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Analysis of In-Situ Moisture Content Data of Arkansas Subgrades

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ANALYSIS OF IN-SITU MOISTURE CONTENT DATA FOR ARKANSAS SUBGRADES

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ANALYSIS OF IN-SITU MOISTURE CONTENT DATA FOR ARKANSAS SUBGRADES

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Dedicated to my mom Mrs. Vijayalaxmi Rao
and
my dad Mr. Padmanabha Rao

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CHAPTER I

INTRODUCTION

The purpose of a pavement is to provide a smooth and durable surface over which vehicles may pass under all climatic conditions. In turn, the performance of the pavement is strongly affected by the characteristics of the subgrade. For centuries road builders have known that water accelerates the deterioration of pavements. The presence of moisture in the subgrade affects the durability and strength characteristics of highway soils, and consequently, the ability of the subgrade to support the pavement. Variations in subgrade moisture, with corresponding changes in volumetric and mechanical properties of subgrade soils, may cause severe damage to the pavement. Changes in water content in the subgrade, have a significant effect on the resilient modulus of the subgrade soil, which is the primary soil property used in pavement design. Therefore, it is vital that the modulus chosen for design accurately reflect the *in-situ* moisture conditions of the project site.

Soil is a highly variable material; the interrelationship of soil texture, density, moisture content, and strength are complex, and in particular, behavior under repeated loads is difficult to evaluate (1). Also, subgrades are generally constructed in the surface soil, which is usually subject to large moisture content variations and is strongly influenced by surrounding climatic conditions (2). Consequently, research into subgrade moisture content has not produced a relatively simple yet reliable tool to accurately estimate the *in-situ* moisture conditions of subgrade soils. With improved procedures for determining subgrade moisture contents, construction and design techniques can be refined and pavement performance predictions can be made more reliable. These refinements and improvements could result in financial savings during the design and construction phases as well as minimization of moisture induced failure of in-service pavement systems. It is for this reason that the problems of moisture movement and accumulation under pavement surfaces, and the reasonable prediction and control of subgrade moisture relative to the construction, design, behavior, and performance of pavements are of prime importance.

In an effort to implement the 1986 AASHTO Guide (3) which recommends that resilient modulus testing be used to characterize highway materials, the Arkansas Highway and Transportation Department (AHTD) sponsored a research project, TRC-94, "Resilient Properties of Arkansas Soils." This research project was performed by the Department of Civil Engineering at the University of Arkansas (4). One of the recommendations that came out of TRC-94 was the development of a reliable and practical method for the prediction of subgrade moisture. Based on this recommendation, the AHTD conducted a program to monitor subgrade moisture levels at sites throughout the state. The analysis of *in-situ* moisture content data can lead to the development of techniques to accurately select moisture contents for resilient modulus testing, and procedures for adjusting modulus estimates from nondestructive testing based on the testing "time of year."

The primary task of this study was to analyze subgrade moisture content data collected by AHTD. Specific objectives follow:

i. Identify factors affecting the *in-situ* moisture content of subgrade soils, and evaluate the sensitivity of *in-situ* moisture content to each of the factors.

ii. Identify seasonal variations in *in-situ* moisture contents for Arkansas subgrades.

iii. Establish guidelines or procedures for estimating *in-situ* subgrade moisture content.

CHAPTER II

LITERATURE REVIEW

Historical Background

From ancient times, road builders have known that water is the greatest enemy of a stable, long-lasting pavement. The ancient Romans, who started building the Imperial Roman road network in 312 B. C., knew of the damaging effects of water and tried to keep their roads above the level of the surrounding terrain. In addition to constructing these roads with thick sections, they often provided a sand layer on top of the subgrade and below the first course of flat stones that were generally cemented together (5).

In 1820, John L. McAdam (6) in his statement to the London Board of Agriculture stated that, "The roads can never be rendered thus perfectly secure until the following principles be fully understood, admitted, and acted upon: namely that it is the native soil which really supports the weight of traffic; that whilst it is preserved in a dry state it will carry any weight without sinking . . . that if water pass through a road and fill the native soil, the road whatever may be its thickness loses support and goes to pieces."

The significance of moisture in the subgrade was clearly brought out by H. Frost (7) in 1910, in statements such as, "A road on a wet, undrained bottom will always be troublesome and expensive to maintain, and it will be economical in the long run to go to considerable expense in making the drainage of the subsoil as perfect as possible."

Resilient Modulus

Under the influence of wheel loadings, a pavement deflects or deforms. The total deflection is composed of two components, a recoverable or resilient component (elastic deformation) and a permanent component (plastic deformation). Figure 1 shows the straining of a specimen under a repeated load test. If the load is small compared to the strength of the material and is repeated for a large number of times, the deformation under each load repetition is nearly completely recoverable and proportional to the load and can be considered as elastic.

The elastic modulus based on the recoverable strain under repeated loads is called the resilient modulus M_R, and is defined as the ratio of the repeated axial deviator stress, σ_d, to the recoverable axial strain, ϵ_r :

$$M_R = \sigma_d / \varepsilon_r$$

The resilient modulus test (AASHTO T-274) is a nondestructive, dynamic triaxial test simulating the subgrade resilient behavior under actual traffic loading. Confining pressure is applied to all sides of the sample of subgrade soil and a deviator stress, σ_d, is applied for 0.1 seconds at repeated intervals of one to three seconds. The sample deforms when the deviator stress is applied and rebounds when the deviator stress is released. The resilient strain, ϵ_r, is defined as the rebound deformation resulting from the deviator stress divided by the original height of the sample. The resilient modulus test is illustrated in Figure 2.

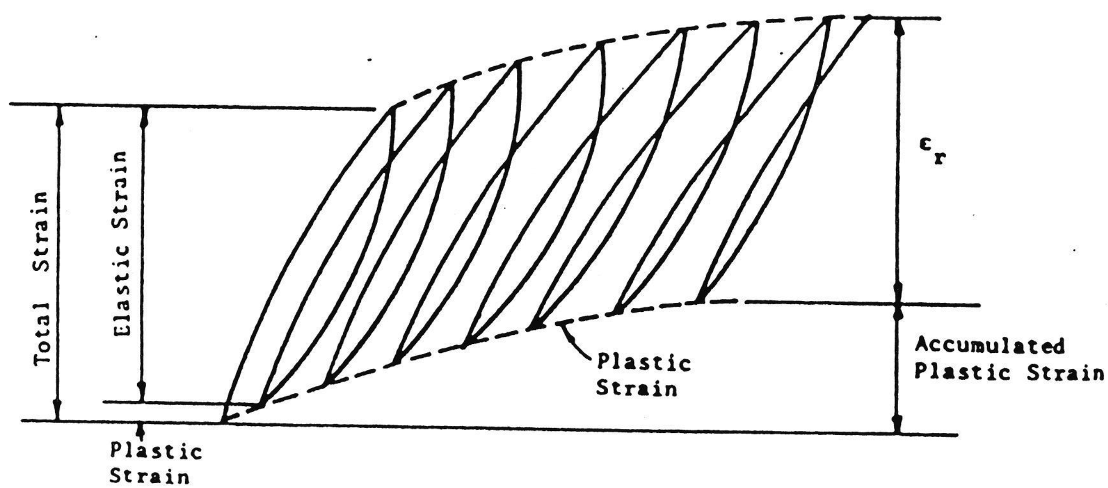

Figure 1. Strain Under Repeated Loads (8).

