SUBGRADE SOIL MOISTURE VARIATION

By

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CHAPTER 1

INTRODUCTION

Premature aging and destruction of pavement and roadways is often attributed to the variations in moisture content within a soil subgrade. These variations can be caused by environmental properties which include, but are not limited to, geographical location, recurring climatic patterns, traffic volume, and man-made alterations at a site. On-going research in this area, provides a means for future revisions in roadway management and preventive maintenance. This and other useful information allows State and Federal agencies to proficiently expand their highway systems in a timely and cost effective manner.

Oklahoma State University conducted a site evaluation at the Medford, Oklahoma Municipal airport, which involved soil sampling and testing, as well as, incorporating a field testing procedure for measuring soil moisture content. This research began in April 1996 with the assistance of the Oklahoma Department of Transportation (ODOT).

Purpose and Scope of Investigation

The purpose of this investigation and thesis is to utilize all data and findings in an attempt to show that 1) both laboratory and field testing procedures prove the direct link between moisture variations and pavement distress for a given soil subgrade and 2) that the Sentry 200 - AP probe yields reliable/ repeatable results in the field, increasing the proficiency and timeliness of current field moisture content testing procedures.

The scope of this investigation consisted of several significant areas of study: variation of moisture content as related to seasonal climate patterns; moisture variations at covered and non-covered areas; direct cause and effect relationships between moisture fluctuations and pavement destruction and stress; and finally, moisture measurement readings from the Sentry 200-AP probe which should yield reliable results.

Data collection and analysis were initially separated into two different categories. The first consisted of readings collected and interpreted from the field testing site. The second involved results obtained through standard laboratory testing. Following preliminary analysis of the two groups, the data were then combined and correlations suggested in an effort to relate variations in moisture content at the site studied, with a focus on the direct relationships between these variations and the pavement distress. Finally, suggestions were proposed based on findings from data analysis as well as results obtained through the use of the Sentry 200-AP probe. This information could provide a basis for permanent revisions to current pavement design and maintenance practices that could prove beneficial to future projects.

CHAPTER 2

LITERATURE REVIEW

The stability of roads, airfields, earth dams, building foundations, and other geotechnical structures is dependent on the water content of soil. Water content is defined as the ratio of the weight of water to the weight of solids in a given volume of soil. Change in water content is due to the migration of moisture within the soil. This occurs when any force upsets the equilibrium in the soil-water system. There are many forces which cause moisture to migrate. Some of the more commonly discussed are hydrostatic pressure, capillary pressure, osmotic pressure, chemical potentials, and temperature gradients. The migration of moisture through soil can occur in the liquid phase, vapor phase, or a combination of both depending on the forces acting on the soil-water system (1).

Hydrostatic pressure refers to the pressure exerted by “free water”. “Free water” is water that is neither in capillary tension nor under excess pore pressures in partly consolidated soils (2). Migration of moisture due to hydrostatic pressure is usually associated with saturated soil. However, if there is sufficient moisture to maintain a continuous capillary channel in the soil pores, hydrostatic pressure could occur in partially saturated soils. In either case, this type of moisture flow obeys Darcy's Law. Moisture will migrate in the liquid phase from areas of higher to lower hydrostatic pressure (3).

The phenomenon of capillary rise can be shown by immersing the lower end of a capillary tube into water. The attraction between the glass and the water molecules due to the surface tension of water pull the water up into the tube above the surface of the water (4). The forces that cause capillary rise are inversely proportional to the size of the capillary tubes. Therefore, height of capillary rise increases with decreasing pore size in soil. However, moisture migration due to capillarity usually occurs more quickly in silts than in clays. Although clays usually have a higher capillary rise, the very small pores restrict moisture flow. Therefore, moisture migration occurs faster in silts than in clays due to the larger pore size of silts. The application of a load on a soil mass can decrease the effect of capillary forces. This is due to the fact that the load will cause compressive stress on the pore water which will reduce tensile capillary stresses. Moisture migration due to capillary pressure usually occurs as a combination of both the liquid and vapor phase. It has also been found that surface tension, and thus capillary force, increases as temperature decreases (1).

In fine-grained soils, the difference in concentration of the cations in the electric double layer surrounding the soil particles and in the free water farther from the particles generates an osmotic pressure (4). The double layer is more viscous than the free pore water causing the free water to become trapped inside a void by the contact of double water layers surrounding two soil particles. Further, the water in the less viscous pore cannot flow freely past the more viscous water plug. The pore water held within the void will migrate in the vapor phase through the viscous double water layer barrier to an adjacent void in order to balance the ion concentrations (5). Moisture movement due to osmosis is usually very small in comparison to moisture migration due to other forces.

Chemical potential can also cause movement of moisture within a soil. Chemical potentials are caused by differences in soil chemical composition due to variations in ion activity. In addition, moisture will migrate from soil with lower ion exchange capacity to soil with higher ion exchange capacity (6).

Temperature gradients are another factor that affect moisture migration. This moisture flow occurs mostly in the vapor phase as the vapor pressure fluctuates. For example, climatic temperature changes cause differences in soil temperature which in turn produce temperature gradients and high vapor differentials within a soil. Further, as the temperature in the soil decreases its ability to absorb moisture increases. Therefore, moisture migrates from high to low temperature areas or high to low vapor pressures. Furthermore, low vapor pressure is associated with low temperatures, and high vapor pressure is associated with high temperatures (7).

In order for moisture migration to occur, there must be a source of free water. Free water can enter subgrades and layers supporting traffic from a number of sources: by flowing downward through porous or cracked surfaces or unsealed construction joints; by flowing laterally into the edges from saturated medians and shoulders; by seeping upward into the structural section from high groundwater and springs; by being pulled by capillarity from the underlying water table; or by accumulating as water vapor resulting from fluctuations in temperature and other atmospheric conditions (2). In addition to the migration of moisture, moisture accumulation in subgrades can occur from any one or a number of the sources listed above. This accumulation could cause damage to overlying pavement. Therefore, it is essential to have an efficient and reliable system for determining the moisture content of subgrade soils.

Soil Moisture Measurement Methods

There are several methods used to measure soil moisture content. Presently, the most common and generally, the most accurate method of measuring moisture content is also the most destructive. Therefore, considerable effort has been devoted to researching and developing in situ methods for measuring changes in water content at a site. Several innovative methods are discussed, along with the standard method, in the following paragraphs.

Gravimetric Method

The gravimetric method has been the most frequently used method for measuring soil moisture to date. It is generally accepted as the standard for calibration of all other techniques. This method defines water content of a soil by expressing the weight or volume of water expelled by oven-drying at 105 °C, per unit weight or volume, respectively. This is based on the fact that water in an unsaturated soil is held by surface tension or surface chemistry forces within a wide range of different pore sizes and shapes. By oven-drying a sample of known volume and/or weight, most of this water is expelled. In addition, water from crystallization of some minerals (e.g. calcium sulfate), volatile organic materials, and water associated with hydrated oxides is also removed. The general procedure involves obtaining a moist representative sample, weighing the "wet" sample, removing the water by drying the sample in an oven at 105°C plus or minus 5°C, and reweighing the sample to determine the amount of water removed (8). The water content can then be calculated by dividing the difference between wet and dry weights by the weight of the dry sample. This yields a ratio between the weight of water and the weight of dry soil expressed as a percent. The gravimetric method is the most accurate and reliable method of measuring water content. However, it is also very time consuming because each sample must be oven-dried. Moreover, this method is destructive and therefore, a new sample must be taken at a different place. This may increase the possibility that a change in water content with position in a sampling area may be misinterpreted as a change in water content with time at a particular location. Consequently, if time is of the essence or destructive sampling is a concern, other methods should be considered.

Thermal Probe Method

The thermal probe is a metal rod which contains an internal heating element and temperature sensor. The probe is pushed into a pre-drilled hole, temperatures are recorded, and from these measurements, thermal properties are estimated. The equipment involved in the thermal probe consists of the probe itself and a power supply. A typical probe would have an inside diameter of 14-16mm and a wall thickness around 2mm. The body and tip are made of a stainless steel to make it rugged and less corrosive.

A detachable handle is used to rotate and push the probe into a hole. Thermistors which measure the temperature, are embedded within the probe wall as close to the surface of the probe as possible (typically about .2mm from the surface). The heating element is placed in a separate stainless steel tube which is sealed at one end with epoxy resin. This tube is then mounted within the probe toward the rear end of the probe tip. The power supply consists of a low and high power circuit which are fitted into a single heat sink box. Field testing is initiated by first preparing the site. The site must be leveled and the hole must be drilled in a controlled manner. The hole is drilled using two drill bits. The outer bit cuts the hole followed by the inner bit which removes waste. The idea is to disturb the hole as little as possible and make it just large enough for the probe to fit. This allows good thermal contact between the probe and the soil. The probe is then lowered into the hole, constant power is supplied to the heating element, and temperatures are recorded at some chosen intervals (e.g. one minute intervals). The thermal properties of the soil are then identified by fitting the temperature data to a curve generated by using a theory of dissipation (9). The practical application of the thermal probe has been proven in both the laboratory and in the field by several independent sources. The probe can be used to rapidly characterize the thermal properties of a soil including soil moisture content. However, there are some problems associated with this method. If the probe does not make good contact with the soil, the readings can be inaccurate. This often occurs in soils that are subject to volume change, such as shrink-swell soils. In addition, the calibration curve which relates thermal conductivity and water content differs amoung different soils (10). For these reasons the thermal probe is generally not a method used in engineering for characterizing soil moisture.

Neutron Method

The neutron method is a non-destructive field method based on the slowing down of fast neutrons emitted by a radioactive source by water (11). Similar to the thermal method, a probe is lowered into an access hole and performs the actual measurements. The neutron moisture meter consists of several components. The essential parts are a radioactive source of fast neutrons, a detector (the probe), and a counter of slowed neutrons. The probe houses the radioactive source, the slowed neutron detector, and electronic circuitry which provides a high voltage to the detector. Again, like the thermal probe, the neutron probe is usually made of stainless steel or aluminum. A separate unit contains a ratemeter and some additional electronic circuitry along with the battery. This assembly is coupled by the cable to the probe. To use the moisture meter, an access tube must be installed into which the probe can be lowered. Careful attention must be given to installation of the access tube. The compaction, failure and/ or yield of the soil in the immediate area of the tube may drastically alter void properties. This will in turn change bulk density, water movement, and water retention in that zone, which is all part of the soil that most affects the neutron count. If the insertion of the tube is slow or sporadic, soil may "stick" to the metal. This will alter the soil structure along the sides of the tube. The greatest distortion will be seen in soft soils, such as wet clays, due to their high adhesion potential and low resistance to shear. Loose sands are also a problem because they tend to collapse during installation of the access tube. Of course, it is almost impossible to prevent some soil distortion around the hole during installation, but it should be minimized by carefully choosing an installation method and a reliable installation team. Once the access tube has been prepared, the probe consisting of the source and a detector is lowered to the required depth (usually several different depths are used) and the measurements are recorded. The neutron method is a reliable, non-destructive method which can sample a relatively large volume of soil (1 cubic foot or more) once installation of access tubes has been established (11). It is also rapid and reliable once the initial setup is complete. However, this method is somewhat less accurate near the surface due to the escape of fast neutrons from the soil. In addition, results are affected by unusually high amounts of organic matter because of its hydrogen content (10). The neutron method is most useful for long term measurements at one site. It provides quick, reliable measurements of soil moisture in the field.

Capacitance Method

The capacitance method uses the functional relationship between dielectric constant and soil content to determine the moisture content for any given soil. It is based on the fact that the dielectric constant of water is very different than that of dry soil. Thus, a correlation can be made between the dielectric constant of soil and its water content. However, when first evaluated this method was considered poor because the results were empirical and special calibration was necessary for each different soil analyzed. It was then discovered that the curves relating capacitance with water content in different soils would probably be of a similar shape and that a single point for each different soil was sufficient for calibration purposes once the general shape was established

(10). The field procedure involves lowering the capacitance probe into an access tube which is installed vertically into the ground. The probe measures the dielectric constant of soil in the field by incorporating the soil as part of the dielectric of a capacitor located within the probe (12). This method is still being researched and improved. The equipment involved has two main components, the probe and the evaluation unit. The probe consists of two electrodes spaced some distance apart (typically around 10mm), which are placed inside an insulating waterproof cylinder along with an oscillator. The oscillator is connected by a coaxial cable to the evaluation unit. The evaluation unit contains the power supply, another oscillator, the mixing stage, the low-pass filter, the counting detector, and the microammeter (13). An electrical field is generated between the two electrodes within the probe; this penetrates into the surrounding soil and the oscillator frequency of the system changes with volumetric soil water content (12). This electrical field is measured and recorded by the evaluation unit. Once the dielectric constant is known, the water content is obtained using the functional relationship between the dielectric constant and the water content. Again, emphasis must be placed on careful installation of the access tube to receive accurate readings. Due to sensitivity of this system the installation of the access tube is even more critical than with methods previously discussed. Therefore, a technique has been developed specifically for the installation of an access tube for the capacitance method. It allows known-volume calibration samples to be extracted while also preventing lateral movement of the tube. This eliminates or minimizes the introduction of gaps between the soil and the tube. This method has many advantages including the speed of measurement, low cost (after initial equipment purchase), portability, and high resolution. In addition, there is no radiation involved as with the neutron probe. The system can also be adapted for use with automatic logging equipment. However, this method also has some disadvantages. The calibration curve is non-linear and soil-dependent which may present difficulties in precision of measurement. Moreover, the access tube installation is much more rigorous, and any imperfection could cause large errors in readings. There are still some questions concerning whether the "soil water content" defined by the capacitance method conforms to the water content established by the gravimetric method. At present, this method is most useful for repeated measurements at the same site over a period of time where the main concern is changes in water content as opposed to absolute values.

Gamma Ray Method

The gamma ray method involves airborne soil measurement. Airborne soil measurements are based on the measured difference of natural terrestrial gamma radiation flux between wet and dry soils. Soil density increases with the presence of moisture in the soil. This results in an increased attenuation of the gamma flux for a relatively wet soil and a lower flux at the ground surface. The gamma flux from the ground is a function of the water mass and radioisotopes concentration near the surface. However, only the water mass affects the attenuation. The gamma flux comes from the potassium, uranium and thorium radioisotopes in the soil. Typically, 99 percent of gamma radiation is emitted from the top 30 centimeters of a soil (8). The equipment involved in the gamma ray method includes 10 detectors; a pulse height analyzer; a minicomputer used to reduce and record the output data onto a magnetic tape; temperature, pressure, and radar altitude sensors; and a remote control system operator or navigator to control and monitor the data collection. This method is performed by accumulating and storing spectral radiation data along a flight line from which estimates of soil moisture can be computed. In addition, ground-based soil moisture measurements are used to make a one-time calibration of the natural terrestrial radioisotope signal over the flight line network (8). This method is new and research is still being performed. Currently this method's largest advantage is the fact that it is very fast. However, it is also very expensive and has not proven to be incredibly accurate.

Radio Frequency Method

This method is based on determining the correlation between in situ measurements and remotely sensed measurements and quantifying the added information value of the remotely sensed data. Like the capacitance method, the radio frequency method uses the theory that the dielectric constant of soil is a potentially sensitive indicator of soil moisture. However, instead of capacitance, it measures the complex electrical impedance of the soil. The probe is a coaxial arrangement of seven tines (one in the center, surrounded by the other six). The probe is connected to a vector voltmeter along with a voltage source. Once inserted into the soil, the probe acts as the bottom element of a voltage divider. The upper element is a resistor. Electrically the probe appears as a capacitor with a shunt resistor. The capacitive reactance is a function of the probe geometry and the real part of the soil (plus water) dielectric constant. The shunt resistance is the parallel sum of the imaginary part of the soil (plus water) dielectric constant and the finite resistivity of the soil. The voltage drop and phase shift across the resistor are measured with the voltmeter (8). The soil impedance can then be used to calculate the volumetric water content of the soil. Like other methods involving the use of a probe this method is also very rapid once the initial setup is complete. However, its accuracy is still being researched and therefore it is not commonly used at the present time.

Summary

It is important to keep some key factors in mind when selecting a soil measurement method. These include, but are not limited to, time, expense, and site specific needs. For the most accurate results, the gravimetric method is still recommended. However, if time is of great concern, this method may not be the most suitable choice. The other five methods are much faster, but there are still some questions as to their accuracy. Accuracy aside, these methods vary in setup time, labor intensity, and cost. The thermal probe and neutron methods have a faster setup time than that of the capacitance, gamma ray, and radio frequency methods. This is mainly due to the sensitivity of equipment of the latter three methods. In addition, the capacitance, gamma ray, and radio frequency methods tend to be more labor intensive due to the rigorous set up procedures involved. The gamma ray method is by far the most expensive because of the highly technological equipment used. The thermal probe, neutron, capacitance, and radio frequency methods are comparable in price and have similar equipment requirements. Keeping all these factors in mind, a careful selection of the appropriate method for a specific site can be chosen.

Previous Moisture Monitoring Programs

Many moisture monitoring programs were initiated to increase knowledge of the link between pavement failures and subgrade moisture conditions. In 1950, the Missouri Highway Department began an extensive study of subgrade moisture conditions (14). They conducted their investigation under new Portland cement concrete slabs. Core samples and soil samples were taken every three months for a five year period. This became somewhat cumbersome because each time the sampling was complete the soil that was removed had to be replaced and the pavement reconstructed. A long drought also occurred during this time, and the dry climatic conditions had some effect on the results of this study. However, they found the moisture variations to be very small with maximum changes occurring near pavement edges and beneath the shoulders. The most moisture infiltration occurred from surface runoff which seeped through the joints between the pavement and shoulder. Their research also indicated that the most stable subgrade moisture conditions could be achieved when slabs were placed at periods when moisture distribution was above optimum compaction moisture (or wet of optimum).

In Australia, the development of electrical resistance equipment first allowed investigators to take repeated measurements of in-situ moisture contents (15). Using gypsum blocks, connected in electrical circuits, correlations were made between the resistance of the blocks to electrical current and soil moisture content. From this study, it was found that the largest moisture variations occurred at shallow depths beneath pavement slabs. Moreover, at depths of eight to ten feet moisture conditions remained relatively constant. In addition, moisture variation was directly related to climatic conditions with the largest variations occurring during the winter months or during seasons of heavy rainfall. It was also noted that during rainfall, the highest moisture variations occurred along the shoulders, probably because runoff infiltration was greatest at the shoulders. In contrast, rainfall had little effect beneath the center of the slabs. The better the drainage conditions were, the less the seasonal moisture varied. This indicates that proper design of pavement drainage could greatly reduce subgrade moisture variations.

