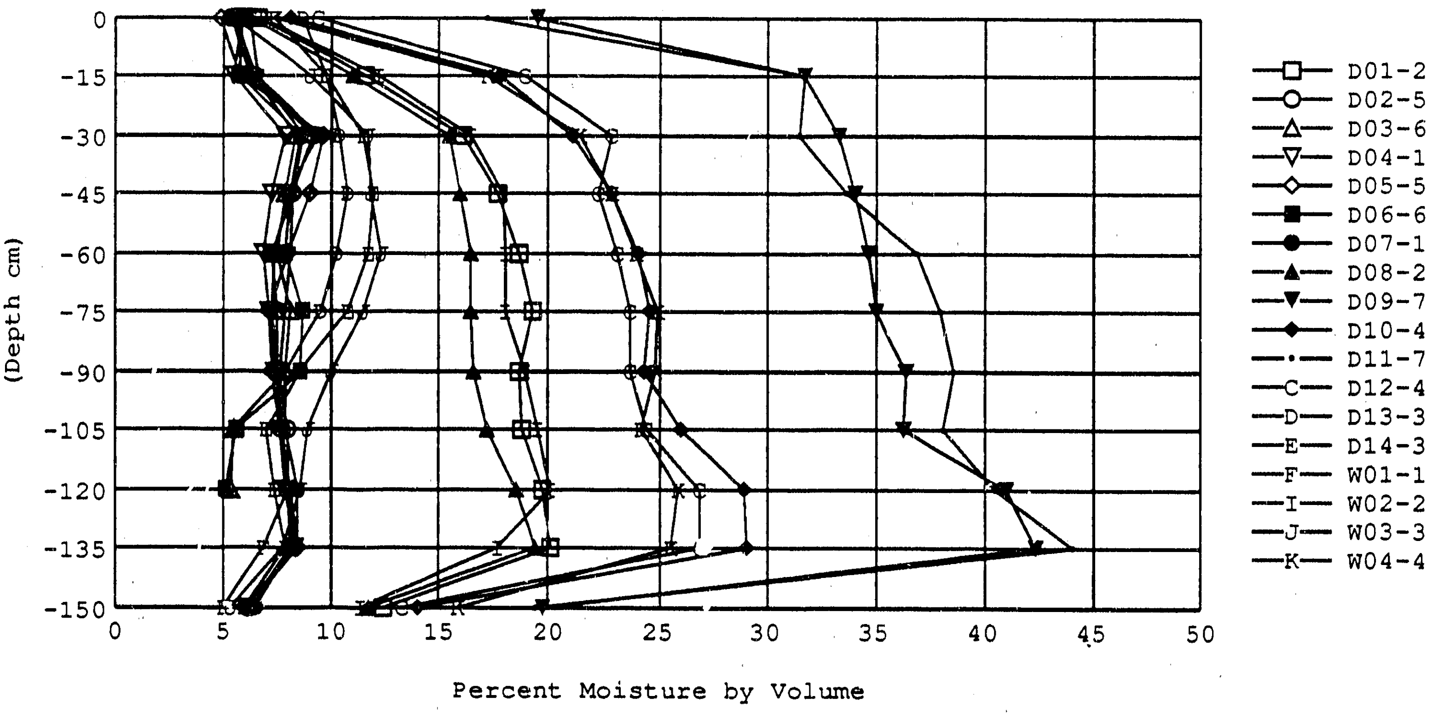
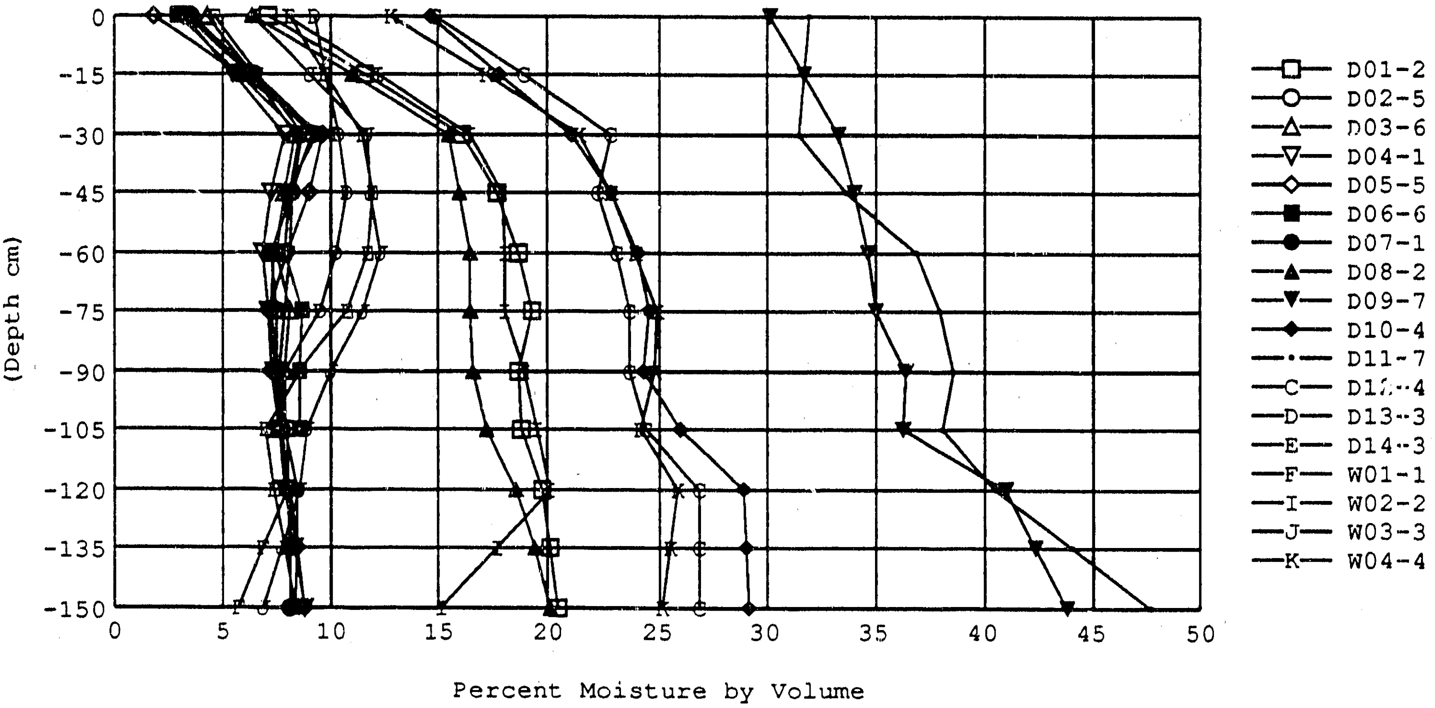
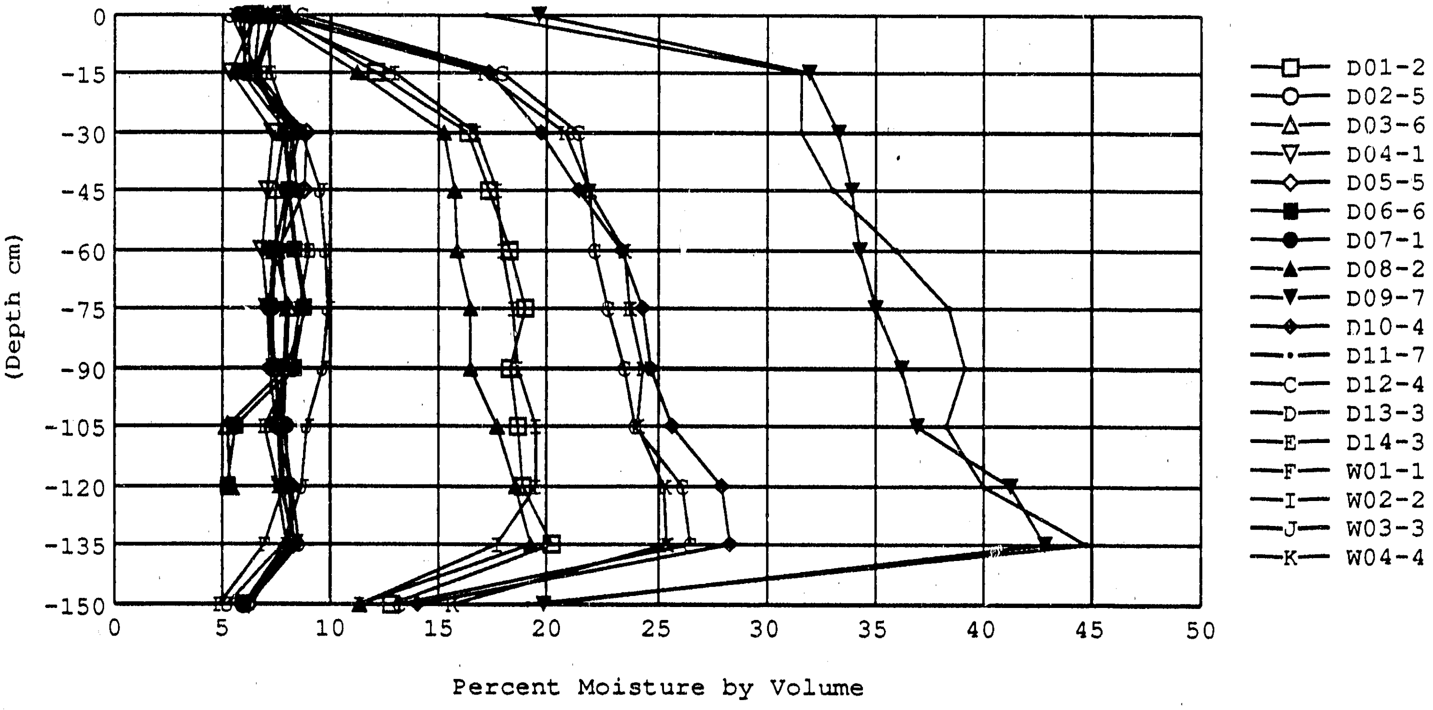
W04-4



17 April 1990





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Percent Moisture by Volume
D01-2
D02-5
D03-6
D04-1
D05-5
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D08-2
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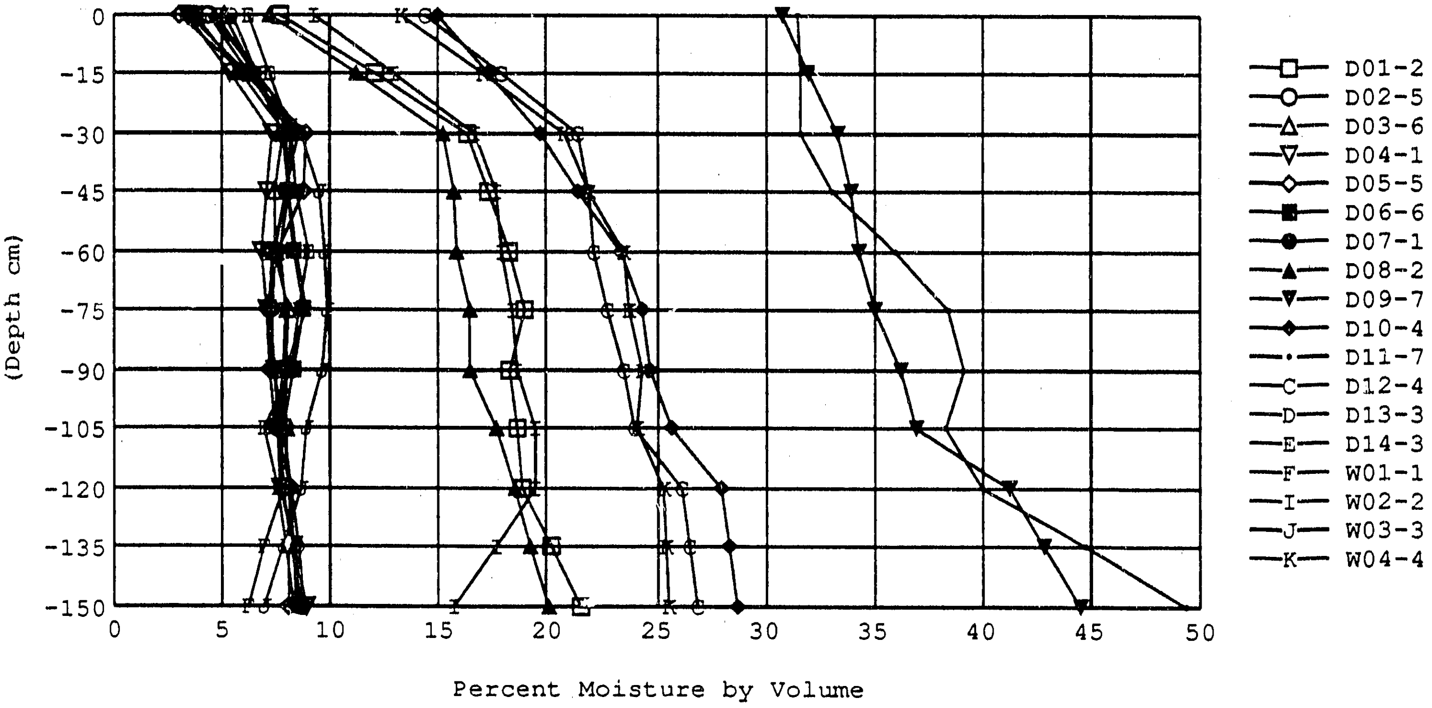