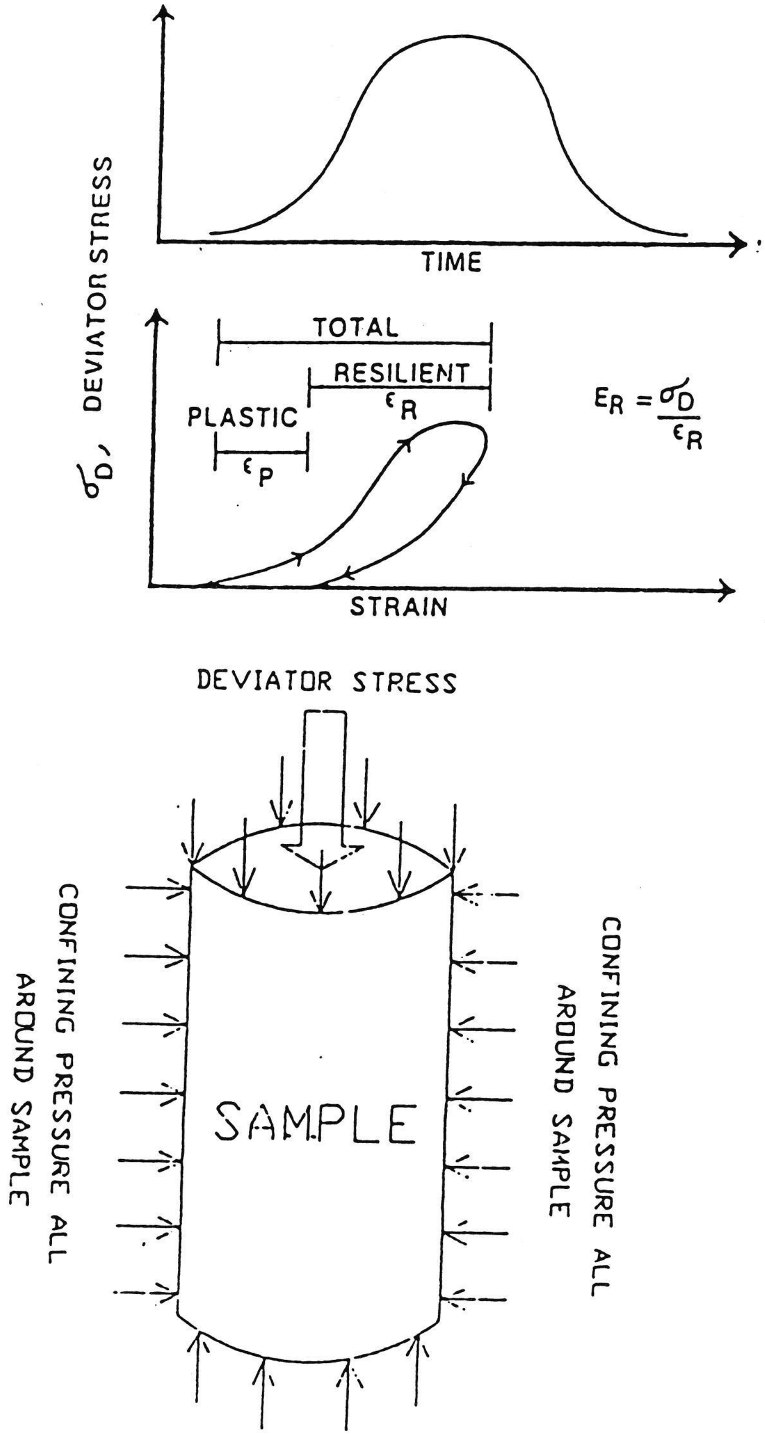

Figure 2. Resilient Modulus Testing (9).

Influence of Resilient Modulus on Pavement Design

Road tests performed in Canada, Great Britain and the United States demonstrate that there is a strong relationship between pavement deflection and pavement life. Figure 3 indicates an increase in pavement life with a corresponding decrease in maximum surface deflection. At the AASHO Road Test, 60 to 80 percent of the surface deflections on the pavements were found to develop within the subgrade (11). It is because of this reason that the stress-strain relationship of the subgrade as defined in terms of the resilient modulus, can be used as a measure of surface deflections, and consequently, pavement performance. The 1986 AASHTO Guide (3) recognizes the importance of the subgrade resilient modulus and requires the use of it in the design of flexible pavements.

Elliot and Thornton (12) used the 1986 AASHTO Guide design nomograph for flexible pavements to illustrate the influence of resilient modulus on pavement design. The relationship between resilient modulus and relative design traffic life is shown in Figure 4. An increase in resilient modulus of the subgrade corresponds to a significant increase in the design life of the pavement. For example, a pavement built on a subgrade with resilient modulus of 10 ksi can be designed to carry nearly 10 times as much traffic as a similar pavement built on a subgrade with resilient modulus of 5 ksi. Figure 5 shows the effect of resilient modulus on the design thickness' of Full Depth Asphalt pavements. As the resilient modulus increases the design thickness of the pavement decreases. For example, the design thickness' corresponding to resilient moduli of 3, 5 and 10 ksi, would be 17.5, 14.9 and 11.8 inches, respectively. Thus, subgrade resilient modulus has a significant impact on the design thickness of pavements.