Another study was conducted at Iowa State University in 1961 which compared theoretical moisture accumulations in order to measure moisture changes beneath covered areas (16). Simulated pavement sections were constructed for field measurements while theoretical quantities were computed from thermodynamic desorption curves. The measured values of variation were very comparable to the ones calculated from the curves. This investigation found that moisture variations resulting from temperature changes were very small. They also concluded that the dry densities of covered soils have an effect on equilibrium moisture content. It was found that at low densities, soils had high moisture content and at high densities, soils had a lower moisture content.

Nuclear depth equipment was used to study the short-term subgrade moisture conditions beneath a city street in College Station, Texas (17). For this study, the instrumentation had to be installed prior to construction of the street which took a great deal of planning. Access tubes were installed up to twenty feet in depth. This allowed moisture probes to be lowered into the subgrade for measurements. Temperature variations were also recorded using thermocouples. Data were collected over a sixteen month period. However, no dramatic changes in moisture variation were noted. Temperatures varied on an annual cycle at depths greater than one foot in the subgrade.

In 1989, a nuclear surface moisture density gauge was used to measure dry density and moisture content under two forest access roads (18). The purpose of the study was to prove that the soil in a road unused for a few weeks after construction would be drier and denser. The results did show a small but consistent pattern of increasing soil density and decreased moisture content over time.

Previous research on subgrade moisture variation indicates that there are many common results yielded using a variety of different methods, programs and techniques. Some of these conclusions include the fact that moisture variation beneath most pavements is minimal with maximum variations occurring at pavement edges due to runoff; the largest moisture changes occur at shallow depths (less than ten feet); and moisture variation can be directly related to climatic conditions.

CHAPTER 3

SITE DESCRIPTION

The site for this study was the Medford Municipal Airport located 1.2 miles southwest of Medford, Oklahoma, in Grant County. US-81 highway runs along the east side of the airport while farmland borders all other sides. This site was chosen because the Oklahoma Department of Transportation has been conducting an ongoing evaluation of the runway pavement condition which was cracked and damaged (19). According to the United States Department of Agriculture Soil Conservation Service Soil Survey of Grant County (20), the subgrade soil in this area is predominantly a Kirkland 0-1 percent slope soil. In addition, a small area is Kirkland 1-3 percent slope soil. It is characterized as a clay which has the potential to be highly plastic. It has a fissured to blocky structure and may contain calcium carbonate and/or iron concentrations at depths of 30 to 75 inches. Moreover, Kirkland series soils are considered to have a high shrink-swell potential. A low plasticity, weathered shale lies beneath this residual soil.

Laboratory Testing

In addition to the use of the Soil Conservation Service Survey, several laboratory tests including Atterberg Limits and percent minus 200 were used for classification of the soils where moisture readings were taken. Moisture content, dry density and soil suction were also determined. Three borings were sampled across the site at similar depths. The first boring was located 335 feet east of the airport runway in an open field. The second boring was 27 feet east of the runway centerline in the runway shoulder. The third boring was 15 feet east of the runway centerline (See Figure 3.1). Each boring involved the extraction of auger samples, push tube samples, and installation of a PVC access tube. The push tube samples were divided in half for laboratory testing. Each sample was then individually wrapped and identified. At the lab, one half of each push tube sample was used to conduct a soil suction test, while the other half was used to determine moisture content and dry density. The auger samples were set aside and used later for classification testing.

The test method used to determine soil suction followed the guidelines listed in ASTM D5298-94 "Standard Test Method for Measurement of Soil Potential (Suction) Using Filter Paper" (21). The test method is conducted by placing filter papers (two for this test) in an airtight container with the soil sample for seven days. This allows adequate time for the vapor pressure of pore-water in the sample, vapor pressure of pore-water in the filter paper, and partial vapor pressure of water in the air inside the container to reach equilibrium. The weight of the filter papers before and after drying is determined and the suction of the sample is calculated from a calibration relationship of the filter paper water

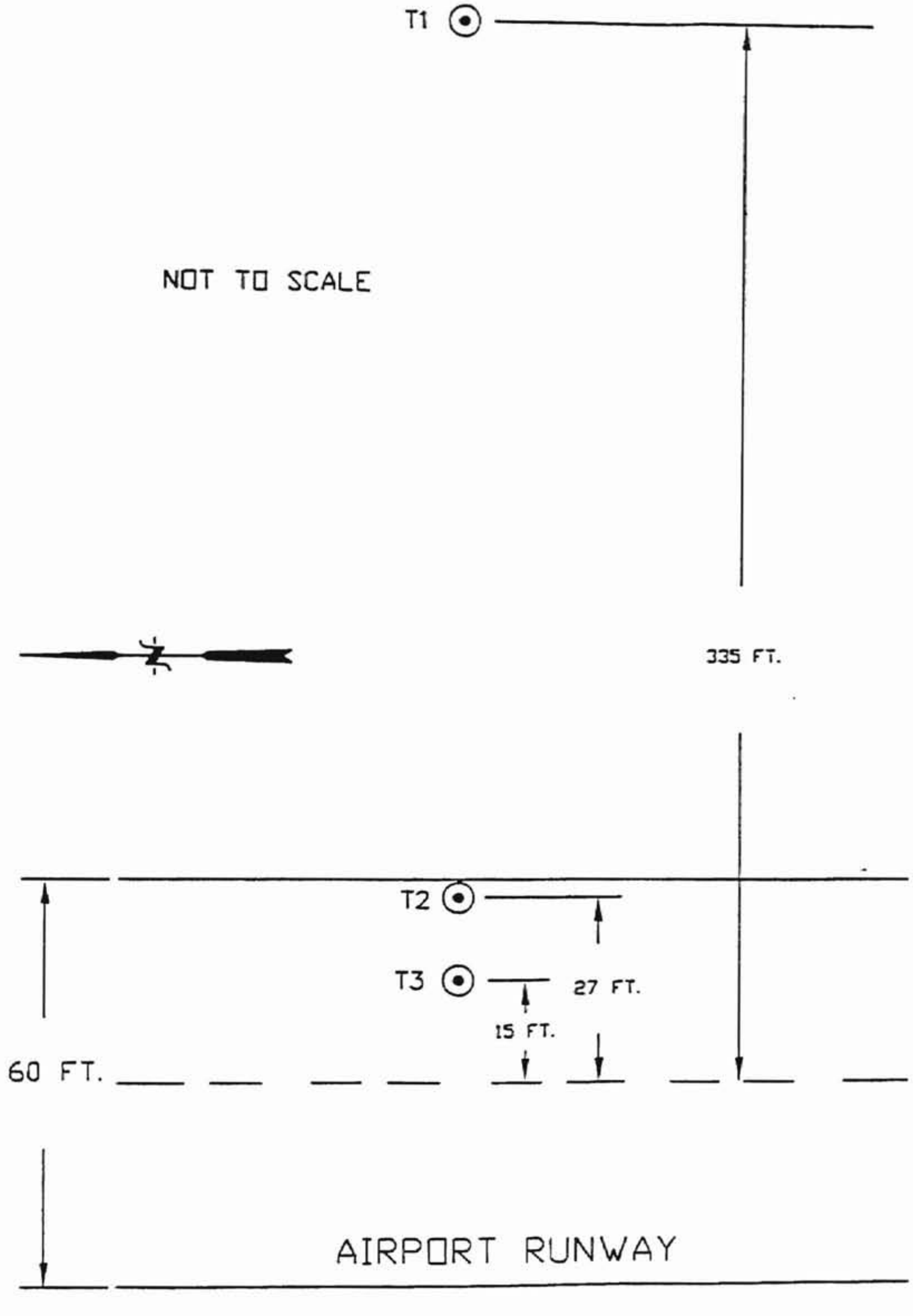


Figure 3.1 Plan View of Boring Locations at Medford Airport

content with suction applicable to the type of filter paper (21). For this test, Whatman No. 42 was used (See Figure 3.2). Figures 3.3-3.5 show the results of the suction tests for each boring location.

Soil suction is a measure of the free energy of the pore-water in a soil (21). Also stated, it is a measure of the affinity of soil to retain water. Soil suction can also be related to other characteristics of soil that are influenced by water. Some examples include volume change, deformation, and strength.

Soil suction is also useful in identifying the cause of pavement distress (22). According to laboratory data collected for a one-year old highway reconstruction project, soil suction increases as moisture content decreases (22). Therefore, during dry periods, the soil suction increases which can result in soil shrinkage. The shrink-swell effect of the soil, as soil suction fluctuates, causes the flexure of pavements which contributes to cracking.

For this study, suction data were collected only for the initial conditions. Therefore, observations about how soil suction changes with time and climatic conditions will be discussed after moisture content data are presented. The results of the suction tests shown in Figures 3.3, 3.4 and 3.5 reveal a large variation for the uncovered boring T1 and less variance for the covered borings, T2 and T3. Boring T1 shows increasing and decreasing suction down to 7 feet and then a steady decrease suggesting cooler more moist soil. The total suction for T2 is constant to 6 feet then decreases to 7 feet after which it steadily increases. The dramatic decrease could be a thin lense around 7 feet