1 May 1990



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Percent Moisture by Volume
D01-2
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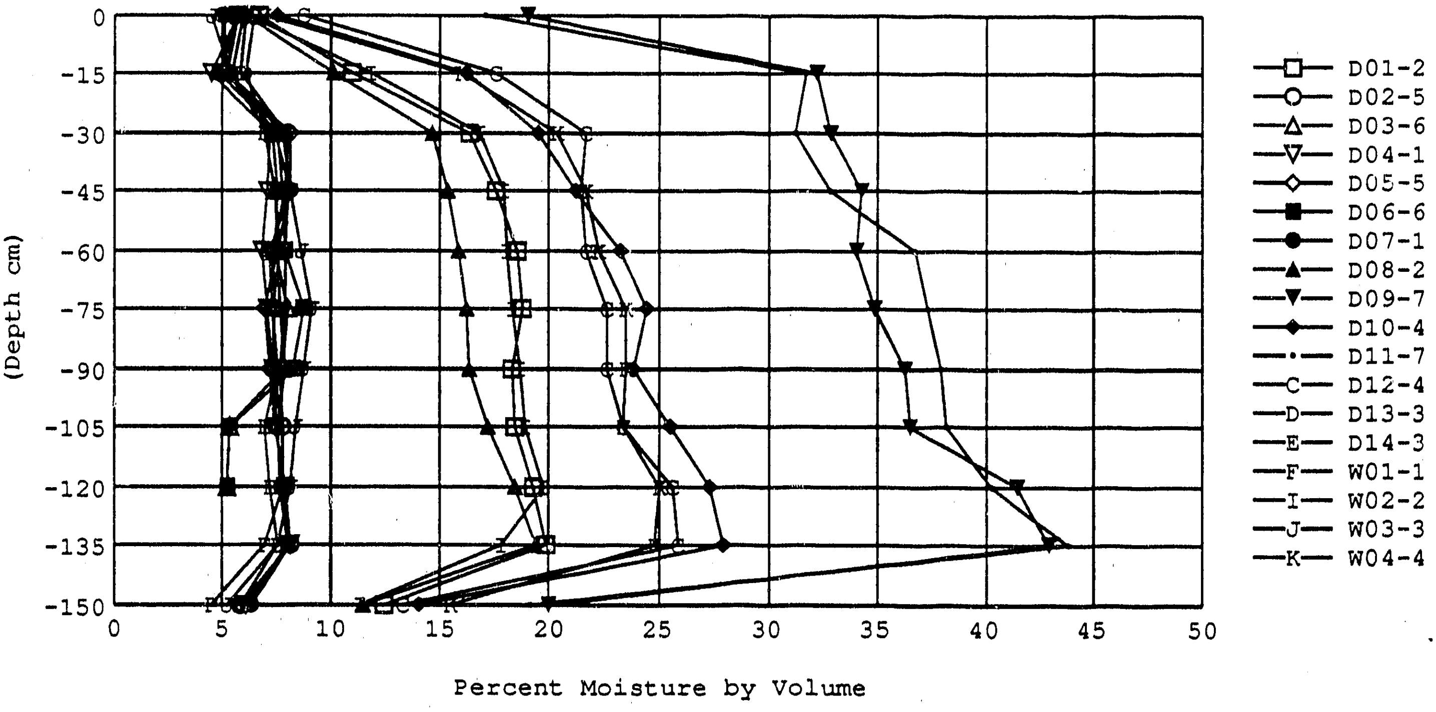
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Percent Moisture by Volume
D01-2
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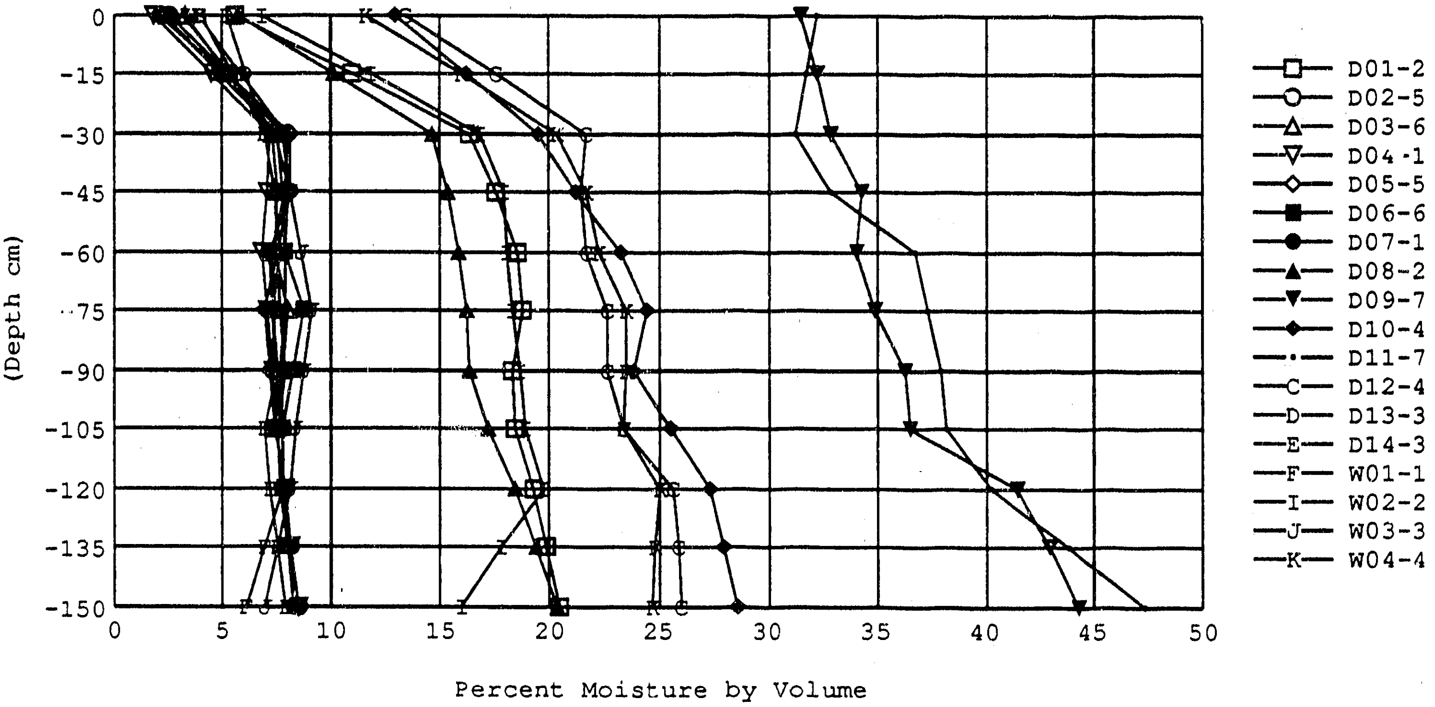