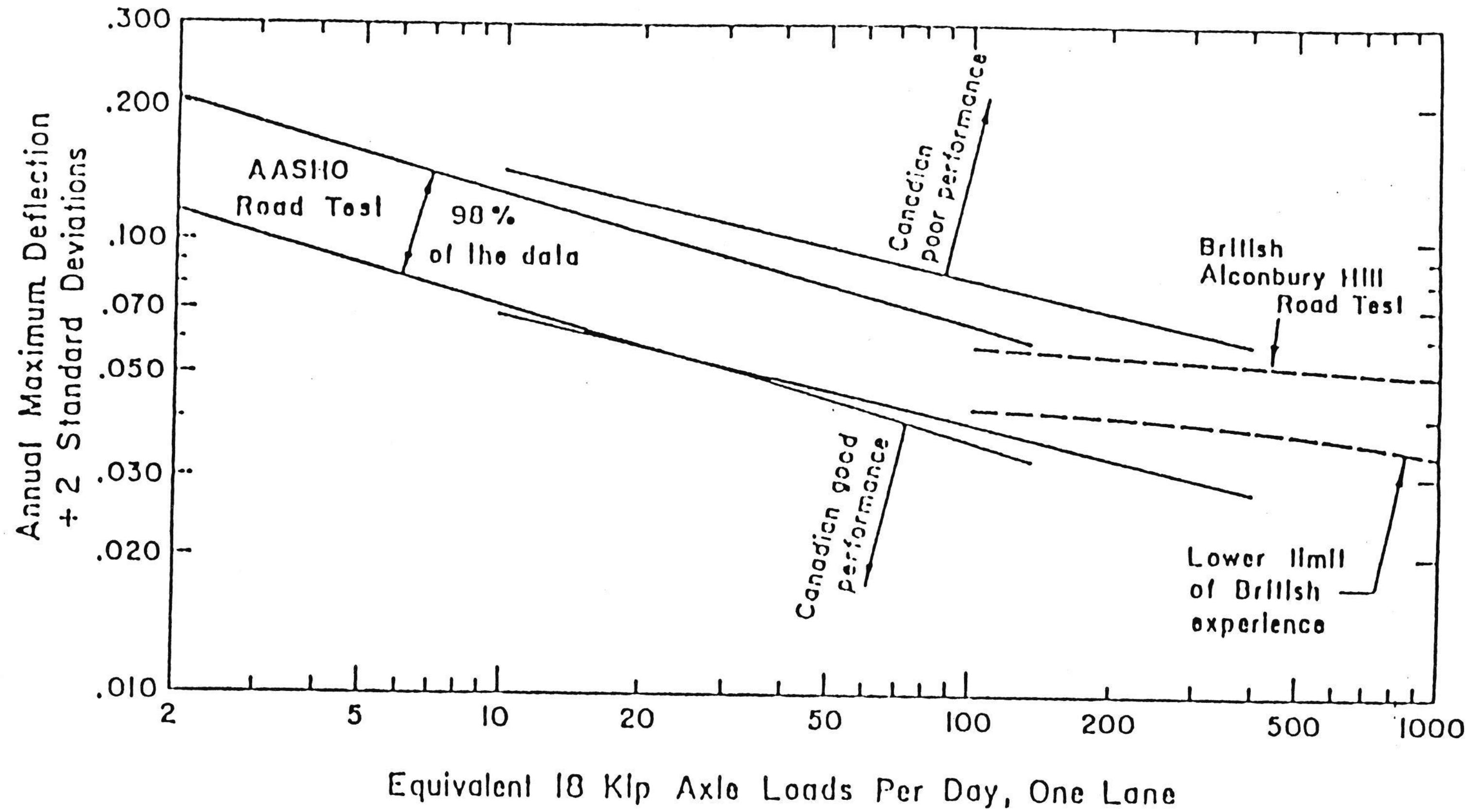

Figure 3. **Relationship Between Pavement Deflection and Pavement Life (11).**

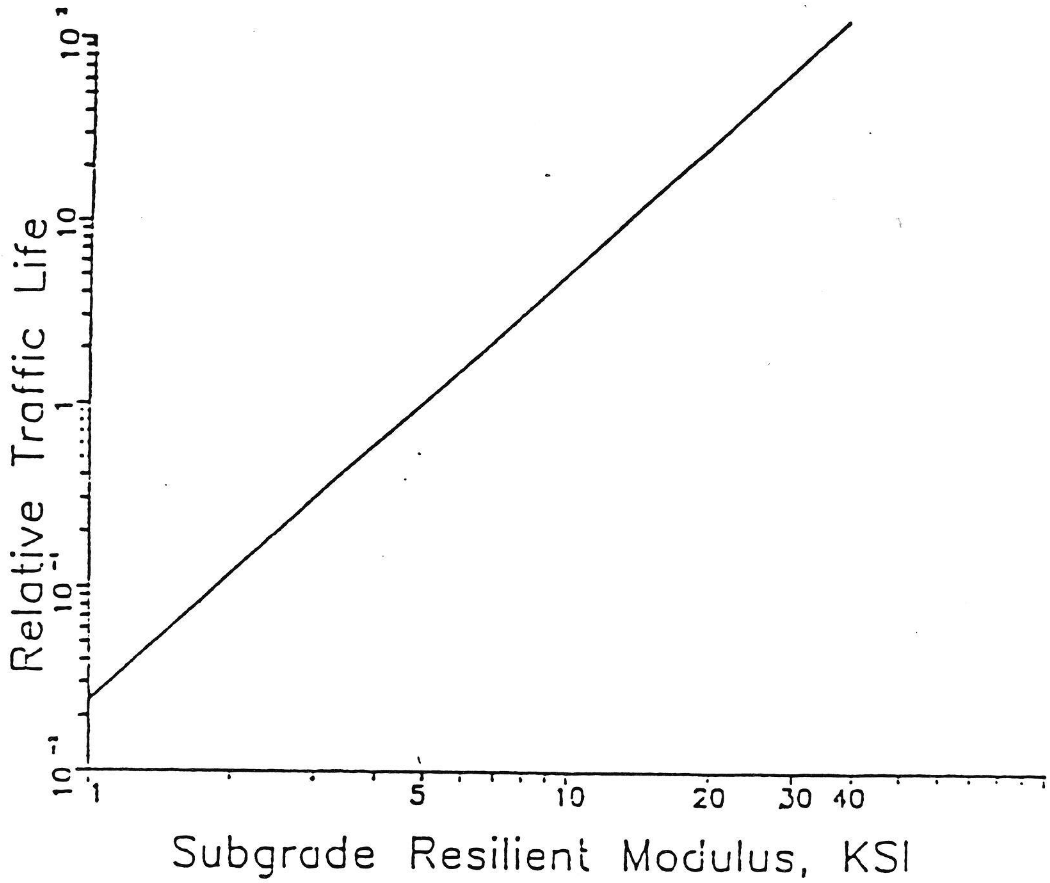

Figure 4. **Effect of Subgrade Resilient Modulus on Relative Traffic Life (12).**