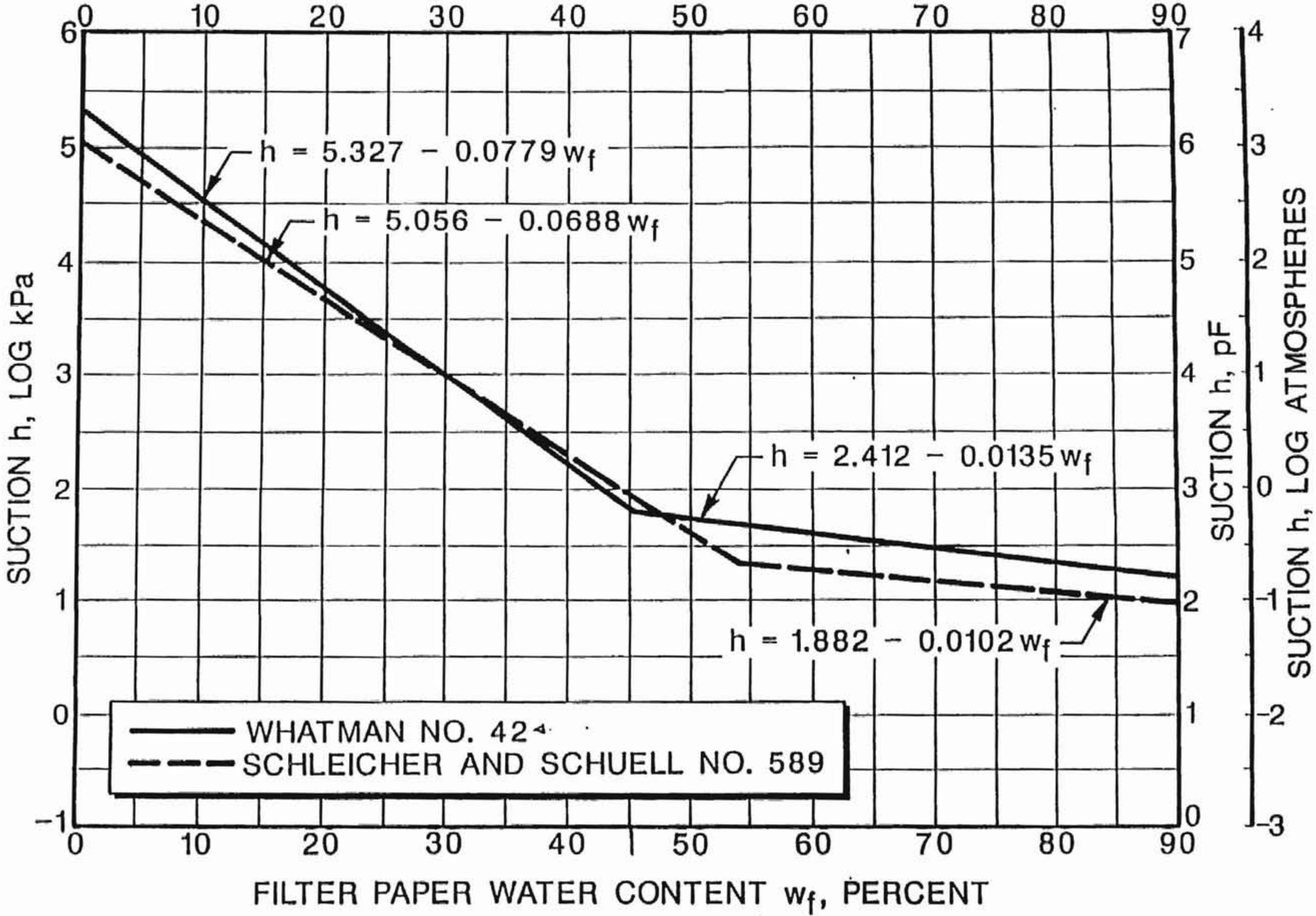


Figure 3.2 Suction vs. Filter Paper Water Content

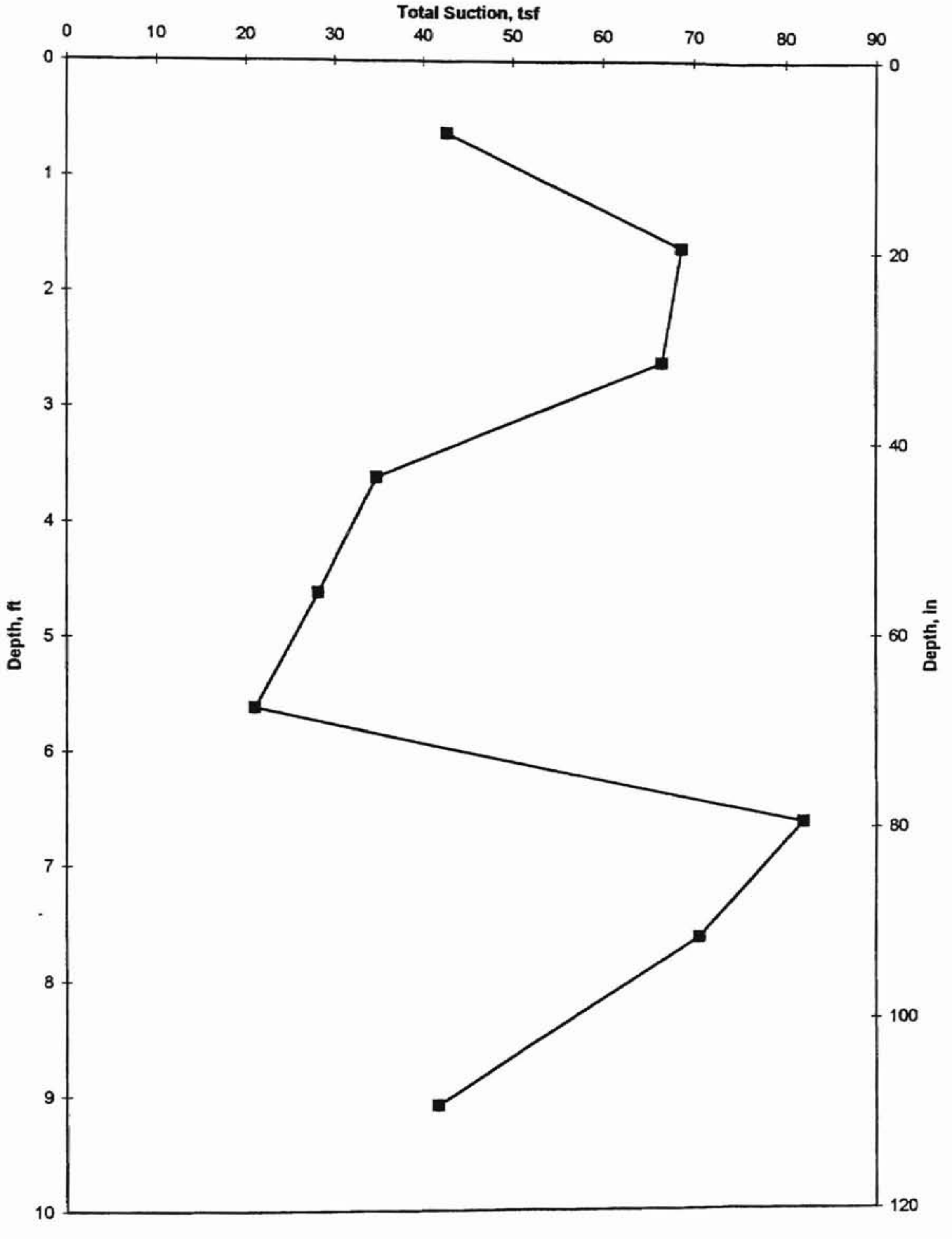


Figure 3.3 Total Suction vs. Depth, Boring T1

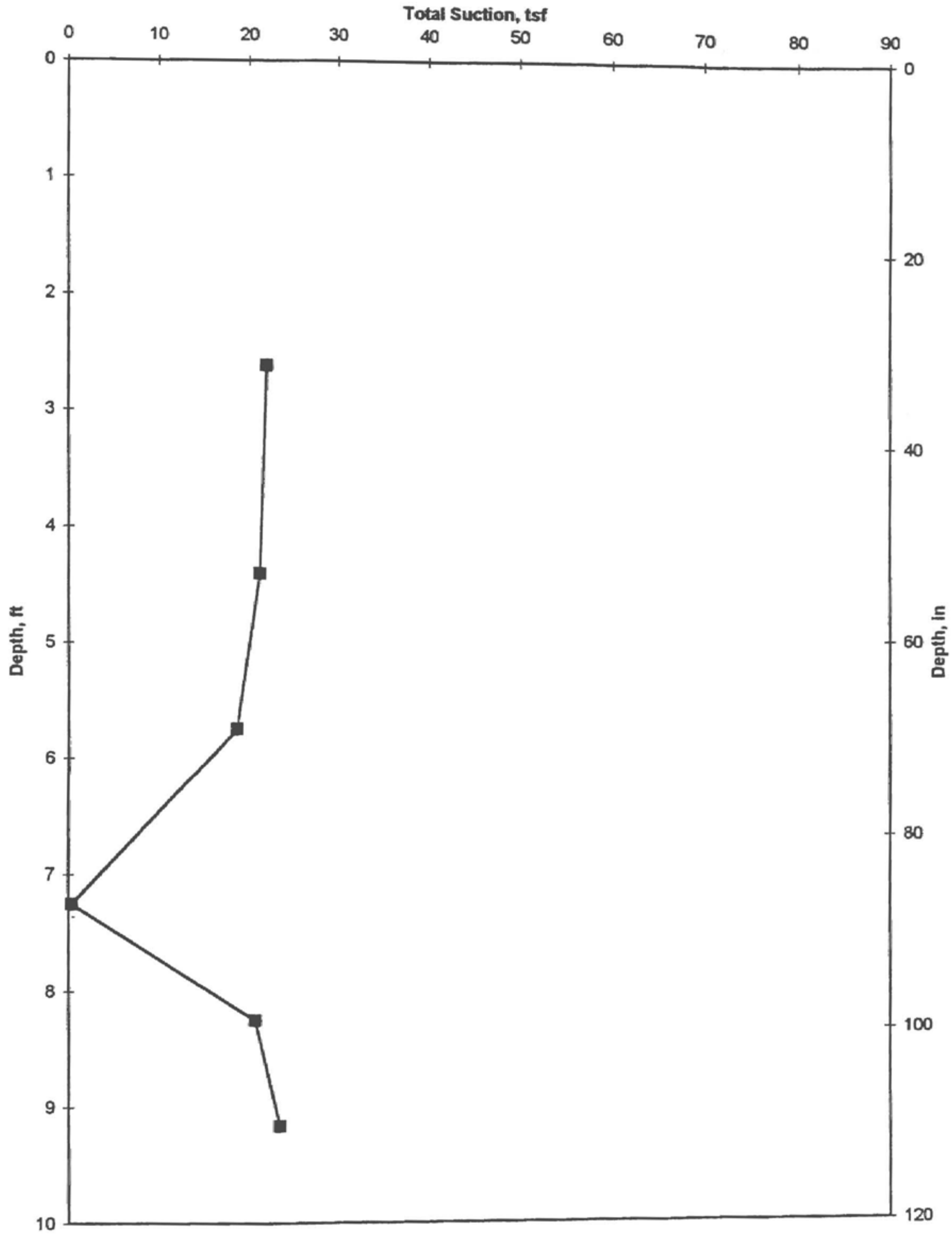


Figure 3.4 Total Suction vs. Depth, Boring T2

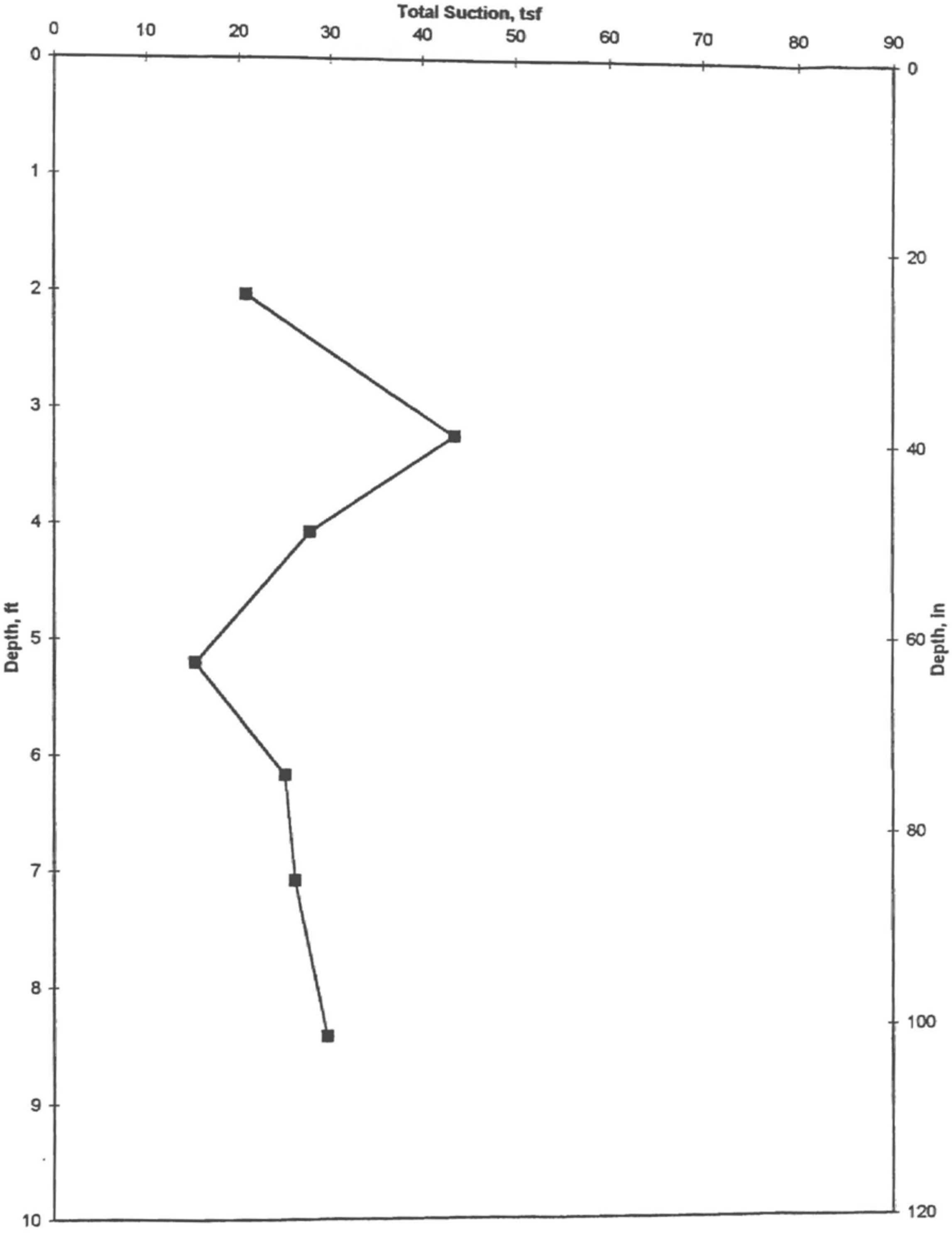


Figure 3.5 Total Suction vs. Depth, Boring T3

causing the soil to be more moist. Figure 3.5 shows boring T3 suction increasing from about 2 to 3 feet, decreasing down to about 5 feet, increasing for another 1 foot, and then remaining essentially constant with a slight increase. All three figures show suction varying most in the top 5 to 7 feet and then becoming relatively constant with depth. Since suction is a function of moisture and the most changes in suction occur in the upper layers, this suggests that the climate could be affecting the fluctuation in moisture causing these large variations in suction.

The second half of each push tube sample was used to measure density and water content. Each sample was unwrapped, weighed, and the dimensions were measured. From this information, the moist density was calculated. The water content was determined in accordance with ASTM D2216-92 (23). The samples were placed in tare cans, weighed, and placed in a drying oven at 110°C for twenty-four hours. After drying, the samples were again weighed in the tare cans. The water content was calculated using the weight of water and the dry weight of each sample. The results from the water content data are shown in relation to depth in Figures 3.6-3.8. The moisture content data for boring T1 show the moisture content near the ground surface to be less (drier) than the deeper soil. It varies some with depth but shows an overall increase with depth. The drier soil at the top indicates that the top layers are being affected by the climate. Boring T2 data show the most variation with depth. It varies dramatically down to about 5 feet, then steadily increases. This large variation could be caused by the effect of , not only climatic changes, but also the excess runoff from the runway that often collects on the shoulder and pavement edge.

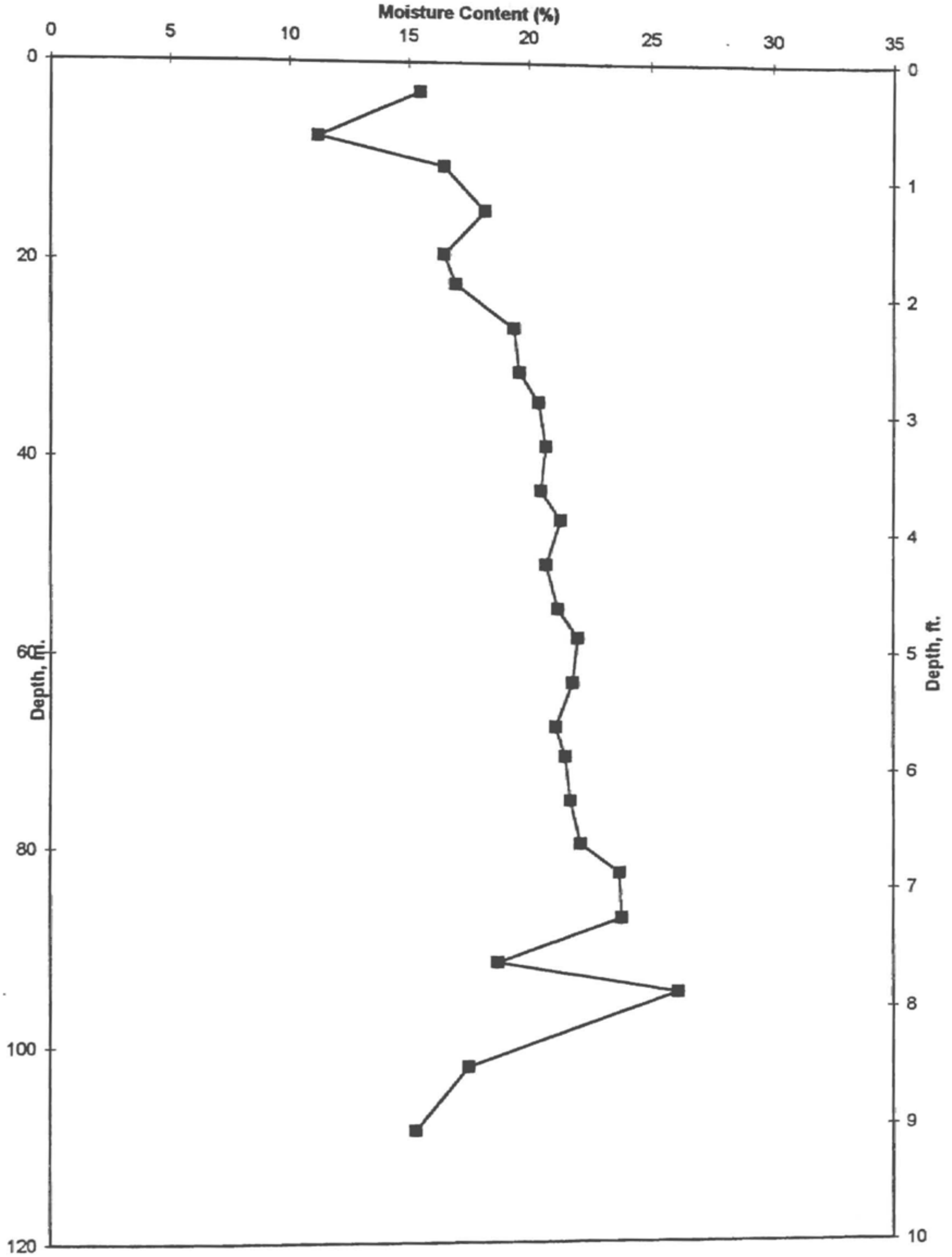


Figure 3.6 Moisture Content vs. Depth, T1

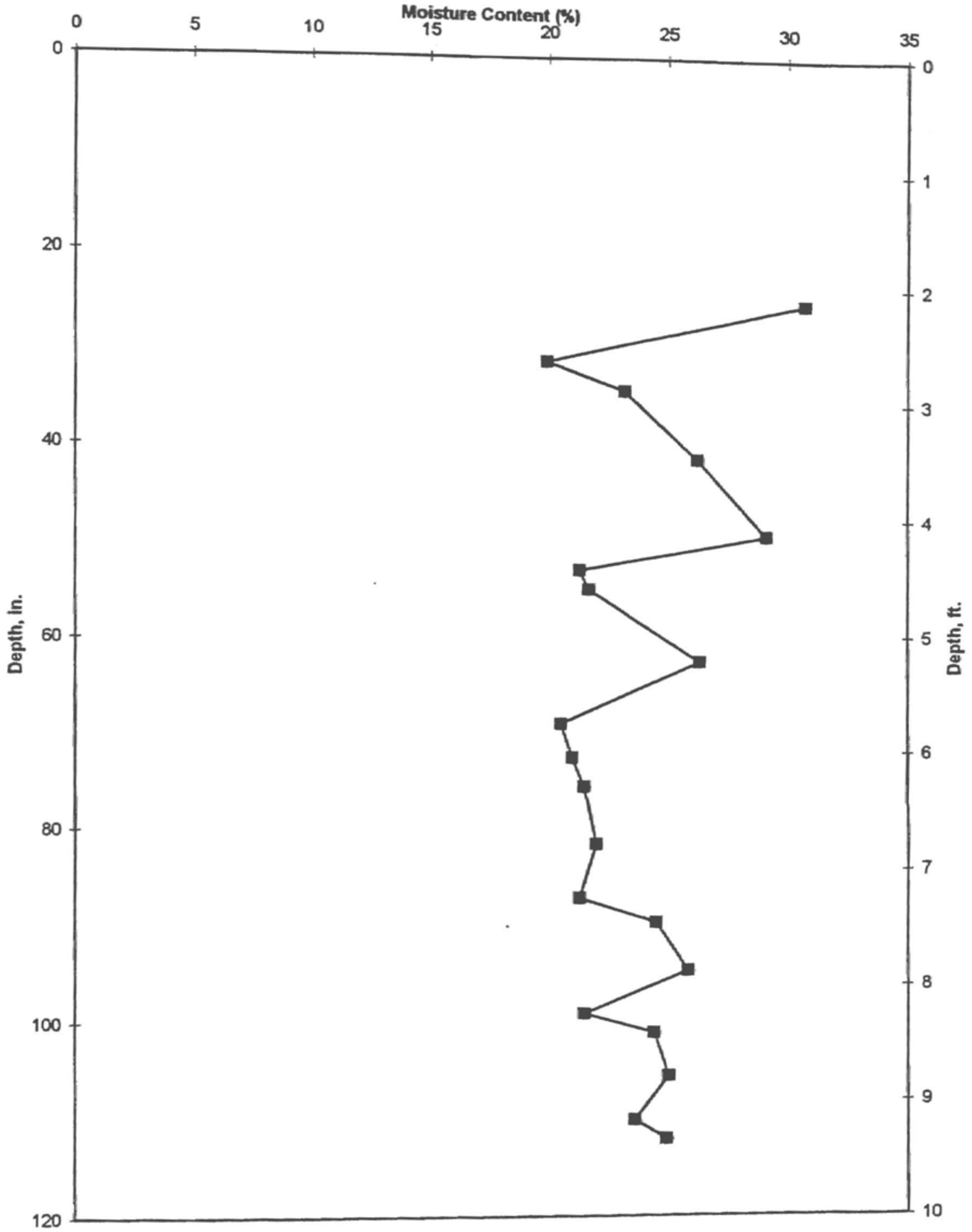


Figure 3.7 Moisture Content vs. Depth, T2

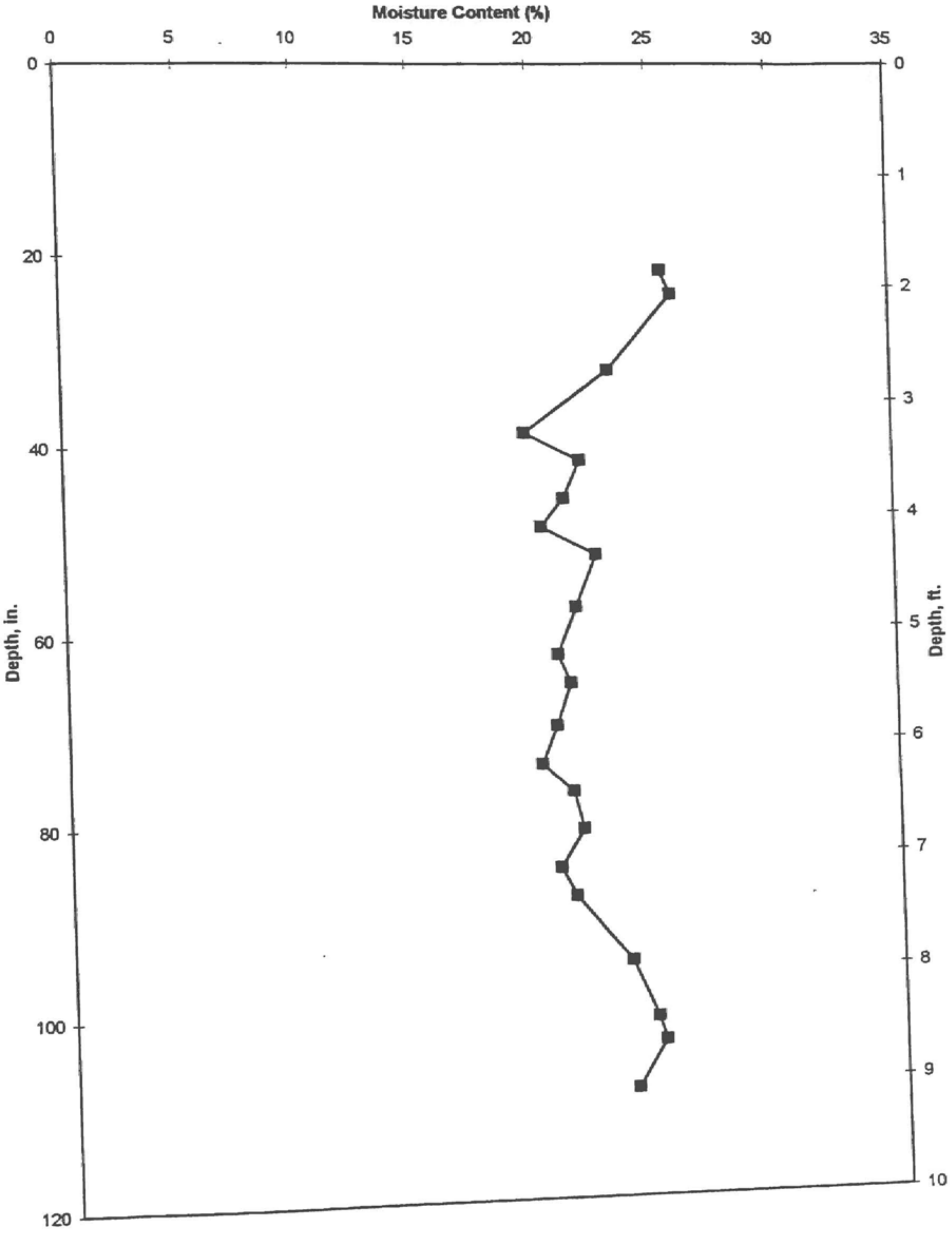
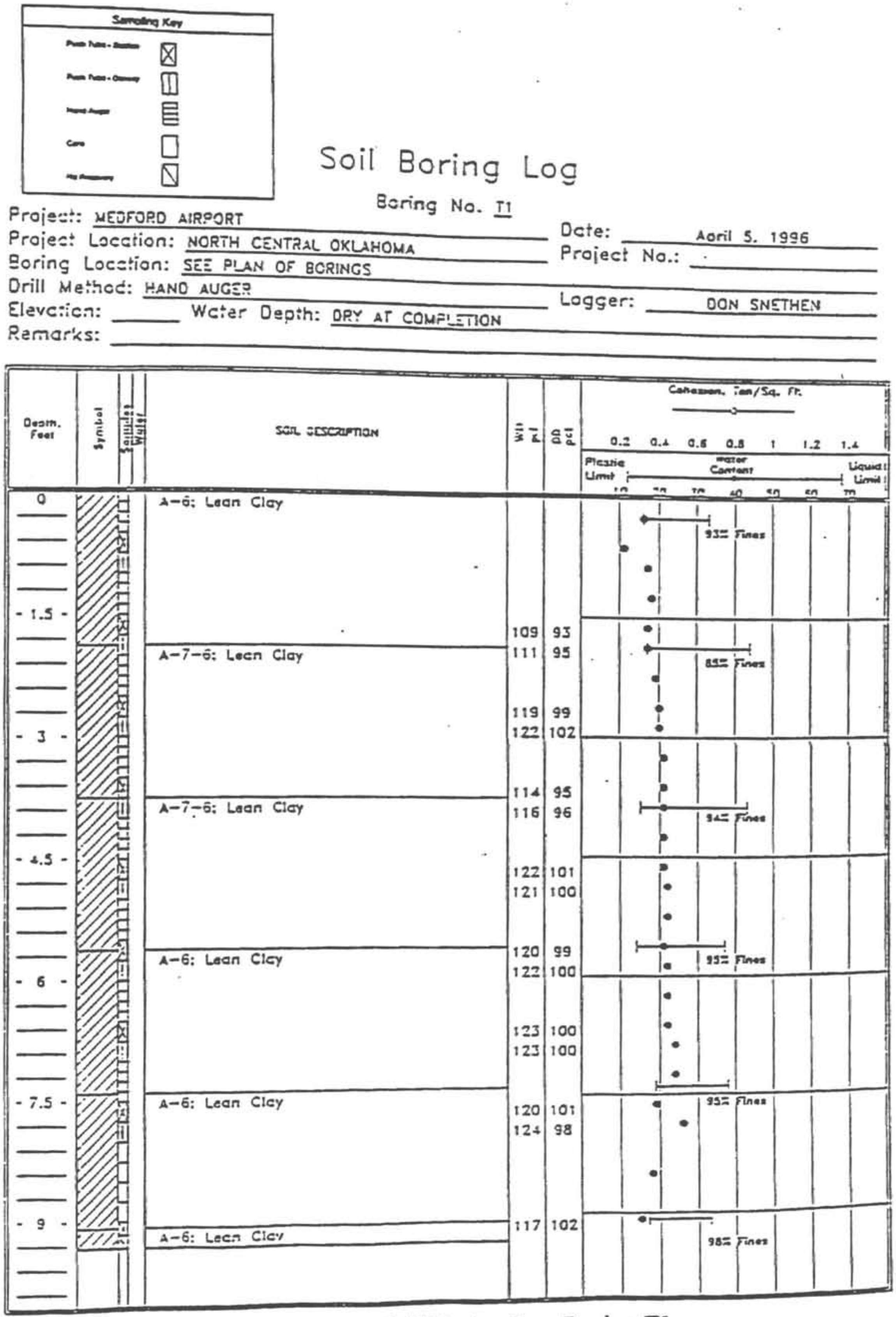