16 May 1990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Percent Moisture by Volume
D01-2
D02-5
D03-6
D04-1
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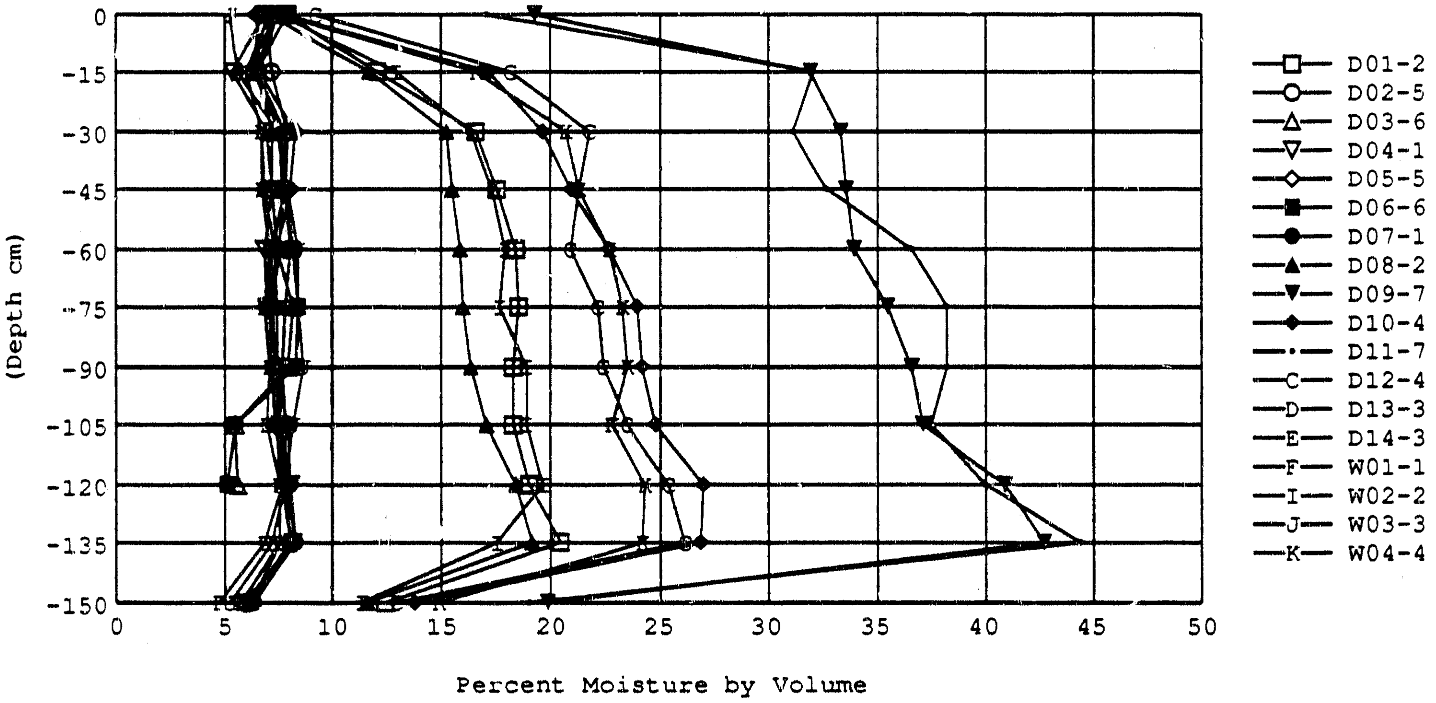
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Percent Moisture by Volume
D01-2
D02-5
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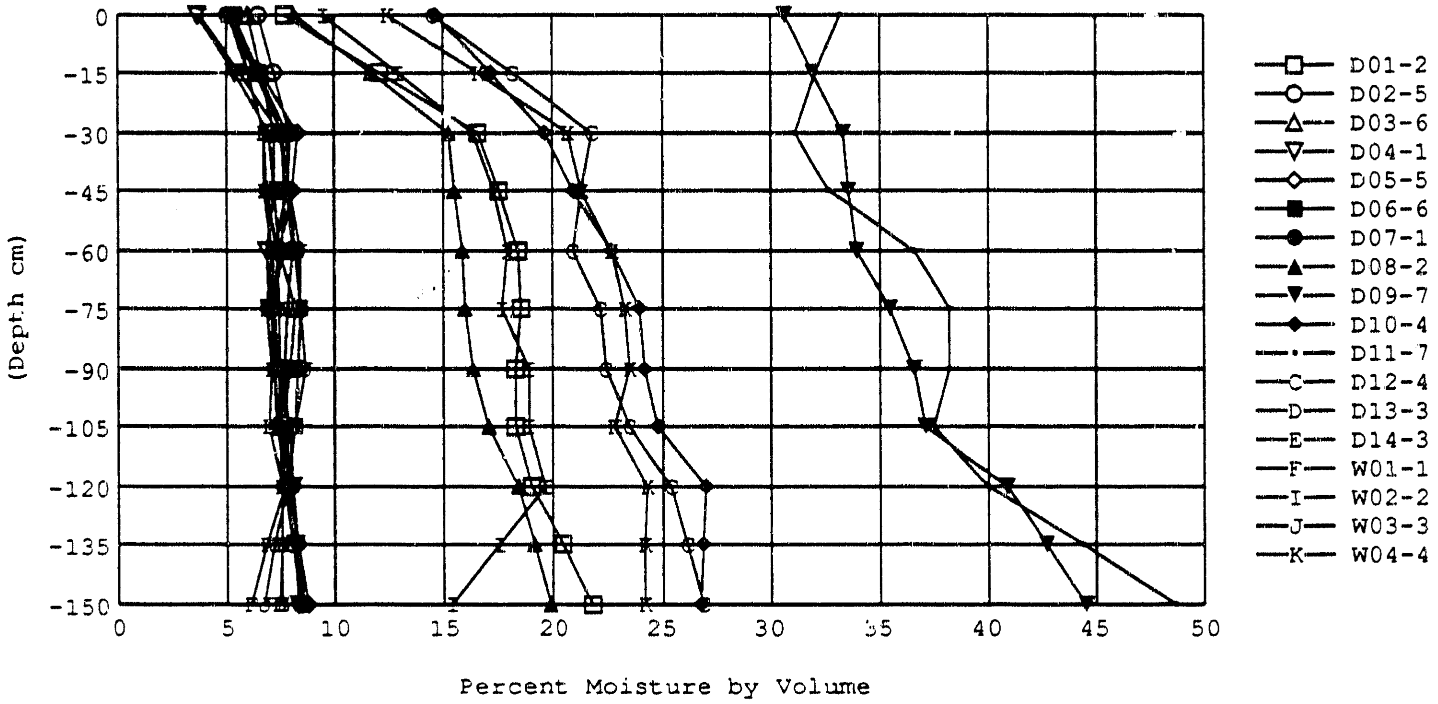