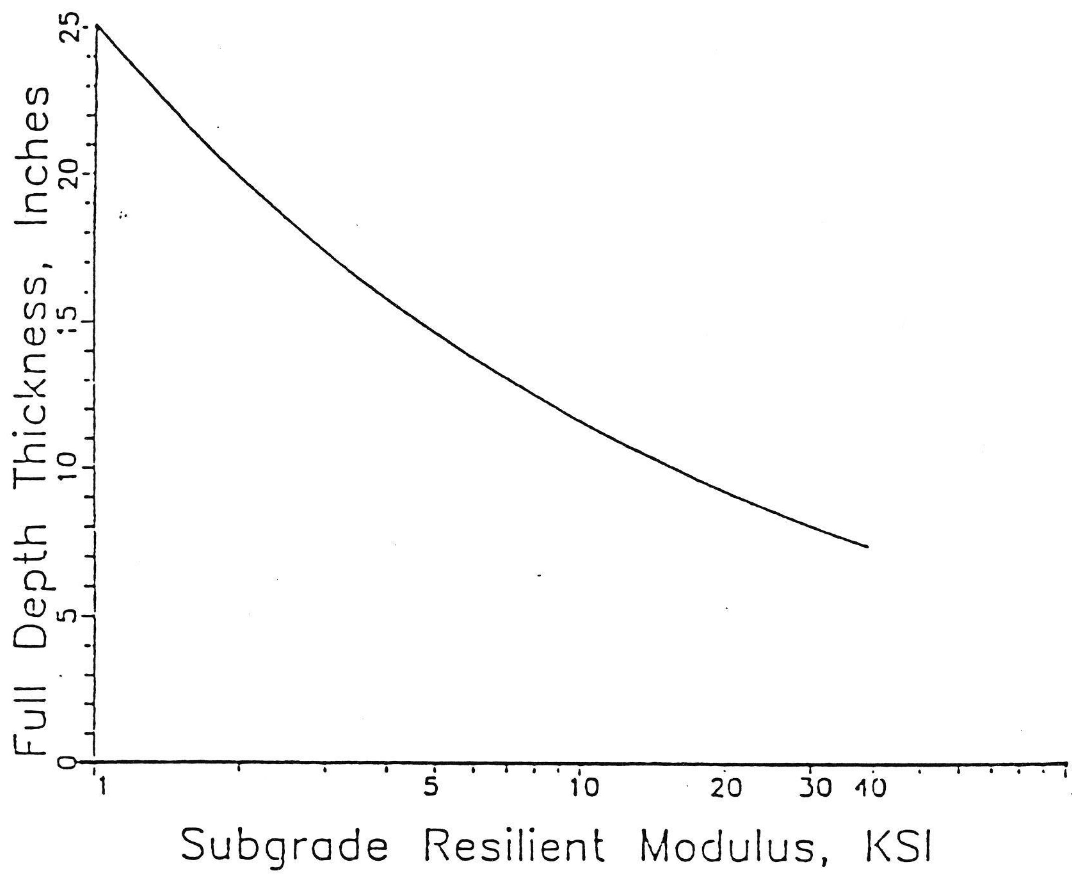

Figure 5. **Effect of Subgrade Resilient Modulus on Pavement Thickness (12).**

Effect of Moisture on Resilient Modulus

Moisture content has a profound effect on resilient modulus. Resilient modulus of a soil decreases with an increase in moisture content. Figure 6 illustrates the effect of moisture content on the resilient behavior of a soil. The resilient modulus of Jackport soil decreases from 16 ksi to 8 ksi corresponding to an increase in moisture content from 2.4 percent below optimum to 5.8 percent above optimum moisture content.

The sensitivity of resilient modulus to moisture content differs from soil to soil. Woodbridge (13) tested 15 Arkansas soils at moisture contents from below optimum to approximately 120 percent of optimum. The moisture sensitivity data shown in Table 1 indicates that Arkansas subgrade soils are very sensitive to moisture content and that the degree of sensitivity varies significantly from one soil to another. The change in resilient modulus corresponding to a change in moisture content of 1 percent ranged from about 0.2 ksi to nearly 4.3 ksi, 1.4 ksi being the average for the 15 soils.

Traditionally, the worst case scenario, usually the fully saturated case, for the subgrade has been adopted for design purposes (14). However, since pavement performance, pavement life and design pavement thickness' are affected considerably by changes in resilient modulus, and because the resilient modulus of soils are very sensitive to moisture content, the moisture content at the time of resilient modulus testing is critical and needs to be representative of the moisture content that will exist in the subgrade after the pavement is in-service. A practical method of realistically estimating *in-situ* moisture content is essential for determining the appropriate resilient modulus to be used for pavement design.