Figure 3.8 Moisture Content vs. Depth, T3

Boring T3 shows the least variation in moisture content. However, the moisture content is higher in the upper region. This is due to moisture accumulation below the covered area. Moisture decreases for about the first 3 feet and then continually increases. Boring T3 data show little variation because this area is covered and is not as affected by climate and/or moisture changes. These data, along with the suction data, suggest that the active zone (where most variation is observed) is approximately 5 to 7 feet below the ground surface. The dry density was also determined by reweighing the dry samples.

Using the water content and density data, the samples were grouped according to depth, similar water content and density measurements. The soil for each depth group was then mixed and soil passing the No. 40 sieve was retained. This soil was used to run Atterberg Limits and % - 200 tests. The Atterberg Limits were conducted as specified by ASTM D 4318-93 "Standard Test Method for Liquid Limit, Plastic Limit, and Plasticity Index of Soils" (24). ASTM D 422-63 "Standard Test Method for Particle-Size Analysis of Soils" was followed to perform the % - 200 testing (25). The results of the classification and other related tests are shown on the boring logs in Figures 3.9 through 3.11.

Climatological data are also helpful in evaluating the site at Medford. Oklahoma Department of Transportation acquired data from the Jefferson recording station which is located about six miles southwest of Medford (19). Records from 1900 to 1995 were evaluated. From these data, it was determined that this site experiences an average precipitation of 30.3 inches with a range of 13.6 to 55 inches on a yearly basis. The



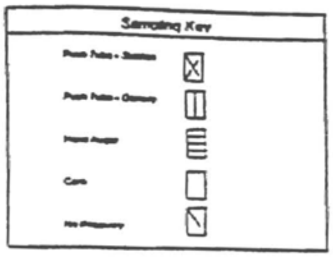
Soil Boring Log

Boring No. T1

Project: MEDFORD AIRPORT
Project Location: NORTH CENTRAL OKLAHOMA
Boring Location: SEE PLAN OF BORINGS
Drill Method: HAND AUGER
Elevation:
Water Depth: DRY AT COMPLETION
Remarks:
Date: April 5, 1996
Project No.:
Logger: DON SNETHEN

SOIL DESCRIPTION	Wt pcf	DD pcf
A-6; Lean Clay	109	93
A-7-6; Lean Clay	111	95
	119	99
	122	102
	114	95
A-7-6; Lean Clay	116	96
	122	101
	121	100
	120	99
A-6; Lean Clay	122	100
	123	100
	123	100
A-6; Lean Clay	120	101
	124	98
	117	102
A-6; Lean Clay		

Figure 3.9 Soil Boring Log, Boring T1



Soil Boring Log

Boring No. T2

Project: MEDFORD AIRPORT

Project Location: NORTH CENTRAL OKLAHOMA

Boring Location: SEE PLAN OF BORINGS

Drill Method: HAND AUGER

Elevation: ______ Water Depth: DRY AT COMPLETION

Remarks: ______

Date: APRIL 5, 1996

Project No.: ______

Logger: DON SNETHEN

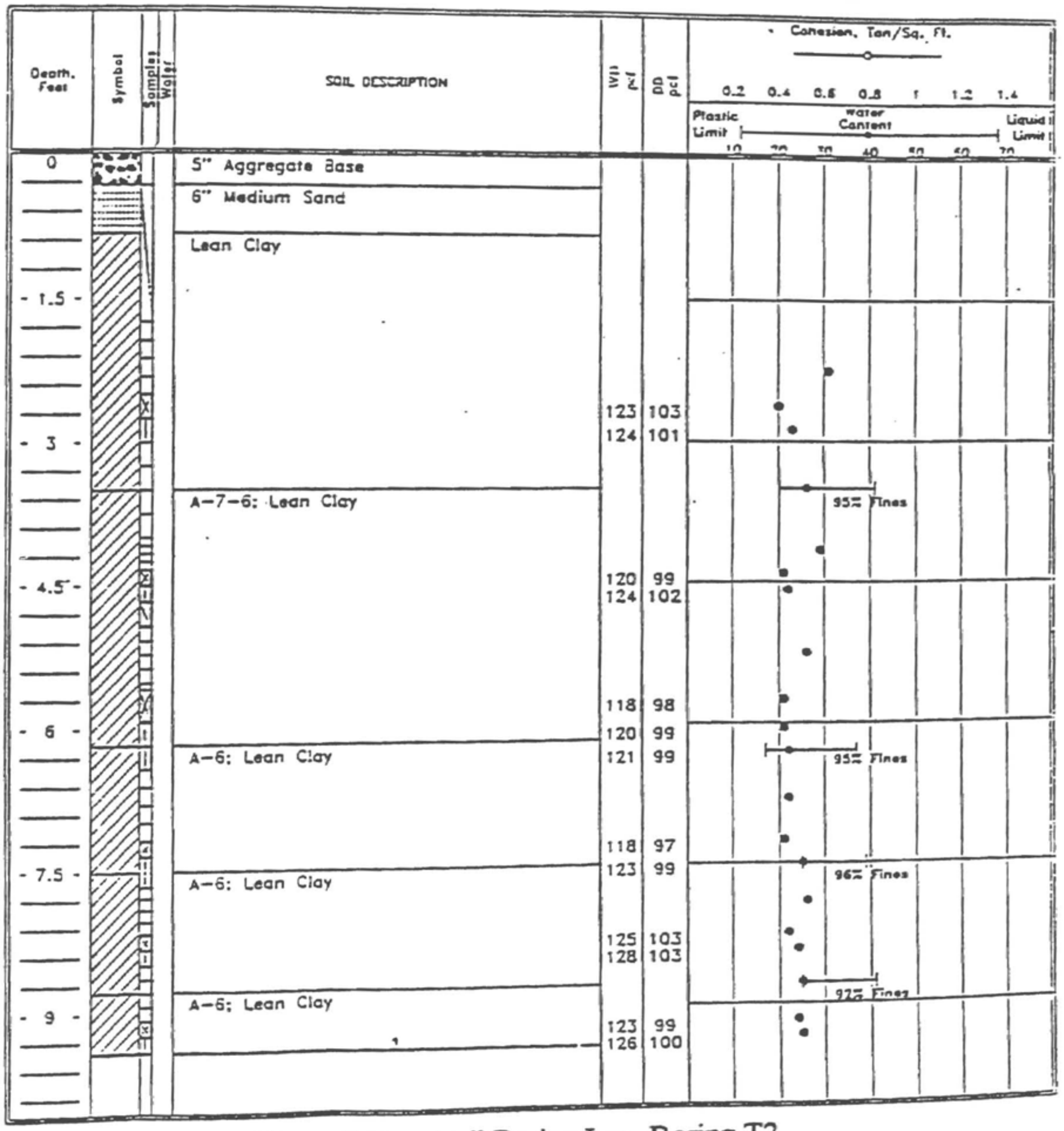
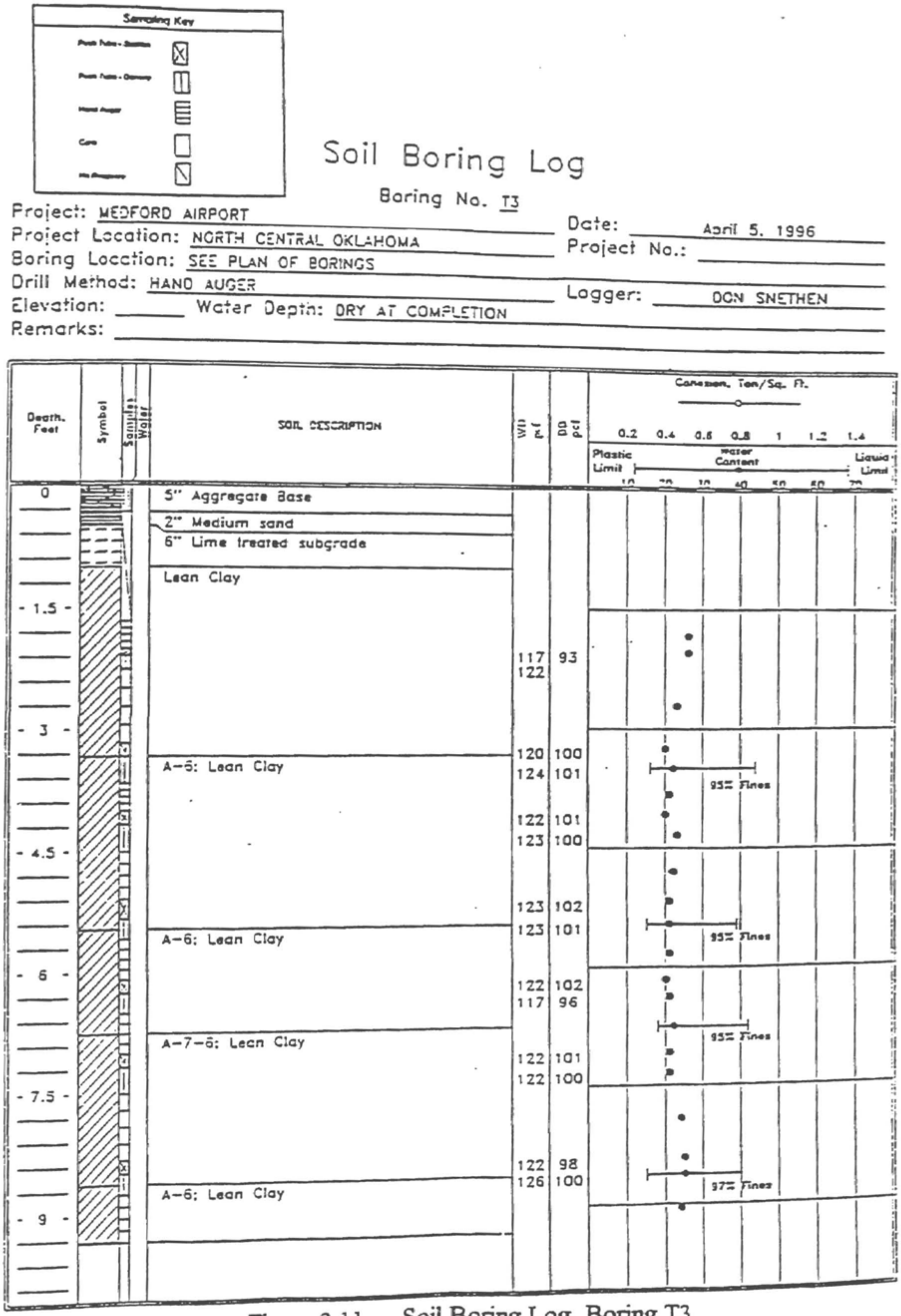


Figure 3.10 Soil Boring Log, Boring T2



Sampling Key

Soil Boring Log

Boring No. T3

Project: MEDFORD AIRPORT
Project Location: NORTH CENTRAL OKLAHOMA
Boring Location: SEE PLAN OF BORINGS
Drill Method: HAND AUGER
Elevation: ______ Water Depth: DRY AT COMPLETION
Remarks:
Date: April 5, 1996
Project No.:
Logger: DON SNETHEN

Depth, Feet	Soil Description	Wt pcf	DD pcf
0	5" Aggregate Base		
	2" Medium sand		
	6" Lime treated subgrade		
	Lean Clay		
1.5			
		117	93
		122	
3		120	100
	A-6: Lean Clay	124	101
		122	101
		123	100
4.5			
		123	102
		123	101
	A-6: Lean Clay		
6		122	102
		117	96
	A-7-6: Lean Clay	122	101
		122	100
7.5			
		122	98
		126	100
	A-6: Lean Clay		
9			

Figure 3.11 Soil Boring Log, Boring T3

Thornthwaite Moisture Index which is based on total monthly precipitation, mean monthly temperature and north latitude of the location was also analyzed by ODOT for this same time period. Two periods of decreasing moisture were observed. In these periods of dryness, soil suction increased, causing soil shrinkage.

To further examine precipitation and climate for the time period of this study, additional data were obtained from Oklahoma MESONET which has a monitoring site located at the airport. The results of these data are shown in Figures 3.12 and 3.13. Figure 3.12 shows average temperature and Figure 3.13 shows the average precipitation from October 1996 to March 1997. These data will be further discussed in Chapter 4 when analyzing the Sentry 200-AP results.

In addition to data collected for the moisture monitoring program, ODOT performed extensive tests on the condition of the airport runway (19). A surface condition survey was conducted using an asphalt rating form. This survey indicated that transverse and longitudinal cracking were the most predominant forms of pavement stress at the site. In order to measure the deflection basin and develop backcalculated elastic moduli for each pavement layer, the Falling Weight Deflectometer was used.

Based on the information collected from the survey and Falling Weight Deflectometer, ODOT concluded that the transverse cracking pattern appears to be caused by temperature changes. Furthermore, the longitudinal cracking is associated with the asphalt construction joints. Both forms of cracking are typical of asphalt pavements. However, the widths of these cracks are extraordinary with ranges from 0.05 - 0.20 feet