30 May 1990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Percent Moisture by Volume
D01-2
D02-5
D03-6
D04-1
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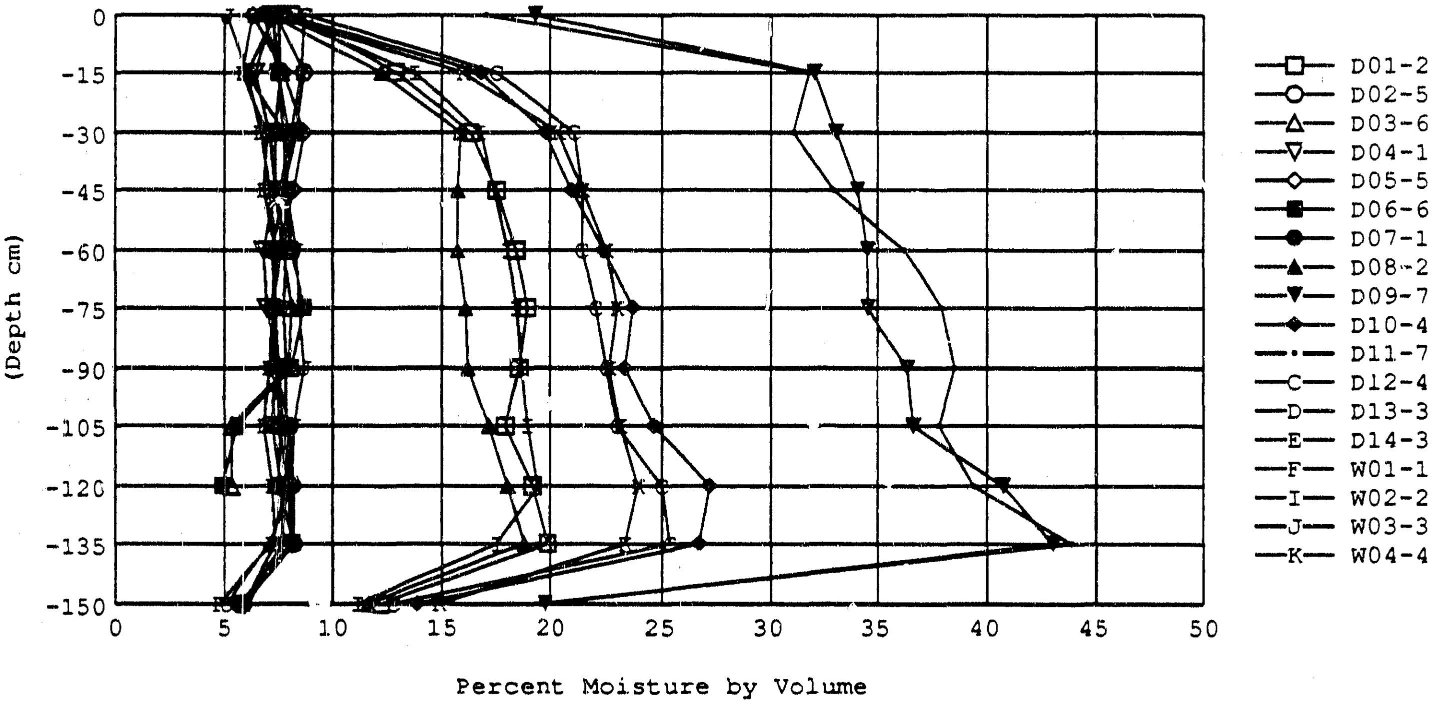
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Percent Moisture by Volume
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D02-5
D03-6
D04-1
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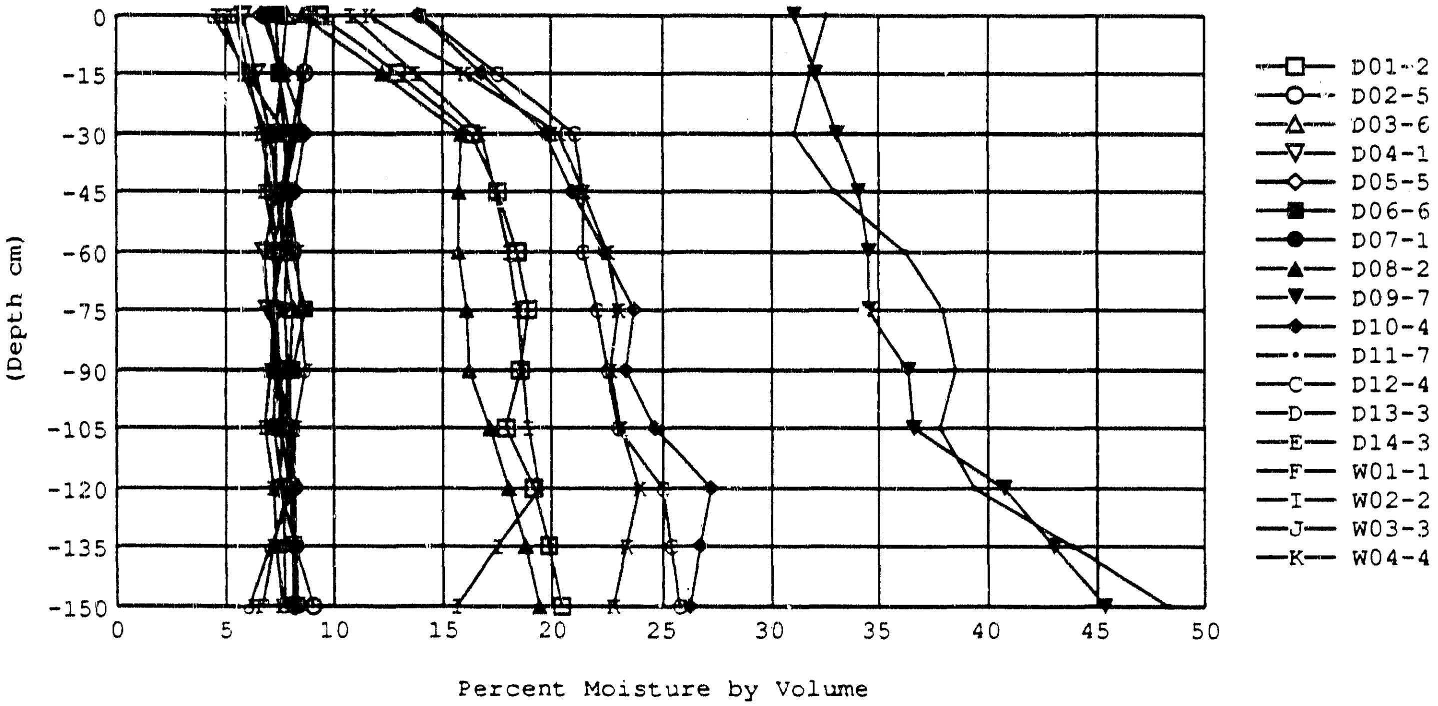