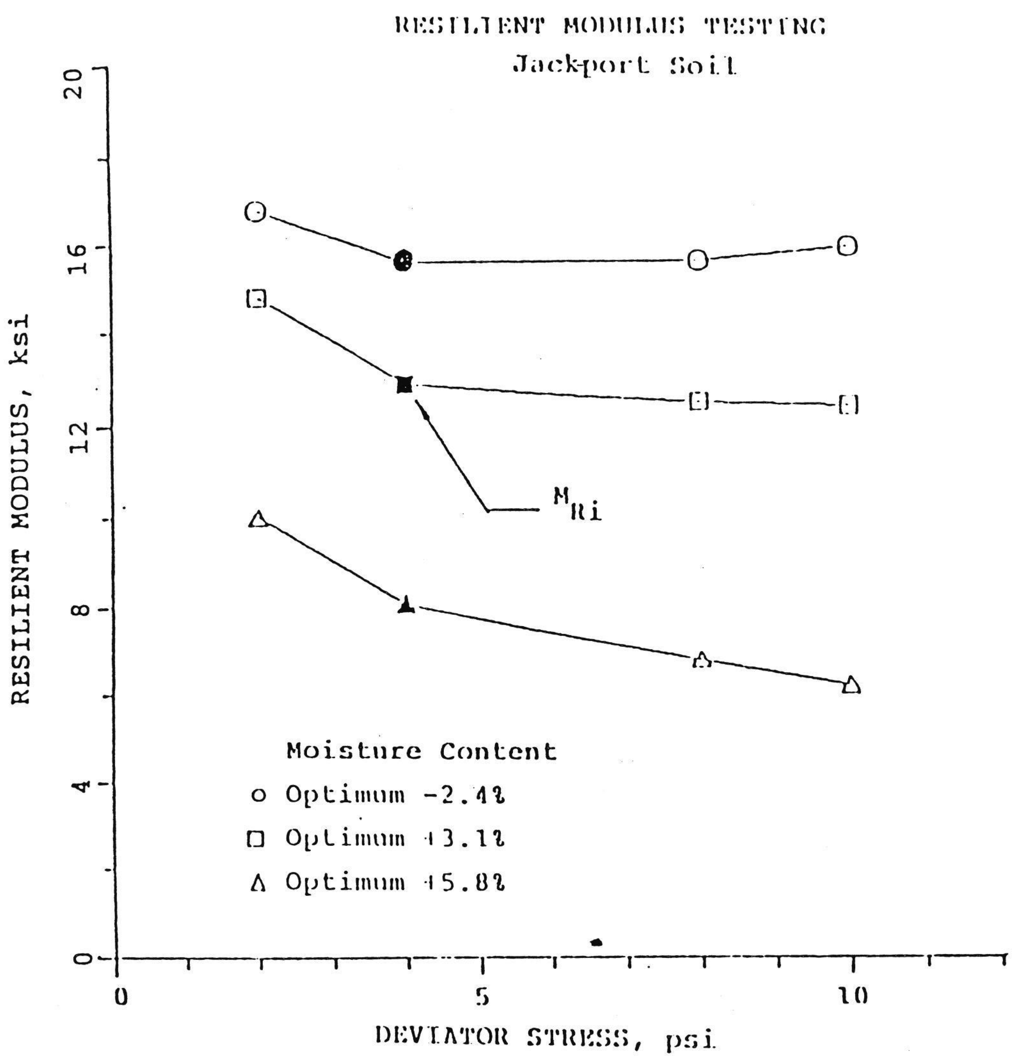

Figure 6. **Effect of Moisture Content on Resilient Behavior of Soil (12).**

SOIL	OPTIMUM MOISTURE %	DEVIATOR STRESS psi	RESILIENT MODULUS ksi @ 120% Optimum	MOISTURE SENSITIVITY ksi per % relative to % Optimum	MOISTURE SENSITIVITY ksi per % relative to % Moisture
Calloway	17.4	4	4.1	.12	.70
		8	3.5	.13	.72
Carnasaw	15.0	4	5.9	.09	.60
		8	4.2	.13	.84
Clarksville	14.8	4	4.6	.18	1.21
		8	4.3	.17	1.12
Enders	17.0	4	2.4*	.10	.61
		8	3.1*	.06	.34
Foley	20.0	4	6.2	.05	.26
		8	6.0	.05	.25
Gallion	25.0	4	10.6	.28	1.12
		8	7.7	.35	1.39
Guyton	16.2	4	6.2	.44	2.70
		8	4.1	.38	2.35
Houston	16.0	4	11.3	.05	.31
		8	9.3	.05	.33
Jackport	20.0	4	12.1	.45	2.27
		8	11.1	.48	2.40
Leadvale	21.5	4	7.0	.24	1.12
		8	5.0	.25	1.16
Perry	37.4	4	2.1	.08	.21
		8	1.6	.16	.44
Sacul	19.5	4	.49*	.77	3.93
		8	.84*	.51	2.59
Sawyer	22.5	4	11.0	.46	2.04
		8	8.8	.51	2.27
Sharkey	28.5	4	6.5	.13	.47
		8	5.9	.14	.47
Smithdale	11.5	4	5.7*	.49	4.28
		8	5.5*	.46	4.03

* These soils failed prematurely when tested at 120% of optimum. The M_r value listed was extrapolated or interpolated from the highest moisture content that could be tested.

Table 1. Moisture Sensitivity of Soils (13).

Moisture in the Subgrade

Sources of Water

Sources of free water must be present for moisture migration and accumulation to occur in subgrades. Primary sources of moisture in subgrades are as follows (15): seepage of water into the subgrade from higher ground, fluctuation of the water table, percolation of water through the pavement surface, penetration at the edges of pavements, migration of water from shoulder slopes or verges, migration of water from water bearing layers below the subgrade, and transfer of water vapor from any of these sources. These sources of water are illustrated in Figure 7. Pavement sections may not be exposed to all of these sources at once, but any one may provide enough moisture to cause premature pavement failure.

Moisture Migration in Soils

Soil moisture may migrate through soil in the liquid phase, vapor phase, or in a combination of the two. Moisture migrates as a result of any force which upsets equilibrium in the soil-water system (16). The description of the force networks in soil water is difficult because of the variety of forces and the different directions in which they act (17). However, it is possible to assess the potential energy associated with an increment of water as a consequence of the forces acting upon it. Potential energy per unit quantity of water is defined as the *potential*. Theoretically, a potential is associated with each force acting on water. Nonetheless, some of the separate potentials are combined into a single potential for practical convenience. Some of the widely discussed potentials are described below.

Matric potential is associated with the attraction of solid surfaces for water as well as the attraction of water molecules for each other. Matric potential includes the *capillary potential*, which is associated with the unbalanced forces across air-water interfaces. *Chemical potentials* caused by the chemical absorption and adsorption of ions on soil particles can also be included under matric potentials. The relationship between matric potential and moisture content differs among soils, primarily because of differences in texture and pore space configuration. *Pressure potential* accounts for the influence of weight on the soil water. Pressure potentials include *gas pressure* caused by the entrapment of air, *submergence potential*, which is the positive hydraulic pressure beneath a water table and may also include the *overburden potential*, which exist wherever soil is free to move and its weight becomes involved as a force acting upon water at a point in question. *Gravity potential* expresses the level of energy in water caused by the constant pull of gravity, and is a function of the elevation of water in the earth's gravitational field. Other potentials include the *osmotic potential* which results from the hydration of ions in the soil solution, *electric potentials* caused by electric forces and *thermal potentials* which are caused by temperature gradients in the soil.

The movement of water through soil is based on Darcy's Law (18), $v = k\,i$, where v is the velocity of discharge, k is the coefficient of permeability and i is the hydraulic gradient. Topographical, geological and hydrological features of a highway affect some of the factors in the above equation and consequently, the movement of water beneath the pavement. The natural flow of water in the soil can be disrupted by the construction of a highway (19). A fill section may act as an obstruction to the natural flow of water, while a cut section in areas of high water tables may intersect the water table.