Figure 3.12 Average Temperature at Medford Airport

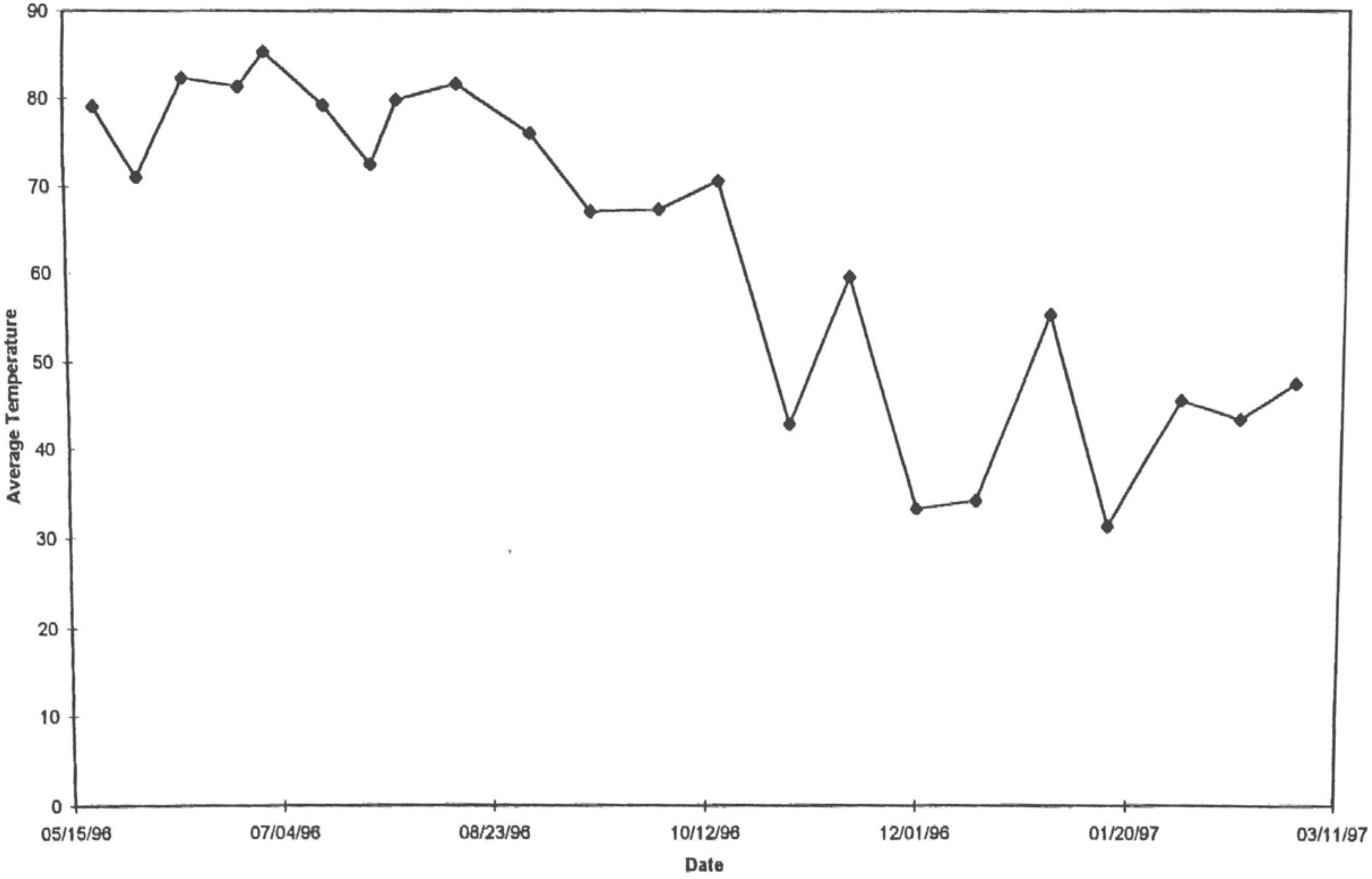
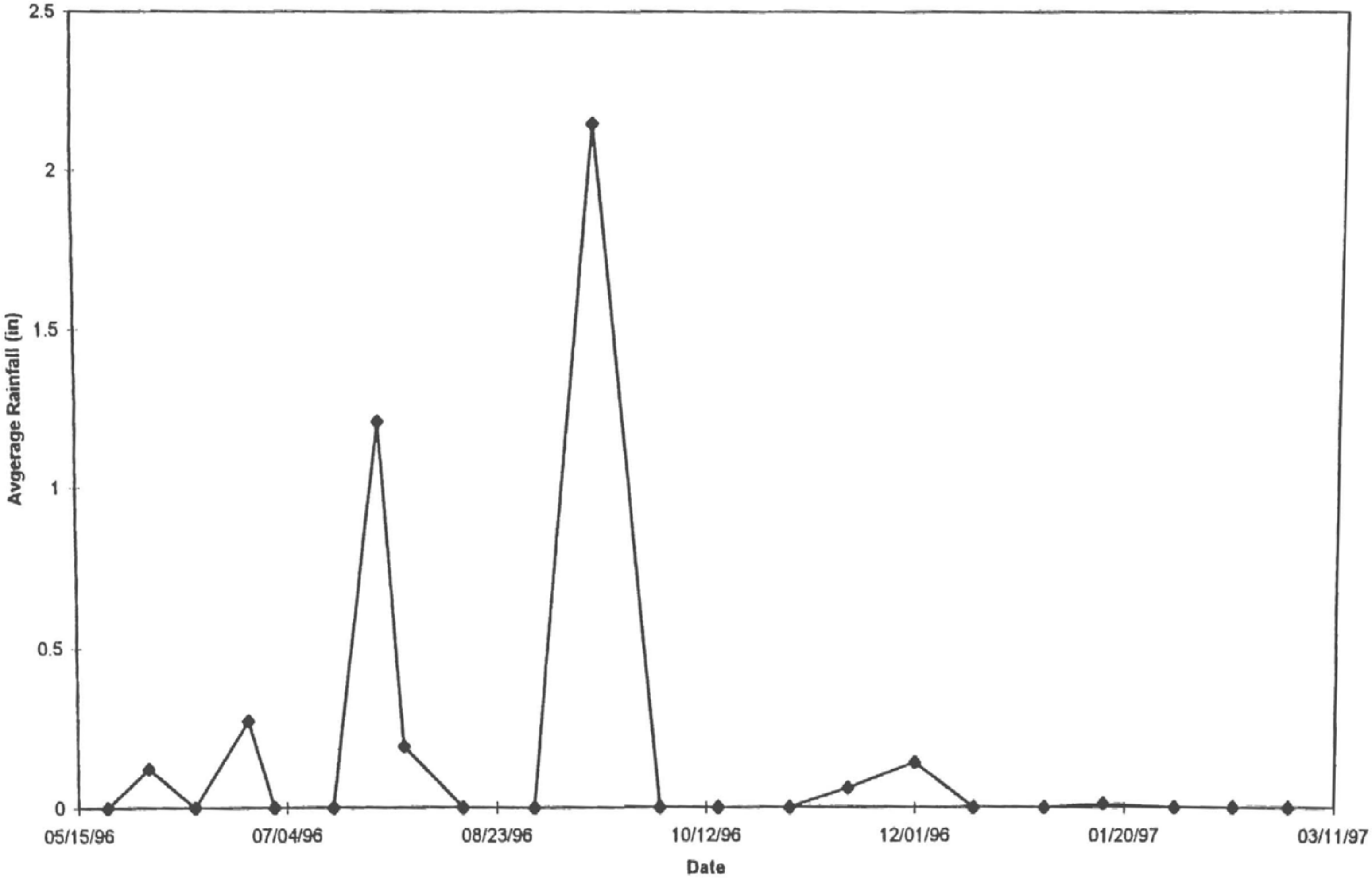


Figure 3.13 Average Precipitation at Medford Airport



for the rubber filled cracks and 0.10 to 0.30 feet for the asphalt filled cracks (19). Although some of the cracks appear quite wide, the survey determined that the pavement is in the "normal maintenance only" category. Moreover, the surface texture of the asphalt shows no significant weathering and the majority of the surface drainage appears positive.

CHAPTER 4

MOISTURE MONITIORING PROGRAM

The moisture monitoring program at the Medford Municipal Airport involved the use of a relatively new measuring system, the Troxler Sentry 200-AP. The procedure for using this system involves lowering a probe into an access tube installed vertically in the ground. The Sentry 200-AP is the only non-nuclear probe that operates in an access tube. A description of this program is described in the following sections.

Overview of Method

This method uses the functional relationship between dielectric constant and soil content to determine the moisture content for any given soil. Using the fact that the dielectric constant of water is very different than that of dry soil, a correlation can be made between the dielectric constant of soil and its water content. The probe, which is lowered into an access tube installed vertically into the ground, measures the dielectric constant of soil in the field by incorporating the soil as part of the dielectric of a capacitor located within the probe (12). The equipment involved has two main components, the probe and the evaluation unit. The probe consists of two electrodes spaced some distance apart. An electrical field is generated between the two electrodes within the probe; this penetrates into the surrounding soil and the frequency of the system changes with volumetric soil water content (12). This electrical field is measured and recorded by the evaluation unit. Once the dielectric constant is known, the water content is obtained using the functional relationship between the dielectric constant and the water content.

Description of Device

The Sentry 200 is designed for a wide variety of industrial and agricultural moisture measurement applications. The Sentry 200-AP, which was used for this program, responds to changes in the dielectric constant of material. This is based on the knowledge that most solids in soils such as sands, clay and organic materials have a dielectric constant from 2 to 4. In contrast, water has a dielectric constant of 78 (26). Therefore, the changes in dielectric constant of a material can be measured and the moisture content can be determined.

The Sentry 200-AP probe can be operated at any depth within the access tube. In addition, the moisture readings can be monitored manually or automatically. The recording device is capable of storing up to 1000 field measurements with a real-time clock and a calendar that records the exact time and date of the measurements. This information can then be printed or downloaded to a computer. The equipment includes a control unit, the calibrated moisture probe, an access tube mount, two sections of probe handle, and a cable stop. See Figure 4.1.

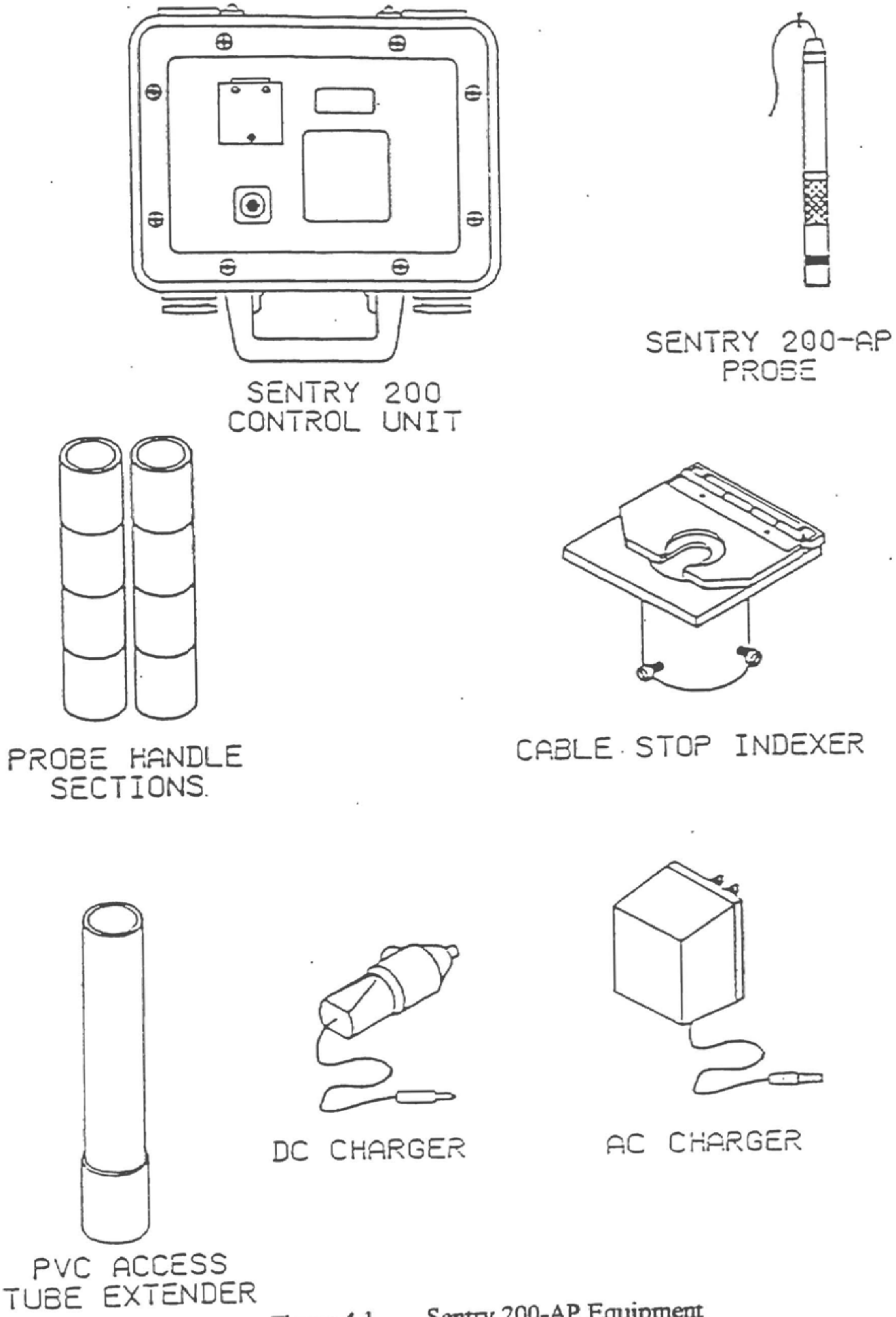


Figure 4.1 Sentry 200-AP Equipment

Access Tube Installation Procedure

In order to take moisture readings, the probe must be lowered into an access tube. Therefore, the access tube installation was the first step once the site was chosen. The tube is made of PVC (polyvinyl chloride) two inches in diameter, schedule 40, and is cut to the desired depth that the moisture readings are to be taken. There is an epoxy set PVC plug and wax covering over the end to be installed in the ground. The following steps were followed for the installation of the access tubes at Medford Airport:

- Location of the area where measurements were to be taken was chosen.
- Maximum measurement depth was determined.
- Auger hole was started to a depth of six inches and a sample taken; a push tube sample was taken over the next six inches. This procedure was repeated to the desired depth.
- The PVC tube was cut to the correct length and pushed into the hole. The pipe fit tightly against the sides of the soil to prevent air voids which could skew moisture readings.

For this project, three access tubes were installed at the locations discussed in Chapter three. It should be noted that due to the runway pavement, the actual depths of the probe are different than the reading depths of probe. This is clarified in Figures 4.2 through 4.4.