12 June 1990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Percent Moisture by Volume
D01-2
D02-5
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D04-1
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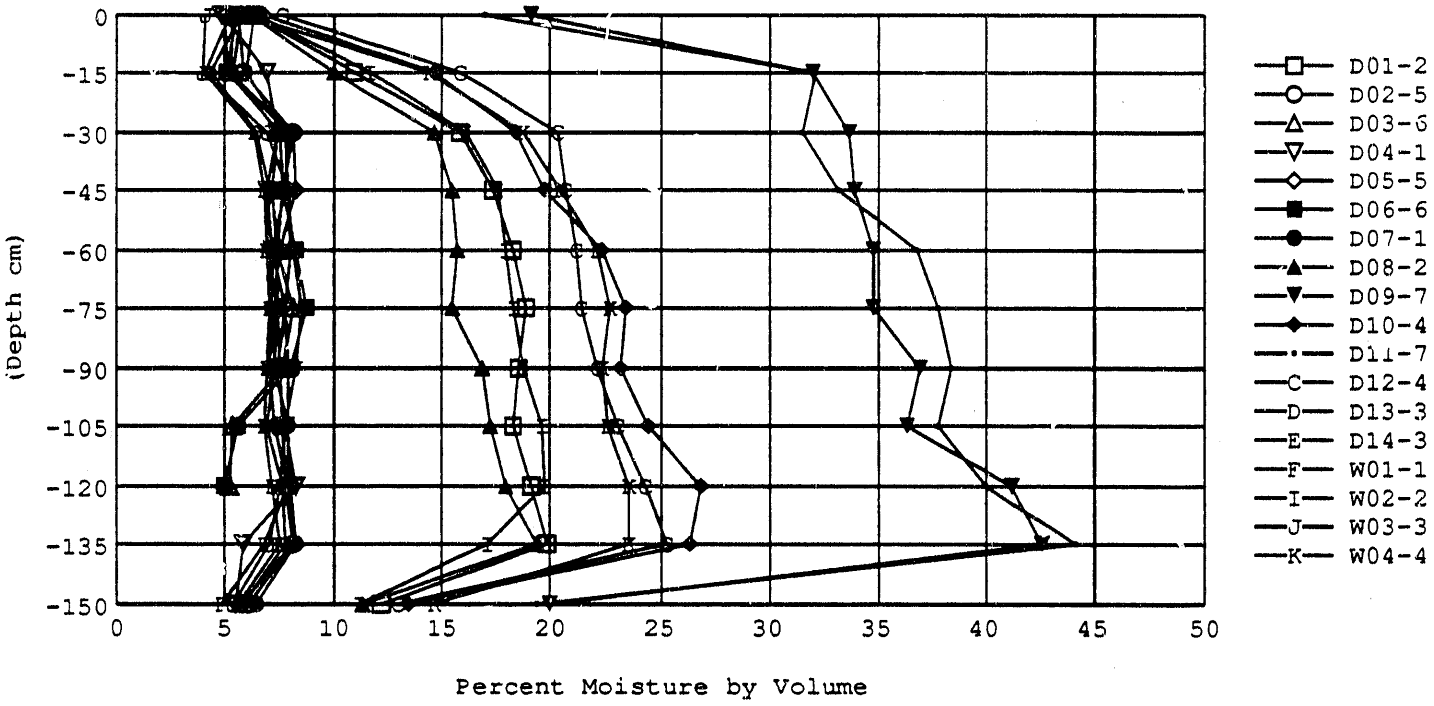
J W03-3
K W04-4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Percent Moisture by Volume
D01-2