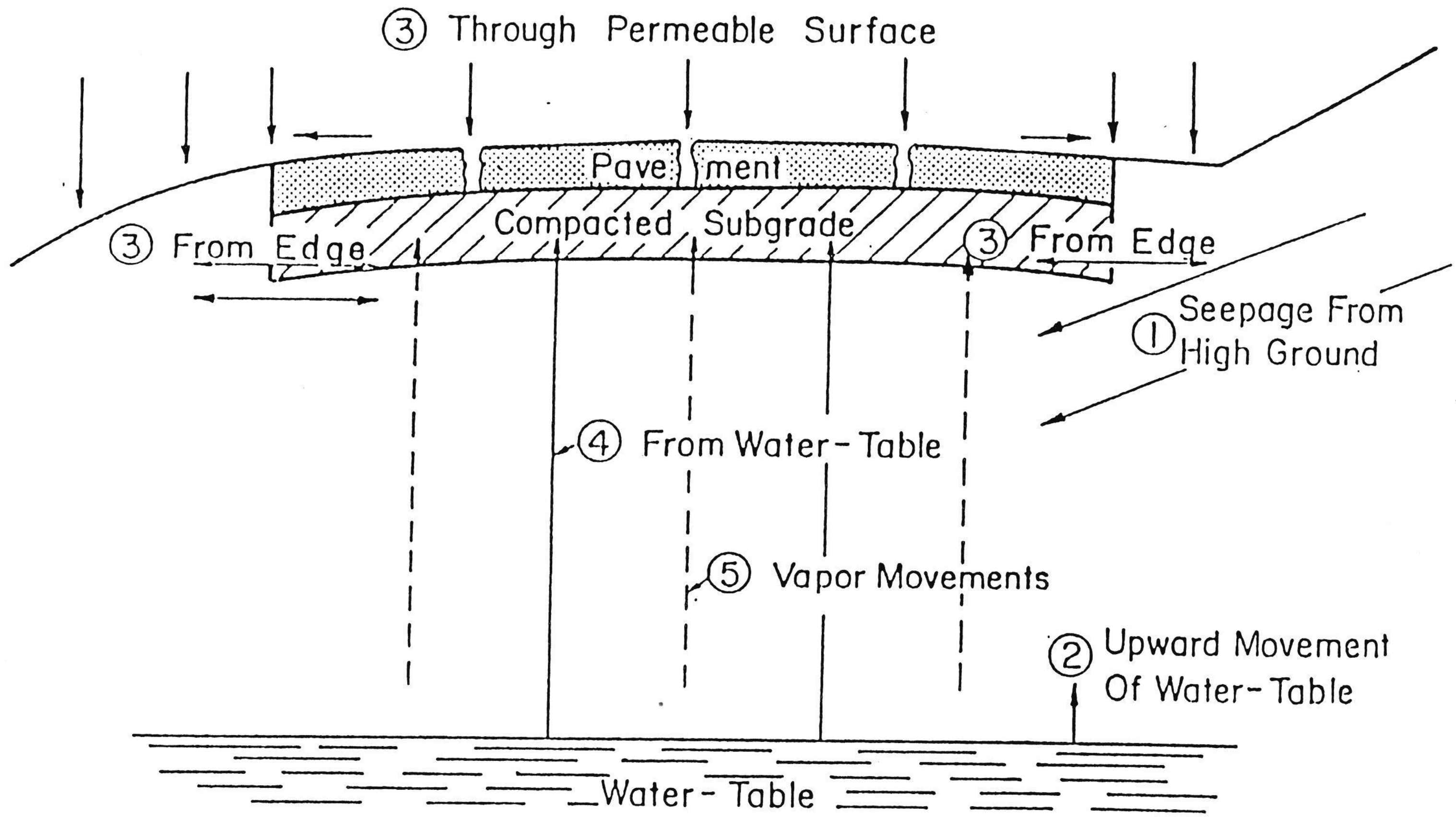

Figure 7. **Source of Moisture in Pavement Systems (16).**

Factors Affecting Subgrade Moisture Content

External Factors

Precipitation

Field studies performed by the Corps of Engineers (20) suggested that the amount of precipitation may have considerable influence on subgrade moisture conditions. However, Kubler (21) in West Germany could not establish a relationship between precipitation and a change in ground moisture content. He concluded that precipitation alone would not be sufficient to predict the ground moisture content. In Oklahoma, Marks and Haliburton (16) found no correlation between moisture variations in the subgrade and measured precipitation. Variations in moisture contents resulting from infiltration of runoff lagged rainfall by 4 to 6 weeks. Comparisons of monthly precipitation with moisture variation at 8 field sites in Pennsylvania performed by Cumberledge et al (22) showed erratic peaks and no definite increases in subgrade moisture due to periods of heavy rainfall. In some instances, however, points of maximum moisture were preceded by a few months by periods of high precipitation. In Kansas, Bandyopadhyay and Frantzen (23) performed a cross-correlation study of time histories of subgrade moduli constructed from pavement deflection parameters and precipitation as shown in Figure 8. They concluded that precipitation directly affected the subgrade modulus, and that the time required for the subgrade to reach its weakest state after a rainfall; depending on local factors, can be as long as three weeks.

Temperature and Seasonal Variation

In North Carolina, Hicks (24) found that during late winter or early spring, the

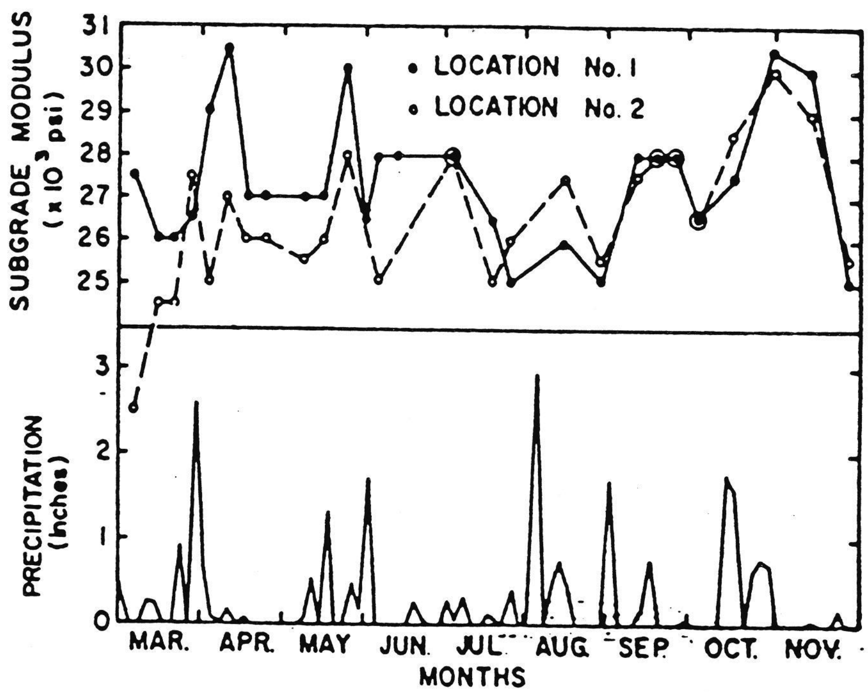

Figure 8. Time Histories of Subgrade Modulus and Precipitation (23).

moisture contents for the subgrades were at their highest. In Virginia, Stevens, Maner, and Shelburne (25) concluded that the large amount of fall precipitation which tended to saturate the base and the subgrade in conjunction with the length of the freezing period was responsible for the spring breakup of pavements. Marks and Haliburton (16) indicated that moisture variations beneath pavements with high ratings were predominantly temperature dependent. Moisture variations resulting from temperature changes were usually between 1 and 5 percent. Variations in moisture were found to occur in an annual cycle with maximum moisture contents occurring during winter months and decreased during summer months. Cumberledge et al (22) noted that subgrade soils perennially reach a base level or minimum moisture content by September and October. After October, the subgrade moisture content tends to increase each month during the winter up to a maximum in March or April. Figure 9 shows the extent of this annual variation for three different soil types. Similar trends were also found by Yao and Broms (26) and by Chu and Humphries (27).