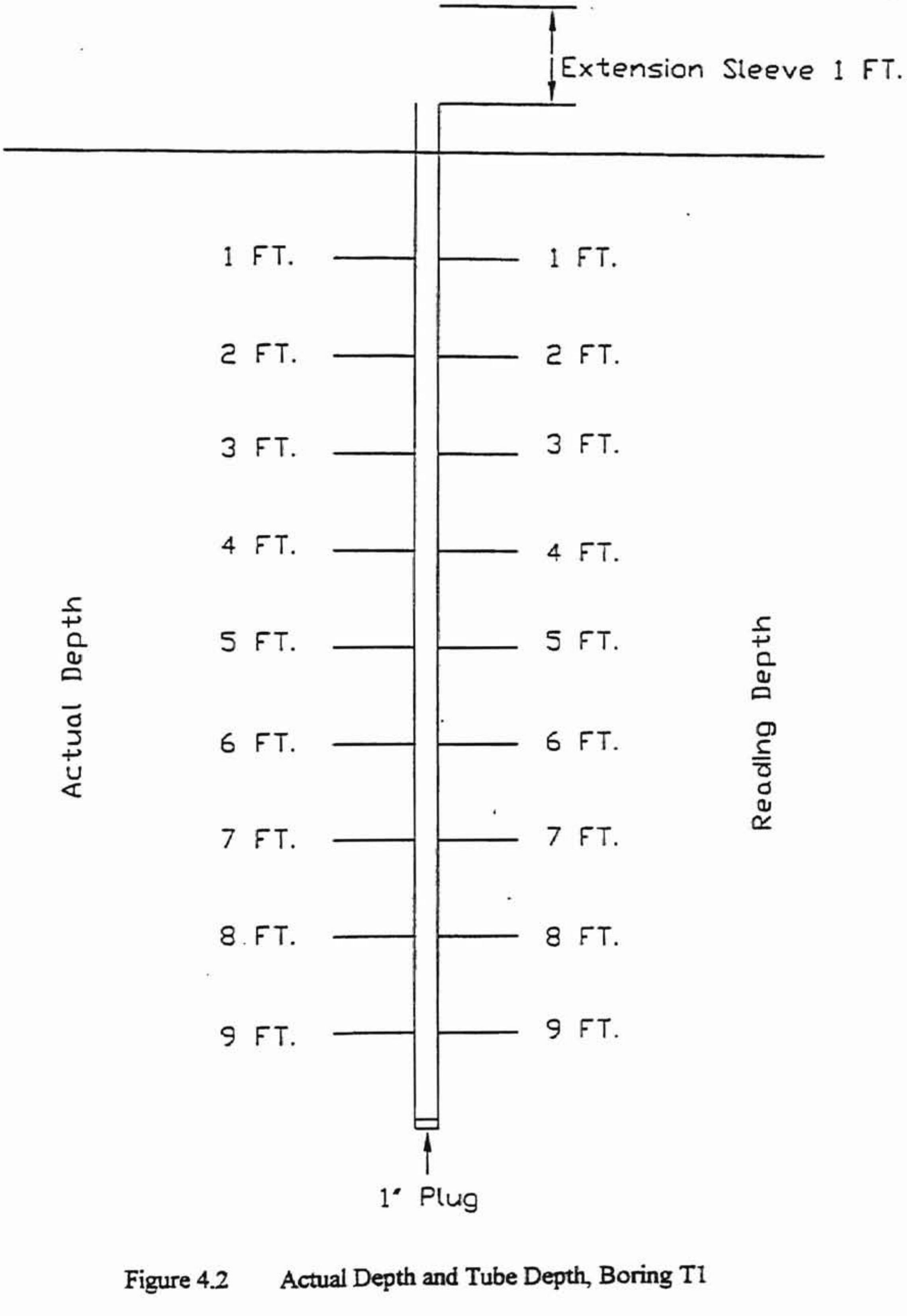


Figure 4.2 Actual Depth and Tube Depth, Boring T1

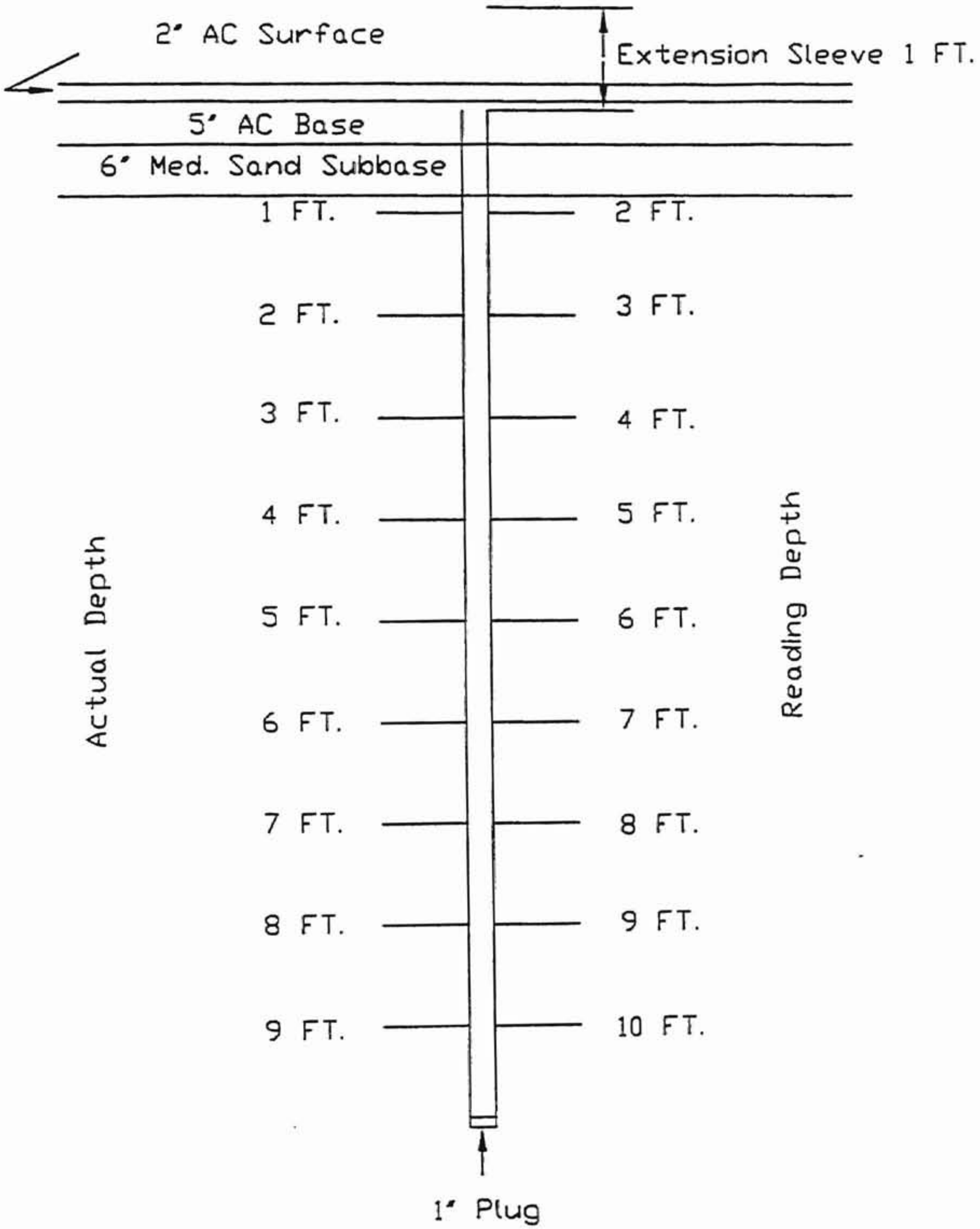


Figure 4.3 Actual Depth and Tube Depth, Boring T2

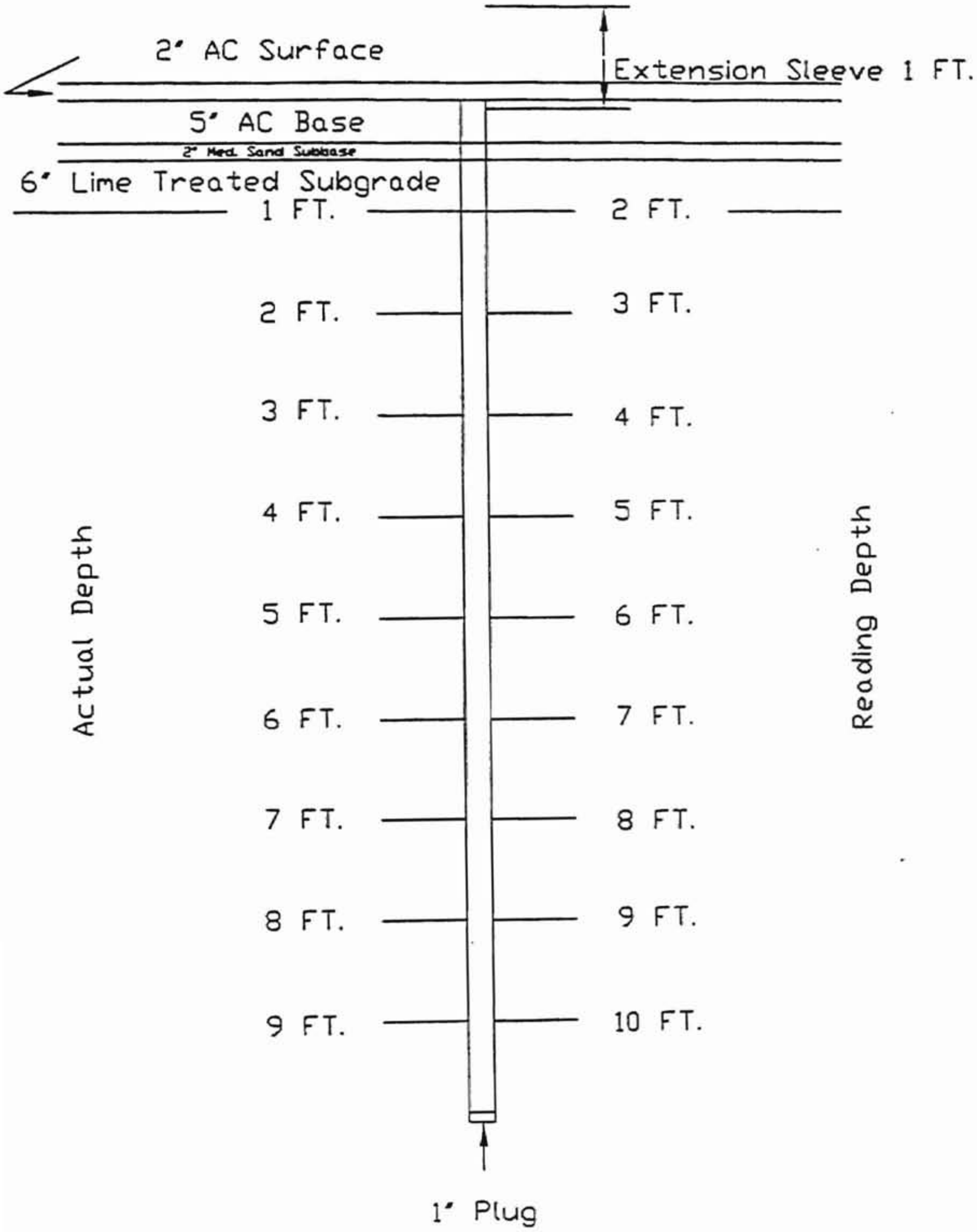


Figure 4.4 Actual Depth and Tube Depth, Boring T3

Calibration Procedure

The Sentry 200-AP factory calibration is accurate in sandy or loamy soils. Since the probe for this study was used in clay (a high moisture content soil), it was necessary to perform a custom calibration. The user's manual gives several recommendations to ensure the most accurate results. It is recommended that core samples be removed from the access tube locations. These samples should then be analyzed for moisture content which is used in performing the calibration. Obtaining samples with varying moisture levels is also recommended. This would be best accomplished by taking samples during both wet and dry periods. In addition, it is recommended that a core sample for each measurement depth be taken. For this study, samples were taken from the access tube locations for each measurement depth and were found to have varying moisture levels. However, samples were only taken for one period. After the core samples were analyzed and the initial Sentry 200-AP gauge readings were taken at the core locations, a new calibration was made. The Sentry 200-AP automatically calculated a new calibration curve based on the actual moisture obtained from core samples and the gauge readings taken at core locations. Since the soil type for this site is similar, it was not necessary to run a separate calibration for each monitoring tube.

Moisture Readings from Sentry 200-AP

After calibration, moisture readings were taken on an intermittent basis for several months. When readings were taken, the unit displayed a gauge reading and corresponding volumetric moisture content. These results were recorded for each depth at each of the boring locations. In order to compare the data to lab results, the volumetric water content was converted to gravimetric water content.

The results of the Sentry 200-AP are shown in Figures 4.5 through 4.10. Figures 4.5, 4.6, and 4.7 show moisture content fluctuating with time for depths of 2 to 9 feet. These figures can be analyzed along with the MESONET climatological data to show the relationship between the changing moisture conditions with changing temperature and precipitation. When comparing the plot of boring T1 data to the climatological plots, an increase in moisture content is noted at the end of July 1996 which coincides with a large increase in precipitation also occurring in late July. Moreover, the overall trend of moisture content increases with decreasing temperature and decreases with increasing temperature. Figure 4.6 shows the results for boring T2 data. The moisture variations are more subtle than for boring T1. There is still a slight increase in moisture content as precipitation increases and temperature decreases. At seven feet there is a significant increase in moisture content occurring in May 1997. Again, this could indicate a lense of sand at that depth. Boring T3 moisture variations are also more subtle compared to boring T1. However, there is more variations at individual depths than with boring T2. For example, at nine feet, the moisture content decreases in June 1997 when all other depths increase. Therefore, this is probably an error. In addition, the moisture content at six feet increases dramatically from June 1996 to July 1996. This could possibly be the same lense discussed for boring T2.