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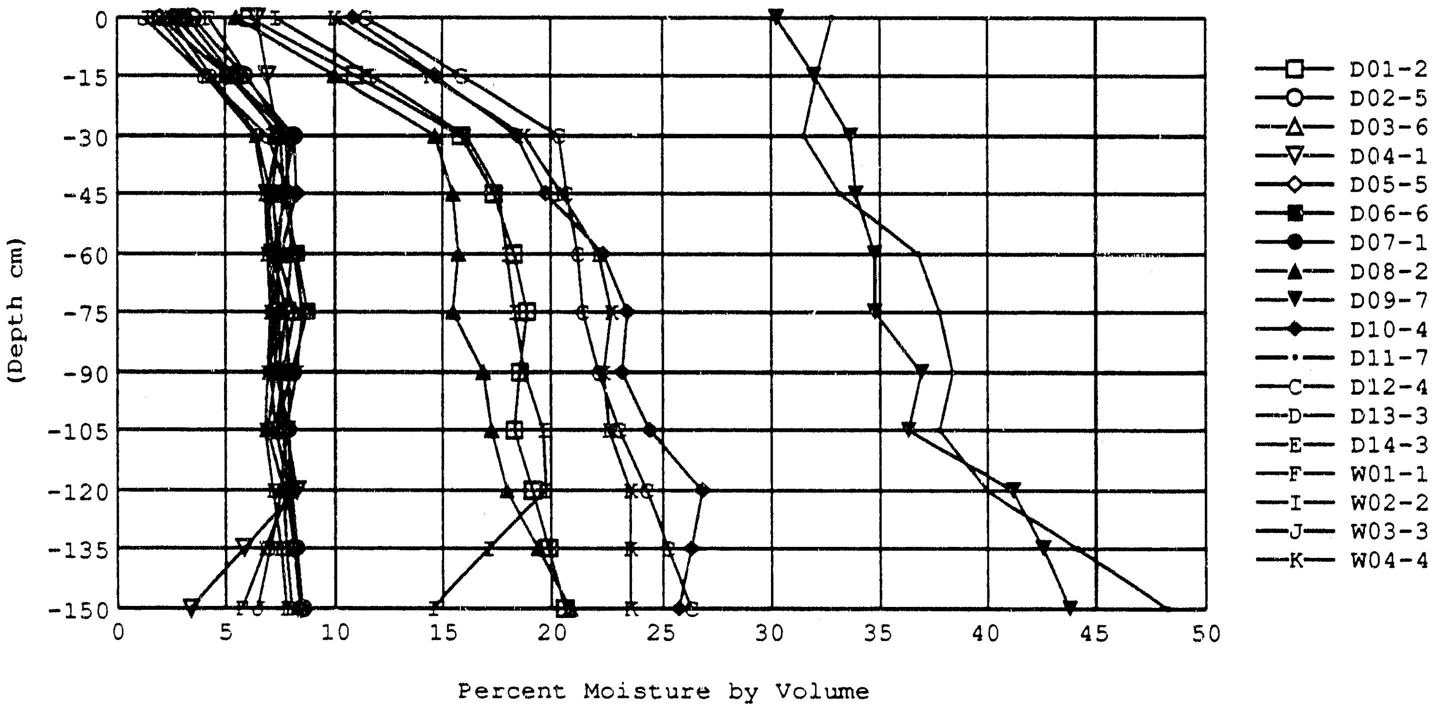
26 June 1990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Percent Moisture by Volume
D01-2
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D04-1
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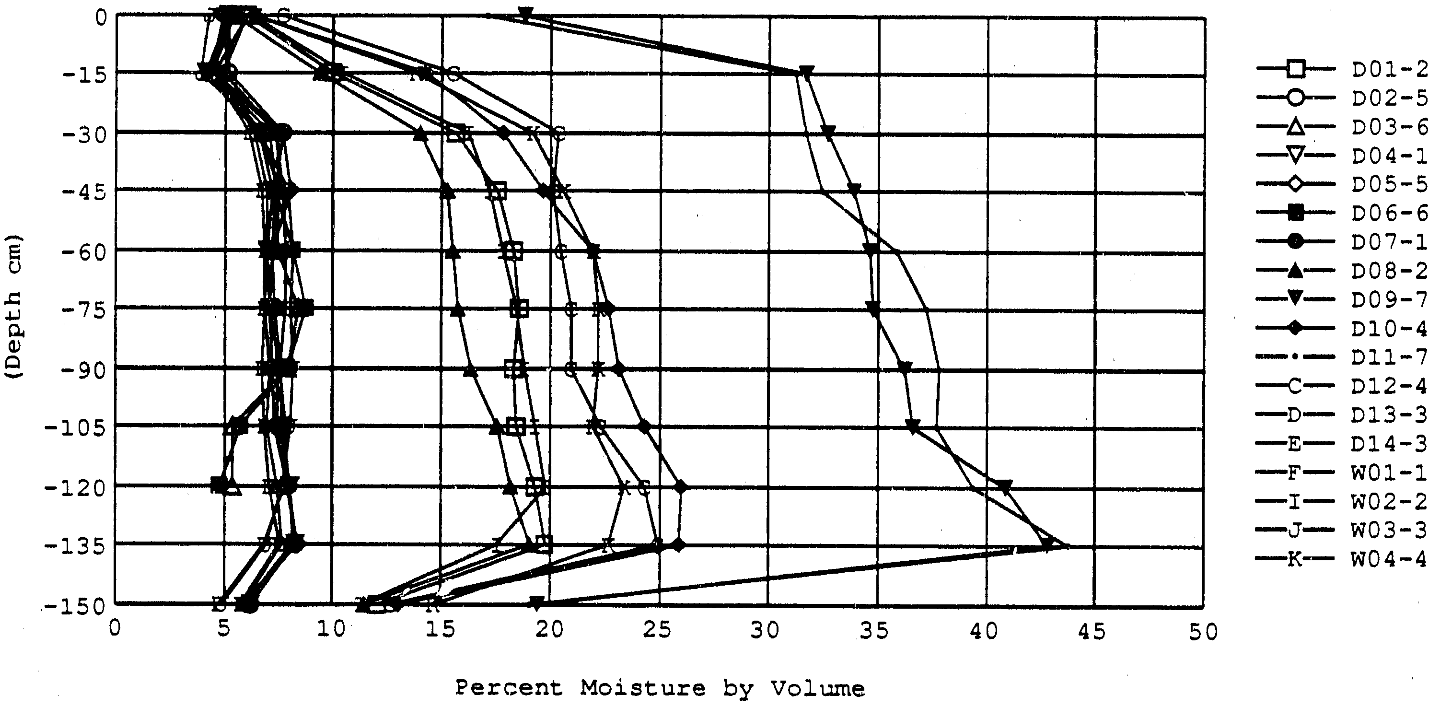

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Percent Moisture by Volume