Groundwater Table

Measurements made under several road and airfield pavements in both tropical and semitropical countries by Russam and Coleman (28) indicated that where close to the surface, the water table was the main factor in determining the moisture condition of the subgrade irrespective of the climate. In South Carolina, Chu and Humphries (27) observed that moisture contents beneath a pavement were influenced by the depth of the groundwater table. Figure 10 shows variation in subgrade moisture contents with fluctuations in the groundwater table. Subgrade moisture contents increase with the decrease in depth of water tables. In Illinois, Dempsey (2) noted the relationship between rainfall and subgrade moisture

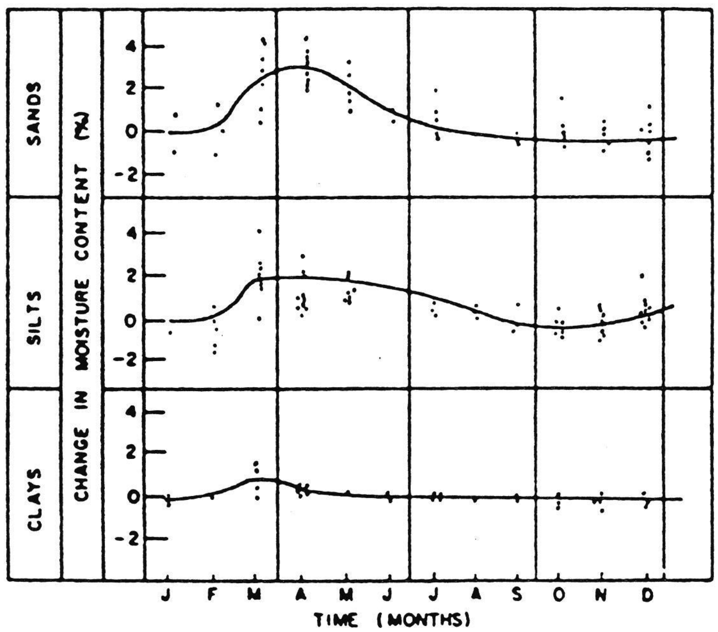

Figure 9. Seasonal Change in Subgrade Moisture Content (22).

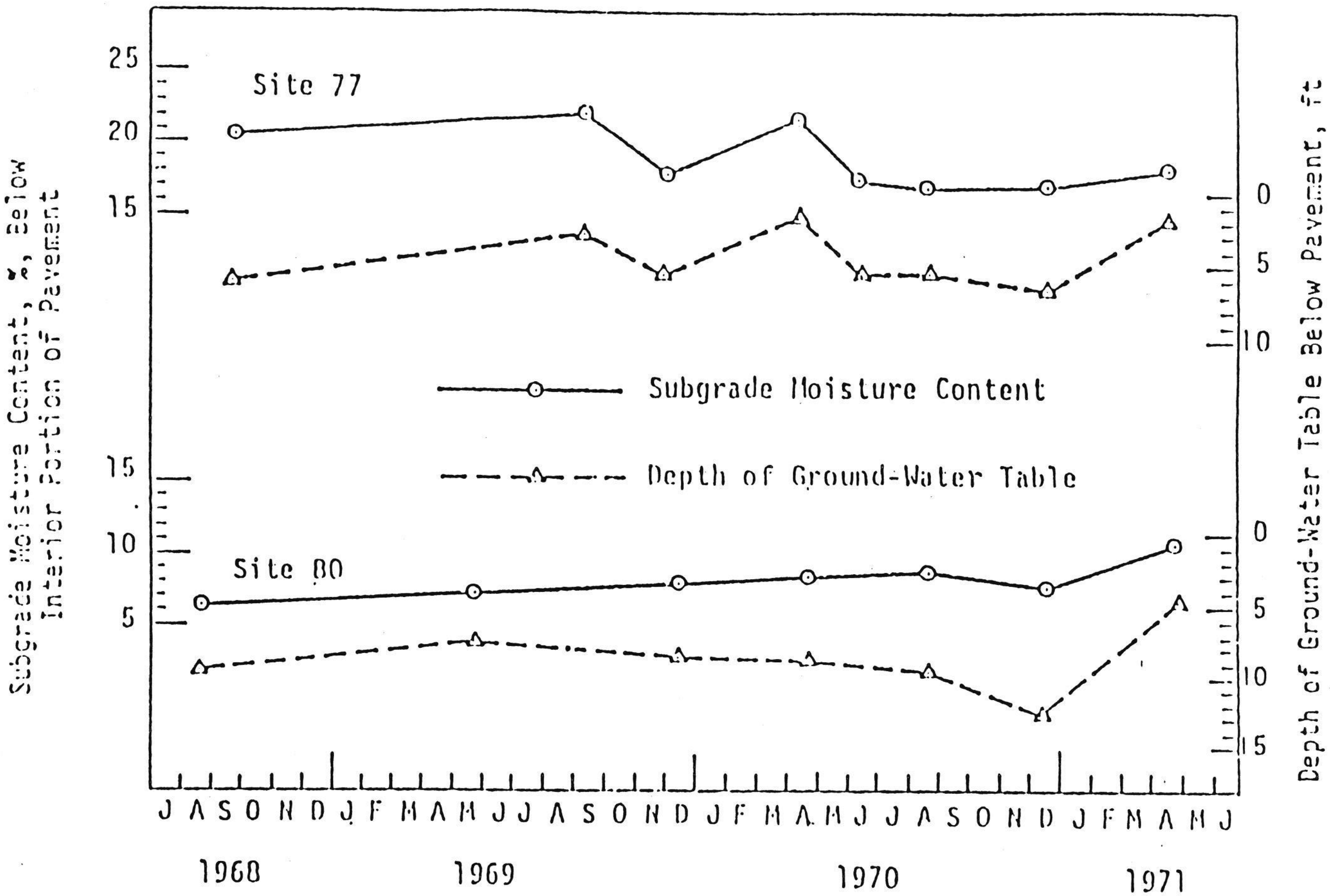

Figure 10. **Variations in Subgrade Moisture Contents Compared With Fluctuations in Groundwater Table (27).**

content as being difficult to determine, and that a better indicator of subgrade moisture content and pavement deflection magnitude would be the water table elevation, as indirectly influenced by rainfall, rather than rainfall itself.