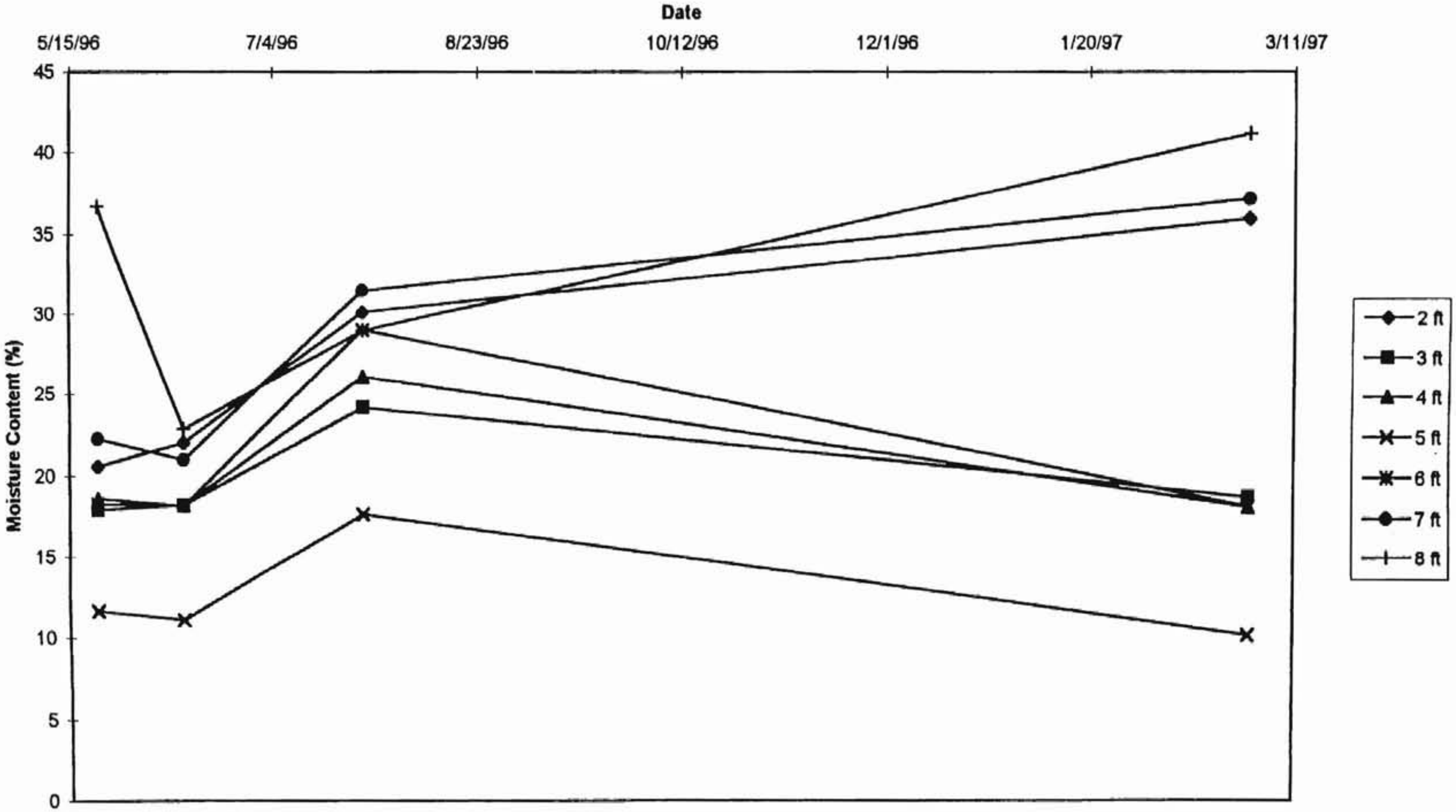


Figure 4.5 Moisture Variations vs. Time for Various Depths, Boring T1

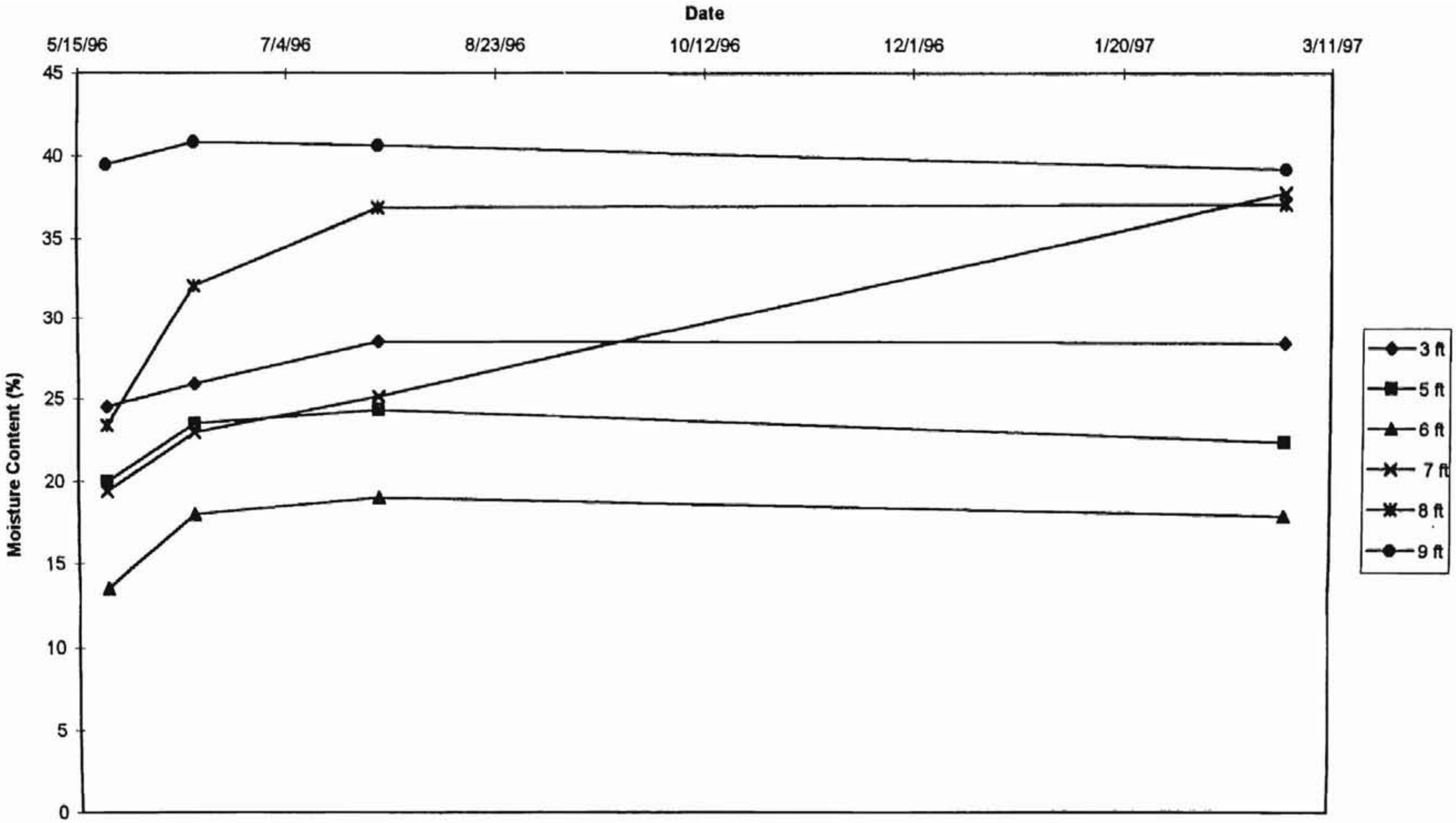


Figure 4.6 Moisture Variations vs. Time for Various Depths, Boring T2

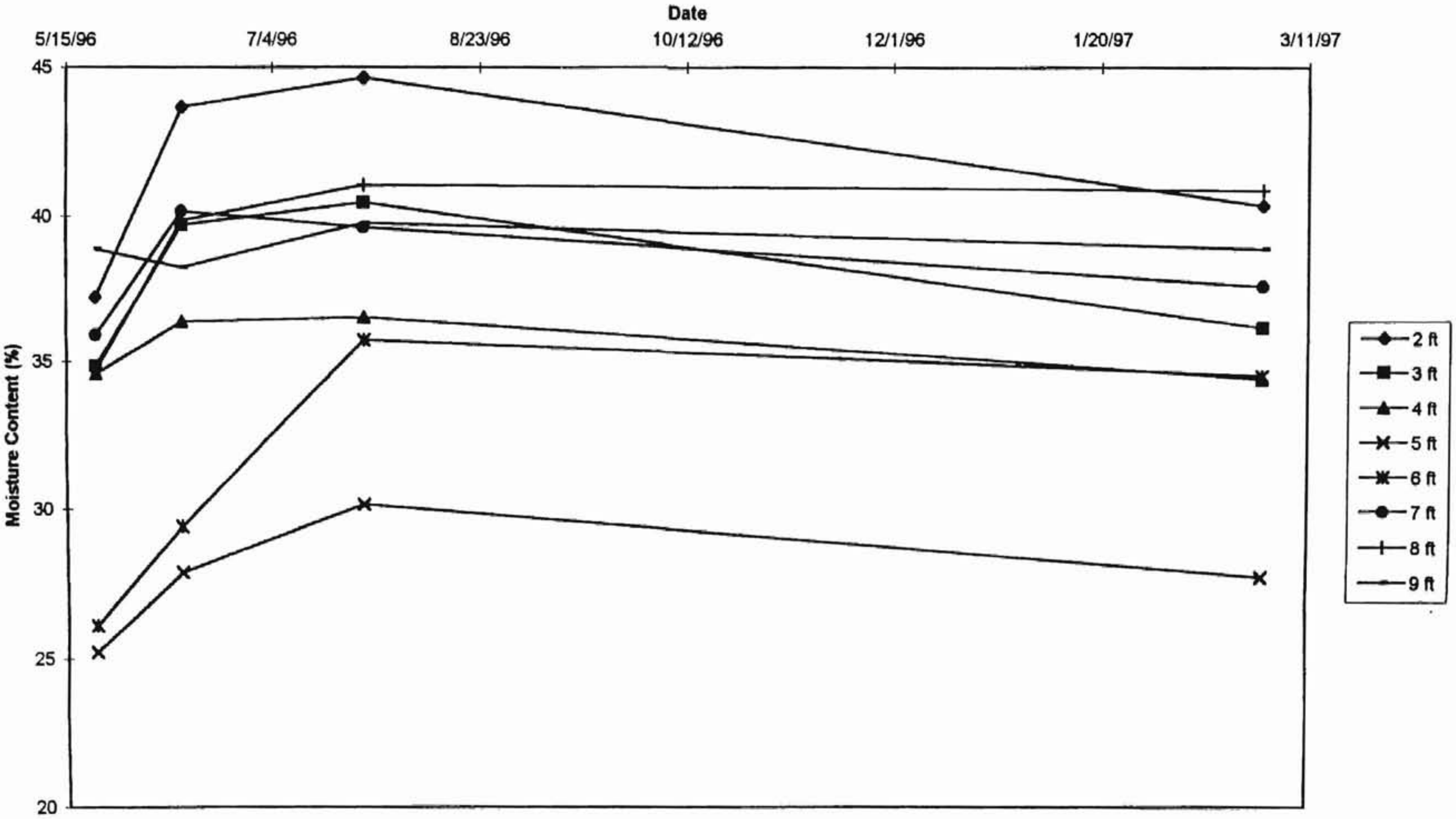


Figure 4.7 Moisture Variations vs. Time for Various Depths, Boring T3

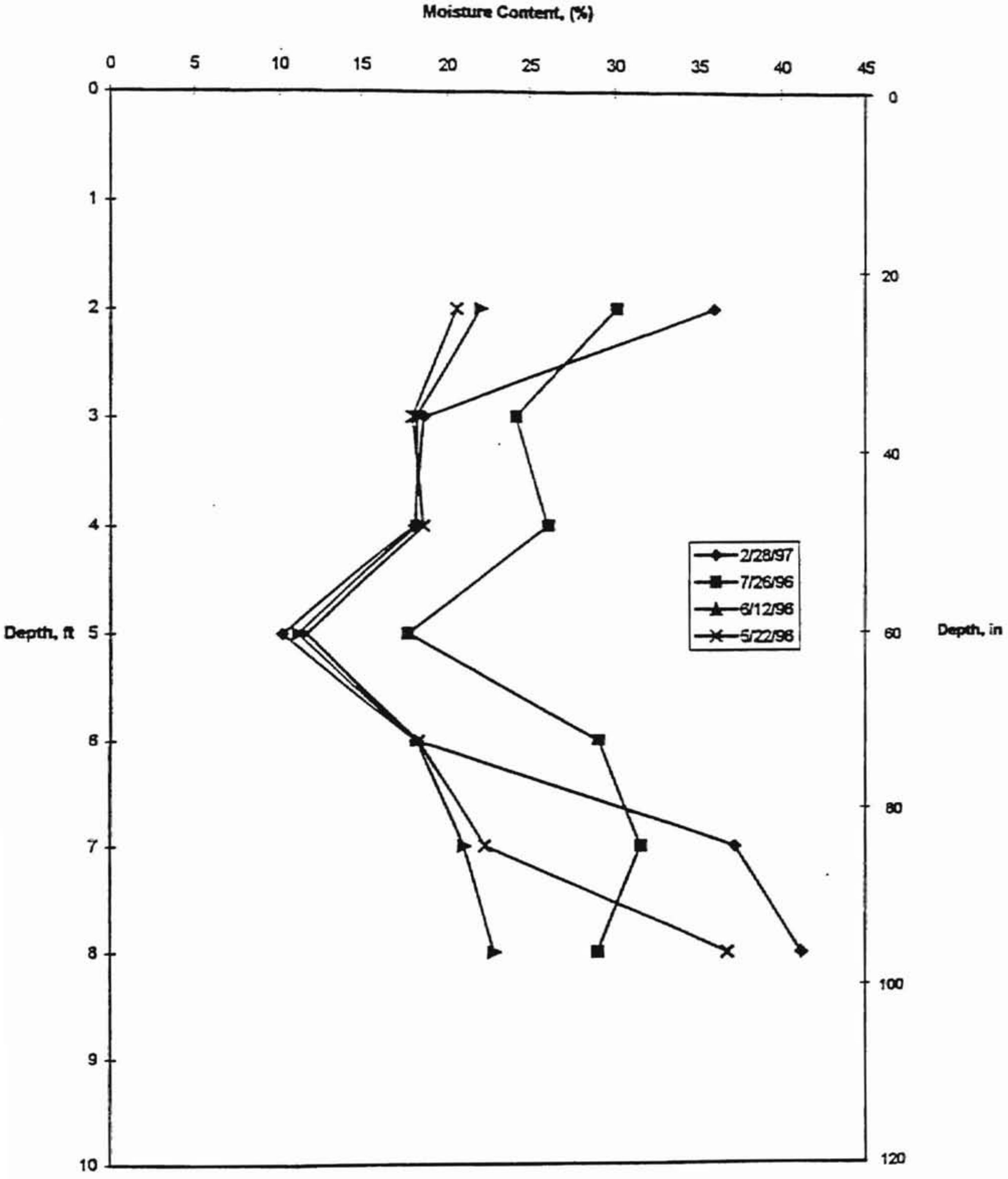


Figure 4.8 Moisture Content vs. Depth
for various Times, Boring T1

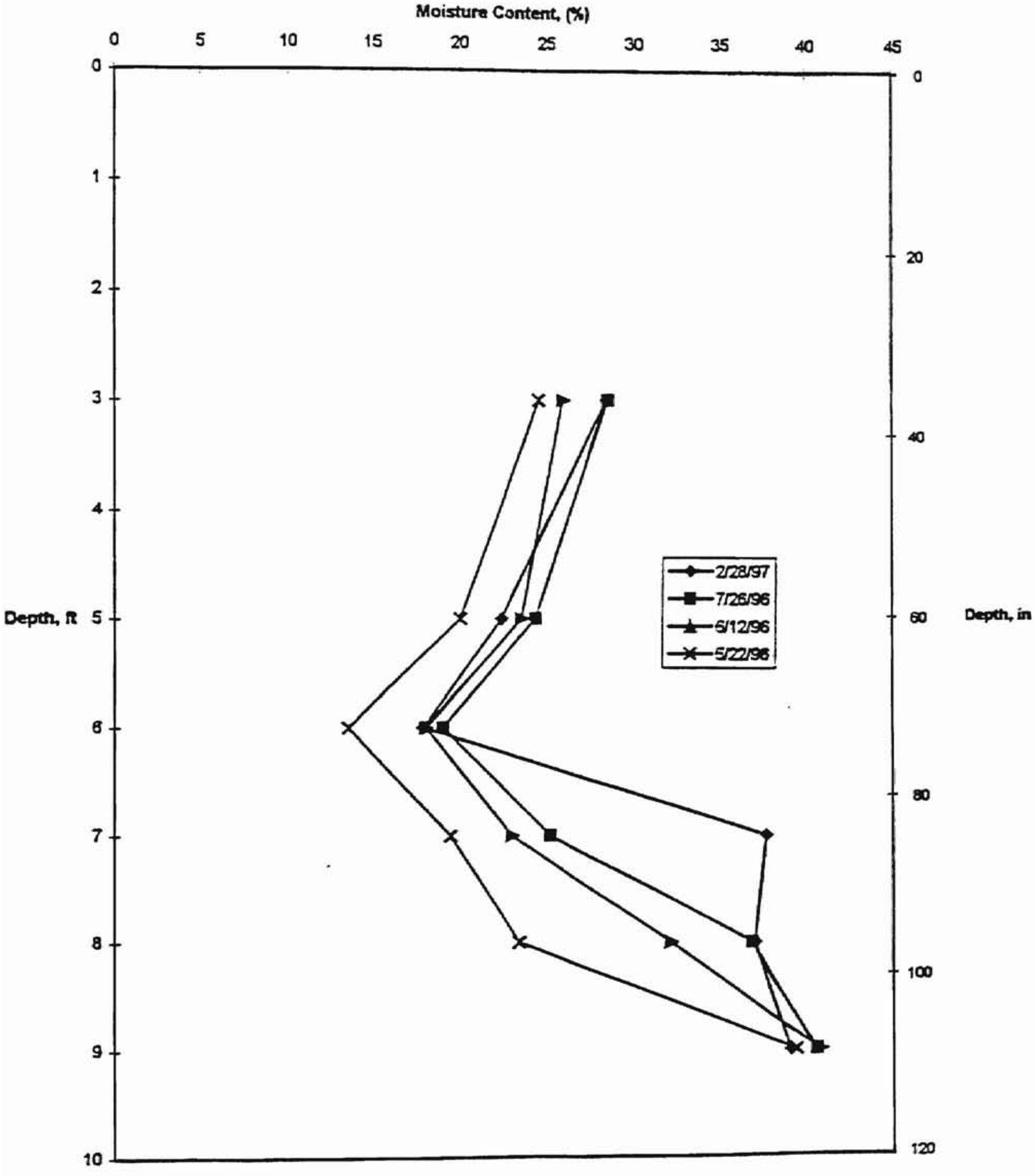


Figure 4.9 Moisture Content vs. Depth for various Times, Boring T2

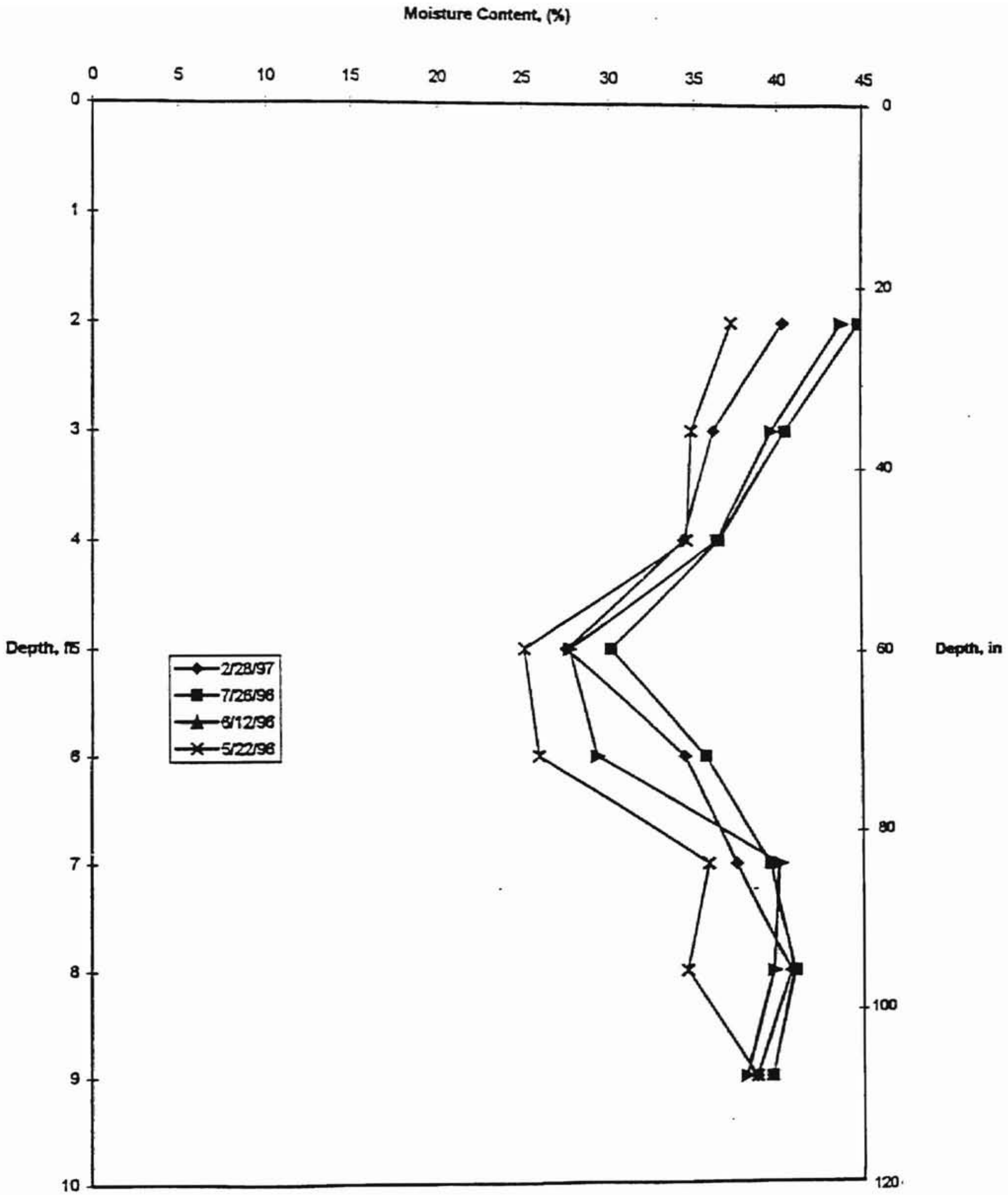


Figure 4.10 Moisture Content vs. Depth for various Times, Boring T3

Figures 4.8, 4.9, and 4.10 can be used to analyze the variation of moisture content with depth. Figure 4.8 shows boring T1 data, which again, have the largest most dramatic variation in moisture content. In addition, the overall moisture content is drier than the covered areas for the upper five feet. This is probably due to effects of the climate. The fluctuations seem most noticeable from the ground surface down to five feet. Therefore, the active zone is probably around five feet. Below five feet, the moisture content constantly increases with depth. Boring T2 also shows the more variation in the upper layers (from the ground surface to six feet) which again indicates the location of the active zone. The moisture content is also higher in boring T2 than for T1 probably because it is covered and not as affected by climatic conditions. The moisture content for boring T3 is considerably higher than the T1 or T2 and the variation in moisture content is also smaller. This is most likely because this boring is covered, and away from the pavement edge which causes moisture accumulation. Thus, it is much less affected by climate than the other two. In summary, boring T1 data show the largest fluctuations in moisture content. Since this boring is not covered by pavement it seems reasonable that it would be most affected by temperature and precipitation changes. Although boring T2 is covered, it is still close to the pavement edge so it is affected but to a less extent by temperature changes. However, since it is near the pavement edge it receives more precipitation than the other covered boring T3 due to runoff from the runway. Therefore, the moisture content is higher than T3. Moreover, T3 shows the least amount of moisture variation with changing climatological conditions indicating that covered areas away from pavement edges are less affected by climate conditions. Although T3 has less moisture content variation, it is significant enough that it could cause the overlying pavement to exhibit stress cracks due to soil shrinkage and swell. This would be more aggravated by aircraft loads which could further propagate cracks. In addition, all boring data indicate that the active zone for this area is around five to seven feet.

Use of the Sentry 200-AP has many advantages including the speed of measurement, low cost (after initial equipment purchase), portability, and high resolution. However, this method also has some disadvantages. The calibration curve is non-linear and soil-dependent which may present difficulties in precision of measurement. The access tube installation is rigorous and any imperfection can cause large errors in readings. At present, this method is most useful for repeated measurements at the same site over a period of time where the main concern is changes in water content as opposed to absolute values. Therefore, for this study the Sentry 200-AP was beneficial. It was effectively used to show changes in moisture content with depth and time for the Medford Airport site.

CHAPTER 5

CONCLUSIONS

The data collected in this study were compiled and analyzed and the following general correlations were noted. There is a larger moisture variation in the unpaved area than the paved areas at the Medford Airport site. The Sentry 200-AP probe was found to yield reliable and repeatable findings. In addition, this new method and the information attained throughout this project supported and confirmed the following:

1) There are new methods and field procedures to measure and record soil moisture content which can greatly increase ease and efficiency.
2) Environmental conditions create definitive changes in moisture variation. These include normal seasonal climatic patterns, variants of geographical location and soil types relating specifically to depths and attributes of active soil zones.
3) Variations in moisture content, particularly in a shrink swell soil, cause cracking in pavement surfaces.
4) If cracking zones become wide enough, they could create increased moisture under the surface further irritating a high shrink swell soil.

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APPENDIX A

Laboratory Test Data

Natural Water Content Lab Data

	T1				T2				T3	
Depth				Depth				Depth		
in	(ft)	%w		in	(ft)	%w		in	(ft)	%w
3.0	0.3	15.5		25.5	2.1	30.7		22.0	1.8	25.5
7.5	0.6	11.2		31.5	2.6	19.9		24.5	2.0	25.9
10.5	0.9	16.5		34.5	2.9	23.2		32.5	2.7	23.2
15.0	1.3	18.2		41.5	3.5	26.2		39.0	3.3	19.6
19.5	1.6	16.5		49.5	4.1	29.1		42.0	3.5	21.9
22.5	1.9	17.0		53.0	4.4	21.3		46.0	3.8	21.2
27.0	2.3	19.4		55.0	4.6	21.7		49.0	4.1	20.2
31.5	2.6	19.6		62.5	5.2	26.3		52.0	4.3	22.5
34.5	2.9	20.4		69.0	5.8	20.5		57.5	4.8	21.6
39.0	3.3	20.7		72.5	6.0	21.0		62.5	5.2	20.8
43.5	3.6	20.5		75.5	6.3	21.5		65.5	5.5	21.3
46.5	3.9	21.3		81.5	6.8	22.0		70.0	5.8	20.7
51.0	4.3	20.7		87.0	7.3	21.3		74.0	6.2	20.0
55.5	4.6	21.2		89.5	7.5	24.5		77.0	6.4	21.3
58.5	4.9	22.0		94.5	7.9	25.8		81.0	6.8	21.7
63.0	5.3	21.8		99.0	8.3	21.5		85.0	7.1	20.7
67.5	5.6	21.1		101.0	8.4	24.4		88.0	7.3	21.3
70.5	5.9	21.5		105.5	8.8	25.0		95.0	7.9	23.6
75.0	6.3	21.7		110.0	9.2	23.6		101.0	8.4	24.6
79.5	6.6	22.1		112.0	9.3	24.9		103.5	8.6	24.9
82.5	6.9	23.7						108.5	9.0	23.7
87.0	7.3	23.8								
91.5	7.6	18.7								
94.5	7.9	26.1								
102.0	8.5	17.5								
108.5	9.0	15.3								

Medford Boring 1 - Suction Data

Sample Number	B1 6-9	B1 6-9	B1 18-21	B1 18-21	B1 30-33	B1 30-33
Tare Number	A124	A138	A107	A180	A131	A67
Filter Paper	Top	Bottom	Top	Bottom	Top	Bottom
Wt. Tare	15.4738	15.5182	15.5915	15.4462	15.5750	15.7333
Wt. Filter Wet + Tare	15.7464	15.7949	15.8510	15.7011	15.8465	15.9999
Wt. Filter Dry + Tare	15.6986	15.7433	15.8107	15.6576	15.8024	15.9560
Wt. Water	0.0478	0.0516	0.0403	0.0435	0.0441	0.0439
Wt. Filter	0.2248	0.2251	0.2192	0.2114	0.2274	0.2227
Filter w%	21.2633	22.9231	18.3850	20.5771	19.3931	19.7126
Suction, Log kPa	3.6706	3.5413	3.8948	3.7240	3.8163	3.7914
Suction, tsf	48.9	36.3	82.0	55.3	68.4	64.6
Sample Number	B1 42-45	B1 42-45	B1 54-57	B1 54-57	B1 66-69	B1 66-69
Tare Number	A154	A25	A27	A153	A38	A45
Filter Paper	Top	Bottom	Top	Bottom	Top	Bottom
Wt. Tare	15.5300	15.5969	15.5941	15.4336	15.5729	15.7585
Wt. Filter Wet + Tare	15.7974	15.8922	15.8810	15.7142	15.8479	16.0391
Wt. Filter Dry + Tare	15.7497	15.8328	15.8256	15.6584	15.7931	15.9788
Wt. Water	0.0477	0.0594	0.0554	0.0558	0.0548	0.0603
Wt. Filter	0.2197	0.2359	0.2315	0.2248	0.2202	0.2203
Filter w%	21.7114	25.1802	23.9309	24.8221	24.8865	27.3718
Suction, Log kPa	3.6357	3.3655	3.4628	3.3934	3.3883	3.1947
Suction, tsf	45.1	24.2	30.3	25.8	25.5	16.4
Sample Number	B1 78-81	B178-81	B1 90-93	B1 90-93	B1 108-110	B1 108-110
Tare Number	A103	A169	A70	A40	A161	A173
Filter Paper	Top	Bottom	Top	Bottom	Top	Bottom
Wt. Tare	15.7234	15.4705	15.7080	15.7335	15.3851	15.3763
Wt. Filter Wet + Tare	15.9912	15.7426	15.9800	15.9959	15.6671	15.6456
Wt. Filter Dry + Tare	15.9533	15.6948	15.9306	15.9572	15.6168	15.5958
Wt. Water	0.0379	0.0478	0.0494	0.0387	0.0503	0.0498
Wt. Filter	0.2299	0.2243	0.2226	0.2237	0.2317	0.2195
Filter w%	16.4854	21.3107	22.1923	17.3000	21.7091	22.6879
Suction, Log kPa	4.0428	3.6669	3.5982	3.9793	3.6359	3.5596
Suction, tsf	115.3	48.5	41.4	99.6	45.2	37.9