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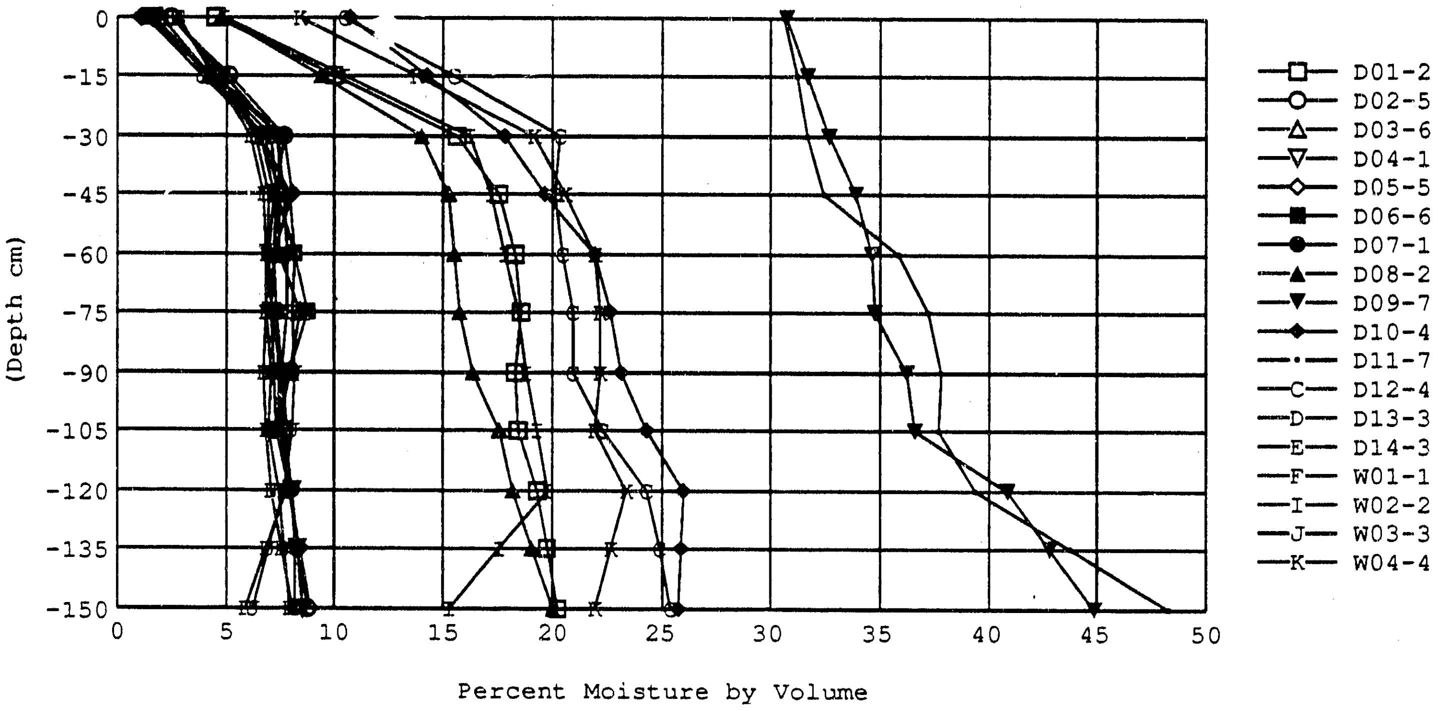
10 July 1990



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Percent Moisture by Volume
D01-2
D02-5
D03-6
D04-1
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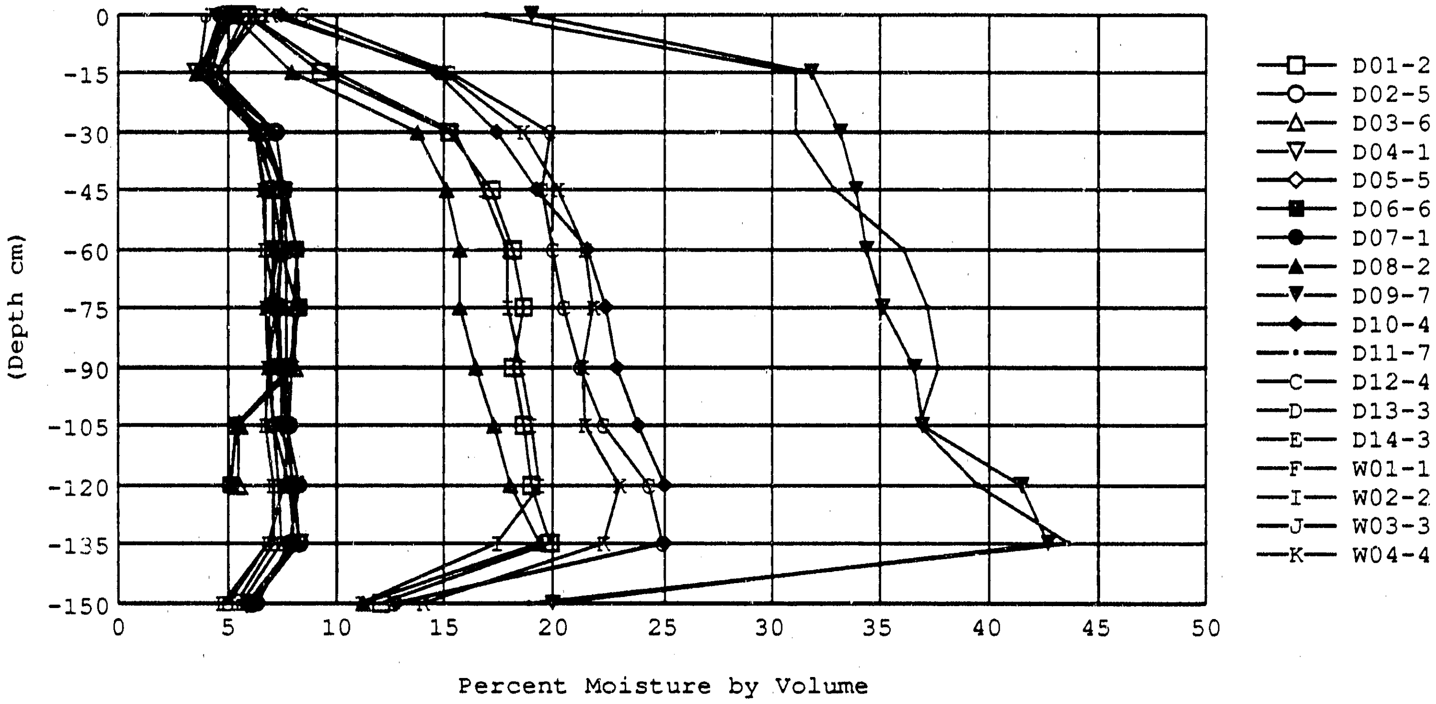
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Percent Moisture by Volume
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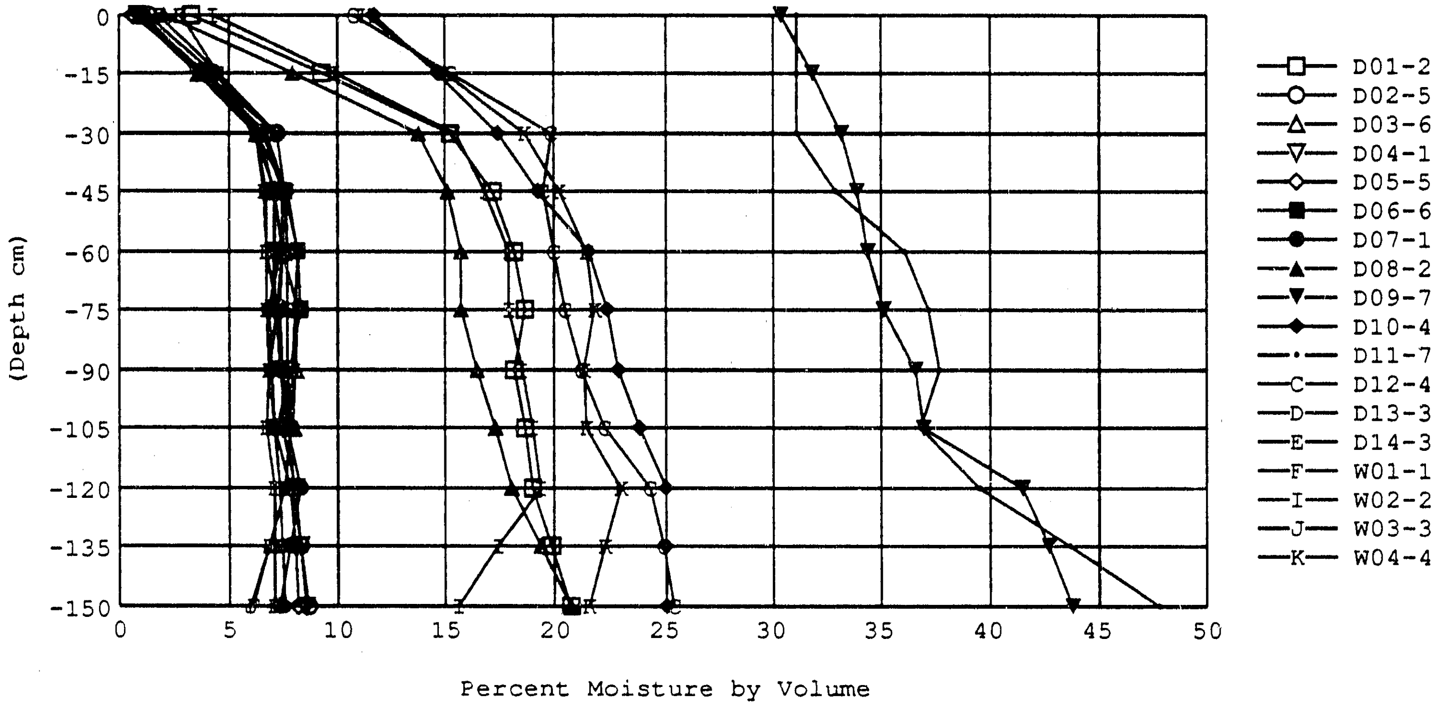
24 July 1990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Percent Moisture by Volume
D01-2
D02-5
D03-6
D04-1
D05-5
D06-6
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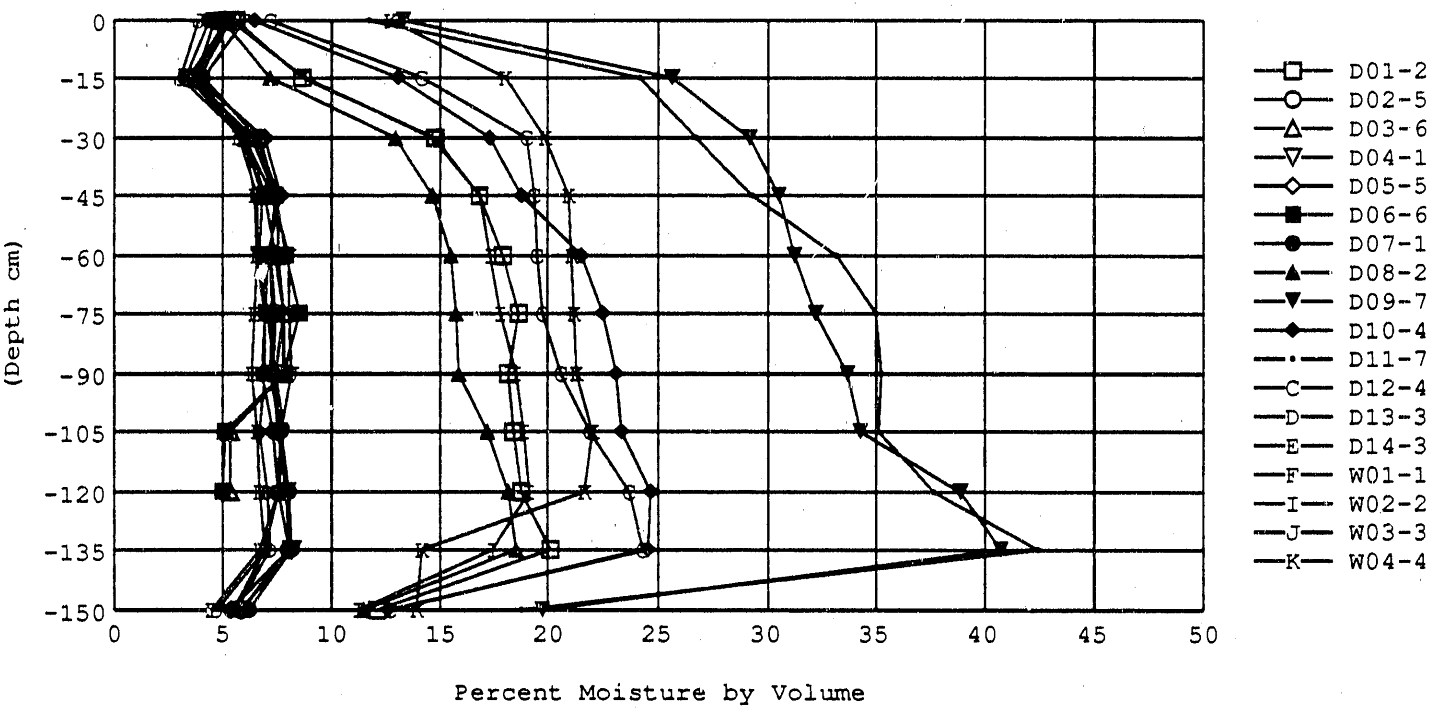
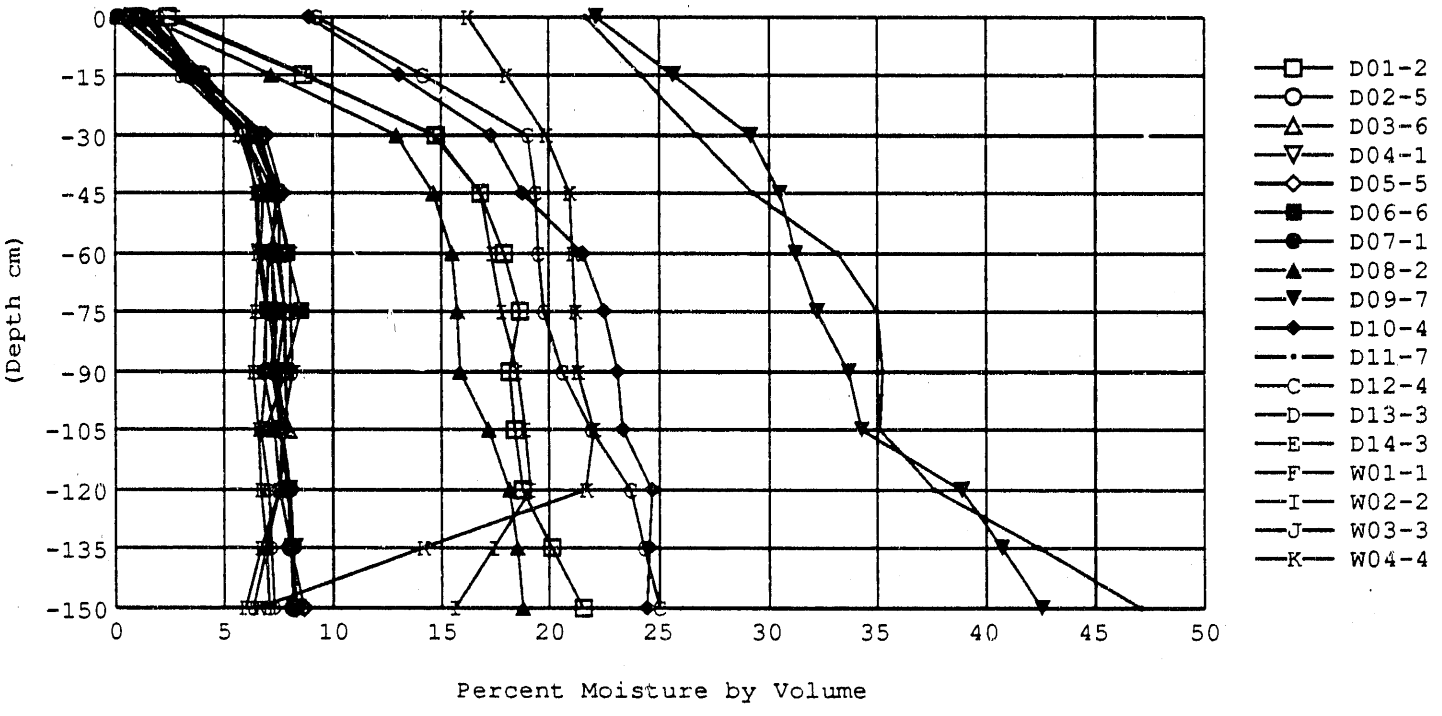


7 August 1990



END

DATE FILMED

01 / 29 / 91