Medford Boring 2 -Suction Data

Sample Number	B2 30-33	B2 30-33	B2 52-54	B2 52-54	B2 67-71	B2 67-71
Tare Number	A31	A171	A151	A162	A81	A140
Filter Paper	Top	Bottom	Top	Bottom	Top	Bottom
Wt. Tare	15.5412	15.5915	15.3618	15.6519	15.6291	15.6134
Wt. Filter Wet + Tare	15.82	15.8674	15.6529	15.9254	15.9067	15.8459
Wt. Filter Dry + Tare	15.7596	15.8134	15.5918	15.87	15.8517	15.7926
Wt. Water	0.0604	0.054	0.0611	0.0554	0.055	0.0533
Wt. Filter	0.2184	0.2219	0.23	0.2181	0.2226	0.1792
Filter w%	27.6557	24.3353	26.5652	25.4012	24.7080	29.7433
Suction, Log kPa	3.1726	3.4313	3.2576	3.3482	3.4022	3.0100
Suction, tsf	15.5	28.2	18.9	23.3	26.4	10.7
Sample Number	B2 86-88	B2 86-88	B2 98-100	B2 98-100	B2 109-111	B2 109-111
Tare Number	A57	A130	A109	A53	A121	A159
Filter Paper	Top	Bottom	Top	Bottom	Top	Bottom
Wt. Tare	15.591	15.6611	15.6228	15.6979	15.6418	15.4566
Wt. Filter Wet + Tare	15.9717	16.0401	15.9123	15.977	15.9194	15.7331
Wt. Filter Dry + Tare	15.8189	15.8863	15.8506	15.9207	15.8641	15.6761
Wt. Water	0.1528	0.1538	0.0617	0.0563	0.0553	0.057
Wt. Filter	0.2279	0.2252	0.2278	0.2228	0.2223	0.2195
Filter w%	67.0470	68.2948	27.0852	25.2693	24.8763	25.9681
Suction, Log kPa	1.5069	1.4900	3.2171	3.3585	3.3891	3.3041
Suction, tsf	0.3	0.3	17.2	23.8	25.6	21.0

Medford Boring 3 - Suction Data

Sample Number	B3 24-25	B3 24-25	B3 38-40	B3 38-40	B3 48-50	B3 48-50
Tare Number	A152	A166	A155	A83	A175	A178
Filter Paper	Top	Bottom	Top	Bottom	Top	Bottom
Wt. Tare	15.4789	15.4157	15.3317	15.5217	15.4203	15.5334
Wt. Filter Wet + Tare	15.7577	15.7010	15.6024	15.7816	15.6919	15.8193
Wt. Filter Dry + Tare	15.6994	15.6427	15.5538	15.7348	15.6392	15.7625
Wt. Water	0.0583	0.0583	0.0486	0.0468	0.0527	0.0568
Wt. Filter	0.2205	0.2270	0.2221	0.2131	0.2189	0.2291
Filter w%	26.4399	25.6828	21.8820	21.9615	24.0749	24.7927
Suction, Log kPa	3.2673	3.3263	3.6224	3.6162	3.4516	3.3957
Suction, tsf	19.3	22.1	43.8	43.2	29.5	26.0
Sample Number	B3 61-64	B3 61-64	B3 73-75	B3 73-75	B3 84-86	B3 84-86
Tare Number	A13	A136	A134	A139	A68	A132
Filter Paper	Top	Bottom	Top	Bottom	Top	Bottom
Wt. Tare	15.6900	15.5319	15.5096	15.4463	15.6810	15.5477
Wt. Filter Wet + Tare	15.9749	15.7930	15.7884	15.7245	15.9502	15.8248
Wt. Filter Dry + Tare	15.9126	15.7366	15.7317	15.6697	15.8951	15.7713
Wt. Water	0.0623	0.0564	0.0567	0.0548	0.0551	0.0535
Wt. Filter	0.2226	0.2047	0.2221	0.2234	0.2141	0.2236
Filter w%	27.9874	27.5525	25.5290	24.5300	25.7356	23.9267
Suction, Log kPa	3.1468	3.1807	3.3383	3.4161	3.3222	3.4631
Suction, tsf	14.6	15.8	22.8	27.2	21.9	30.3
Sample Number	B3 100-102	B3 100-102				
Tare Number	A21	A146				
Filter Paper	Top	Bottom				
Wt. Tare	15.6881	15.7053				
Wt. Filter Wet + Tare	15.9638	15.9751				
Wt. Filter Dry + Tare	15.9100	15.9231				
Wt. Water	0.0538	0.0520				
Wt. Filter	0.2219	0.2178				
Filter w%	24.2452	23.8751				
Suction, Log kPa	3.4383	3.4671				
Suction, tsf	28.7	30.6				

APPENDIX B

Field Monitoring Data

Moisture Variations by Sentry 200-AP at Monitoring Tube T1

2/28/97			T1			
Depth (ft)	Reading 1	Reading 2	Avg. Vol. w (%)	Density (psf)	Density (g/cm3)	Grav. w (%)
1	56.3	56.3	56.3	X	X	X
2	54.3	54.6	54.45	94.7	1.5152	35.93585
3	30.2	30.5	30.35	101.7	1.6272	18.651672
4	27.7	27.4	27.55	95.5	1.528	18.030105
5	16.3	15.9	16.1	99.5	1.592	10.113065
6	29	29	29	100.2	1.6032	18.088822
7	59.4	59.1	59.25	99.7	1.5952	37.142678
8	65.2	63.9	64.55	98	1.568	41.167092
9	68.6		68.6	101.6	1.6256	42.199803
7/26/96						
Depth (ft)	Reading 1	Reading 2	Avg. Vol. w (%)	Density (psf)	Density (g/cm3)	Grav. w (%)
1	52.1		52.1	X	X	X
2	45.6		45.6	94.7	1.5152	30.095037
3	39.3		39.3	101.7	1.6272	24.151917
4	39.8		39.8	95.5	1.528	26.04712
5	28.1		28.1	99.5	1.592	17.650754
6	46.5		46.5	100.2	1.6032	29.004491
7	50.2		50.2	99.7	1.5952	31.469408
8	45.4		45.4	98	1.568	28.954082
9	198.7		198.7	101.6	1.6256	122.23179
6/12/96						
Depth (ft)	Reading 1	Reading 2	Avg. Vol. w (%)	Density (psf)	Density (g/cm3)	Grav. w (%)
1	21.4	20.5	20.95	X	X	X
2	33.1	33.6	33.35	94.7	1.5152	22.010296
3	29	30.3	29.65	101.7	1.6272	18.221485
4	27.4	28.2	27.8	95.5	1.528	18.193717
5	17.5	17.8	17.65	99.5	1.592	11.086683
6	28.7	29.6	29.15	100.2	1.6032	18.182385
7	33.3	33.6	33.45	99.7	1.5952	20.969157
8	36.4	35.2	35.8	98	1.568	22.831633
9		65.4	65.4	101.6	1.6256	40.231299
5/22/96						
Depth (ft)	Reading 1	Reading 2	Avg. Vol. w (%)	Density (psf)	Density (g/cm3)	Grav. w (%)
1	19.2	18	18.6	X	X	X
2	32.1	30.2	31.15	94.7	1.5152	20.558342
3	29.9	28.5	29.2	101.7	1.6272	17.944936
4	29.6	27.3	28.45	95.5	1.528	18.61911
5	19.7	17.4	18.55	99.5	1.592	11.65201
6	29.4	29.2	29.3	100.2	1.6032	18.275948
7	36	35	35.5	99.7	1.5952	22.254263
8	56	59.1	57.55	98	1.568	36.702806
9				101.6		

Moisture Variations by Sentry 200-AP at Monitoring Tube T2

2/28/97			T2			
Depth (ft)	Reading 1	Reading 2	Avg. Vol. w (%)	Density (psf)	Density (g/cm3)	Grav. w (%)
1	46.8	46.8	46.8	X	X	X
2	44.6	42.1	43.35	X	X	X
3	45.4	46.4	45.9	100.8	1.6128	28.459821
4	48.6	48	48.3	X	X	X
5	36.7	36.1	36.4	101.8	1.6288	22.347741
6	28.7	27.9	28.3	99.1	1.5856	17.848133
7	59.4	58.2	58.8	97.4	1.5584	37.731006
8	61.4	60.7	61.05	103	1.648	37.044903
9		62.3	62.3	99.4	1.5904	39.172535
7/26/96						
Depth (ft)	Reading 1	Reading 2	Avg. Vol. w (%)	Density (psf)	Density (g/cm3)	Grav. w (%)
1	48.6	48.6	48.6	X	X	X
2	47.5	47	47.25	X	X	X
3	47.4	44.6	46	100.8	1.6128	28.521825
4	49	50.4	49.7	X	X	X
5	39.7	39.5	39.6	101.8	1.6288	24.312377
6	29.6	30.6	30.1	99.1	1.5856	18.98335
7	39.2	39.2	39.2	97.4	1.5584	25.154004
8	59.5	62	60.75	103	1.648	36.862864
9	65.1	64.1	64.6	99.4	1.5904	40.618712
6/12/96						
Depth (ft)	Reading 1	Reading 2	Avg. Vol. w (%)	Density (psf)	Density (g/cm3)	Grav. w (%)
1	45.8	45.6	45.7	X	X	X
2	41	40.8	40.9	X	X	X
3	41.7	42	41.85	100.8	1.6128	25.948661
4	49.5	49.9	49.7	X	X	X
5	38.3	38.3	38.3	101.8	1.6288	23.514244
6	28.7	28.4	28.55	99.1	1.5856	18.005802
7	35.5	36	35.75	97.4	1.5584	22.940195
8	51.1	54.6	52.85	103	1.648	32.069175
9	66.2	63.7	64.95	99.4	1.5904	40.838783
5/22/96						
Depth (ft)	Reading 1	Reading 2	Avg. Vol. w (%)	Density (psf)	Density (g/cm3)	Grav. w (%)
1	35.6	35.6	35.6	X	X	X
2	42.6	41.1	41.85	X	X	X
3	39.7	39.4	39.55	100.8	1.6128	24.522569
4	44.4	44.4	44.4	X	X	X
5	32.4	32.7	32.55	101.8	1.6288	19.984037
6	21.6	21.3	21.45	99.1	1.5856	13.528002
7	30.6	29.9	30.25	97.4	1.5584	19.410934
8	38.8	38.3	38.55	103	1.648	23.39199
9	62.8	62.8	62.8	99.4	1.5904	39.486922

Moisture Variations by Sentry 200-AP at Monitoring Tube T3

2/28/97			T3			
Depth (ft)	Reading 1	Reading 2	Avg. Vol. w (%)	Density (psf)	Density (g/cm3)	Grav. w (%)
1	51.7	51.7	51.7	X	X	X
2	60.3	60.2	60.25	93.3	1.4928	40.360397
3	58.2	57.9	58.05	100.3	1.6048	36.172732
4	55.3	56	55.65	101.1	1.6176	34.402819
5	45.1	45.4	45.25	102.2	1.6352	27.672456
6	56	56.1	56.05	101.5	1.624	34.513547
7	60.6	60.7	60.65	100.8	1.6128	37.605407
8	64.1	64.1	64.1	98	1.568	40.880102
9	62.6	62.3	62.45	100.4	1.6064	38.875747
7/26/96						
Depth (ft)	Reading 1	Reading 2	Avg. Vol. w (%)	Density (psf)	Density (g/cm3)	Grav. w (%)
1	57.2	57.2	57.2	X	X	X
2	66.5	66.8	66.65	93.3	1.4928	44.647642
3	64.6	65.3	64.95	100.3	1.6048	40.472333
4	59	59.2	59.1	101.1	1.6176	36.535608
5	49.3	49.3	49.3	102.2	1.6352	30.149217
6	57.5	58.6	58.05	101.5	1.624	35.745074
7	63.7	64.1	63.9	100.8	1.6128	39.620536
8	63.8	65	64.4	98	1.568	41.071429
9	63.9	63.9	63.9	100.4	1.6064	39.778386
6/12/96						
Depth (ft)	Reading 1	Reading 2	Avg. Vol. w (%)	Density (psf)	Density (g/cm3)	Grav. w (%)
1	52.8	52.9	52.85	X	X	X
2	64.8	65.6	65.2	93.3	1.4928	43.676313
3	63.2	64.2	63.7	100.3	1.6048	39.69342
4	58	59.7	58.85	101.1	1.6176	36.381058
5	45.7	45.4	45.55	102.2	1.6352	27.85592
6	47.7	47.8	47.75	101.5	1.624	29.402709
7	61.9	67.7	64.8	100.8	1.6128	40.178571
8	62.2	62.8	62.5	98	1.568	39.859694
9	61.3	61.6	61.45	100.4	1.6064	38.253237
5/22/96						
Depth (ft)	Reading 1	Reading 2	Avg. Vol. w (%)	Density (psf)	Density (g/cm3)	Grav. w (%)
1	43.3	43.3	43.3	X	X	X
2	55.4	55.8	55.6	93.3	1.4928	37.245445
3	56	55.9	55.95	100.3	1.6048	34.864158
4	56.5	55.4	55.95	101.1	1.6176	34.588279
5	41.6	40.9	41.25	102.2	1.6352	25.226272
6	42.9	41.9	42.4	101.5	1.624	26.108374
7	58	57.9	57.95	100.8	1.6128	35.9313
8	54.9	53.9	54.4	98	1.568	34.693878
9	62.6	62.3	62.45	100.4	1.6064	38.875747

APPENDIX C

Climatological Data

Mesonet Climatological Data Summary							January 1996						Time Zone:Midnight-Midnight CST					
(MEDF) Medford							Nearest City: 1.0 SW Mford						County: Grant					
Latitude: 36-47-31							Longitude: 97-44-44						Elevation:1082feet					
	TEMPERATURE (øF)				HUMIDITY (%)			RAIN	PRESSURE		WIND SPEED		(mph)	SOLAR	SOIL TEMPERATURE			
DATE	MAX	MIN	AVG	DEW	MAX	MIN	AVG	(in)	STN	MSL	DIR	AVG	MAX	(MJ/m2)	TS10	TB10	MAX	MIN
1996 05 22	94	64	79.1	63.2	77	44	59	0	28.6	29.7	SE	15.4	36	23.96	71.7	77.3	85	71
1996 06 01	83	63	71	60.3	94	41	72	0.12	28.9	30	NE	6.9	23.7	23.66	70.8	72.4	81	66
1996 06 12	95	69	82.3	63.1	84	28	55	0	28.7	29.88	SE	6.2	20.4	23.71	74.4	81.3	91	73
1996 06 25	91	74	81.3	72.3	91	52	75	0.27	28.8	29.98	ESE	7.1	47.9	21.2	77.7	80.1	88	74
1996 07 01	100	72	85.3	69.3	92	29	63	0	28.8	29.95	NNE	4.9	15.2	27.25	81.5	89	100	80
1996 07 15	91	65	79.2	65.8	95	38	67	0	28.9	30.01	SSE	7.4	21.9	29.69	77.8	78.8	88	70
1996 07 26	79	67	72.5	67.9	94	72	86	1.21	28.9	30.09	ENE	8.2	22.3	8.45	77.7	76.5	82	72
1996 08 01	91	73	79.8	71.3	94	49	77	0.19	28.8	29.95	NNW	5.3	30.7	20.56	80.2	79.8	87	74
1996 08 15	92	72	81.6	67.1	85	40	63	0	28.9	30.06	SSW	7.5	20.9	22.62	78.1	80.6	87	75
1996 09 01	86	68	76	66.1	94	48	73	0	28.7	29.89	SSE	7.3	21.6	22.26	77.6	77.3	82	74
1996 09 15	70	63	67.1	65.4	96	91	94	2.15	28.5	29.61	E	11	24.1	2.61	72.1	70.8	72	69
1996 10 01	81	57	67.4	55.1	86	40	67	0	28.8	29.98	SSE	12.2	32	20.22	66.2	66.1	69	64
1996 10 15	83	59	70.6	59.3	89	46	69	0	28.7	29.9	SSW	11.6	28.7	16.59	65.6	65	71	60
1996 11 01	50	36	43	29.9	89	36	62	0	29	30.16	N	8.5	19.5	9.81	52.6	46.6	52	44
1996 11 15	63	55	59.6	55.9	95	82	88	0.06	28.7	29.9	SSE	22.3	42.5	1.98	51.5	52.8	55	49
1996 12 01	42	24	33.3	28.3	98	72	82	0.14	28.8	29.94	W	9.4	16.7	12.29	42	38	39	37
1996 12 15	42	25	34.2	23.5	91	49	66	0	29.2	30.34	NNW	14.3	37	11.28	43.7	39.5	43	37
1997 01 01	63	48	55.3	53.7	99	78	94	0	28.8	29.96	S	8.7	21.6	3.56	42.9	46.8	51	43
1997 01 15	42	25	31.3	23	95	37	74	0.01	28.8	29.9	NW	15.9	31.9	10.47	34.1	32.9	33	33
1997 02 01	63	29	45.6	31.8	86	33	61	0	28.7	29.81	N	4.3	15.3	9.4	37.8	36.7	43	33
1997 02 15	65	25	43.4	29.5	94	22	65	0	29.1	30.22	SW	10.9	38.5	13.49	39.2	39.5	46	35
1997 02 28	55	39	47.5	44.2	97	80	88	0	28.5	29.68	SE	11.2	24.9	5.3	43.6	44.2	49	40

VITA

Shannon D. Hudson

Candidate for the Degree of

Master of Science

Thesis: SUBGRADE SOIL MOISTURE VARIATION

Major Field: Civil Engineering

Biographical:

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