Fluctuations in groundwater levels can be related to temperature and seasonal variations. Fang (29) noted that groundwater levels generally fall in the winter period and rise in the spring. Meyer (30) observed in both laboratory and field investigations that groundwater levels fell during the winter as the air temperature decreased and rose approximately the same amount in the spring as the air temperature increased. Benz et al (31) also demonstrated that changes in soil moisture content and water table elevation were associated with soil temperature. As the soil temperature decreased during the winter, the water table fell and the soil moisture content increased in the surface horizons by migration of water from the subsoil.

Time and Equilibrium

In his study of subgrades beneath thirteen United States airfields in the non-frost regions, Redus (32) indicated that soil moisture contents may fluctuate following construction but appear to stabilize after about 2 years. Marks and Haliburton (16) observed that although variations were cyclic, the general trend appeared to be a gradual increase in subgrade moisture content beneath pavements. No stable conditions were indicated by collected data except at sites where the groundwater table was consistently high. Atchison and Richards (33) conducted studies throughout Australia and concluded that although the climatic conditions at the various sites were widely different, all sites were similar with respect to moisture stability beneath the greater part of the paved area.

In Virginia, Vaswani (34) found that subgrade moisture content increased sharply from the beginning to the end of construction. For 1 or 2 years from the date of the subgrade construction, moisture content increased because of precipitation and after this time the rate of increase in moisture decreased. After about 10 years the increase in the subgrade moisture content was minimal. This behavior is depicted in Figure 11.

Pavement-Related Factors

Pavement Condition

Marks and Haliburton (16) noted that the infiltration of runoff where pavements were not impervious greatly affected the magnitude and frequency of subgrade moisture variations. Cyclic variations were affected considerably by precipitation at sites located on poor pavements. Smallest moisture variations were found beneath newly constructed highways with excellent pavement and shoulder ratings. Similar conclusions were drawn by Russam (35) who indicated that when a relatively impervious surface covered the ground, the seasonal moisture changes were reduced and except for a zone close to the pavement edge, the moisture condition tended to a relatively stable value.

Drainability

Marks and Haliburton (16) observed that in cases where proper design and gradation of sand base courses were employed, moisture variations resulting from infiltration were reduced, producing good pavement performance. They concluded that good drainage conditions necessary to remove runoff completely and quickly, reduced moisture variations from infiltration through shoulders. Comparisons of moisture variations at sites indicated the

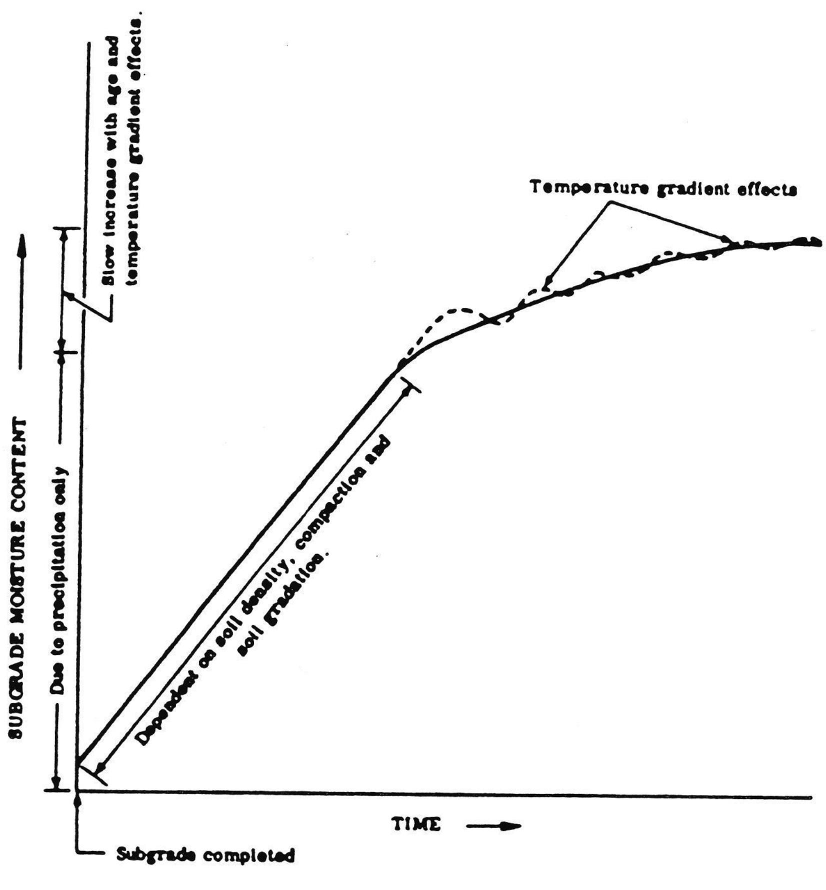

Figure 11. Subgrade Moisture Variation with Time (34).

large effect of slight differences in drainage conditions on moisture variations. In West Virginia, Moulton and Dubbe (36) concluded that the drainage characteristics of the materials and the site had a greater impact on the moisture content in the base, subbase and subgrade, rather than the precipitation at the site.

Shoulders and Edges

In Missouri, Guinnee and Thomas (37) found that water enters a pavement with greater ease and in larger volumes at the edge of the pavement as compared to the center of the pavement. Benkelman (38) correlated inner and outer wheel path deflections with degree of saturation in an analysis of the WASHO Road Test and concluded that adverse moisture conditions existed at the pavement edges. Similar findings were reported by Dempsey (2), who found that the outer wheel path experienced higher deflections than the inner wheel path in most cases. Marks and Haliburton (16) reported that variations in moisture content resulting from infiltration of runoff were particularly noticeable at highway shoulders. Sealed shoulders as compared with open shoulders reduced infiltration, resulting in smaller variations beneath pavements. Also, as shoulder widths increased, moisture variations under pavement center lines were found to decrease and be less dependent on precipitation. Field studies conducted by Kersten (39), Atchison and Richards (33) and Chu and Humphries (27), all indicate that moisture contents are higher and fluctuations are greater at the edges of the pavements than under the central portion of the surfacing as shown in Figure 12.

Pavement Cross-Section

Marks and Haliburton (16) indicated that fill and transition sections were found to produce the worst moisture conditions, resulting in poor pavement ratings. Pavements

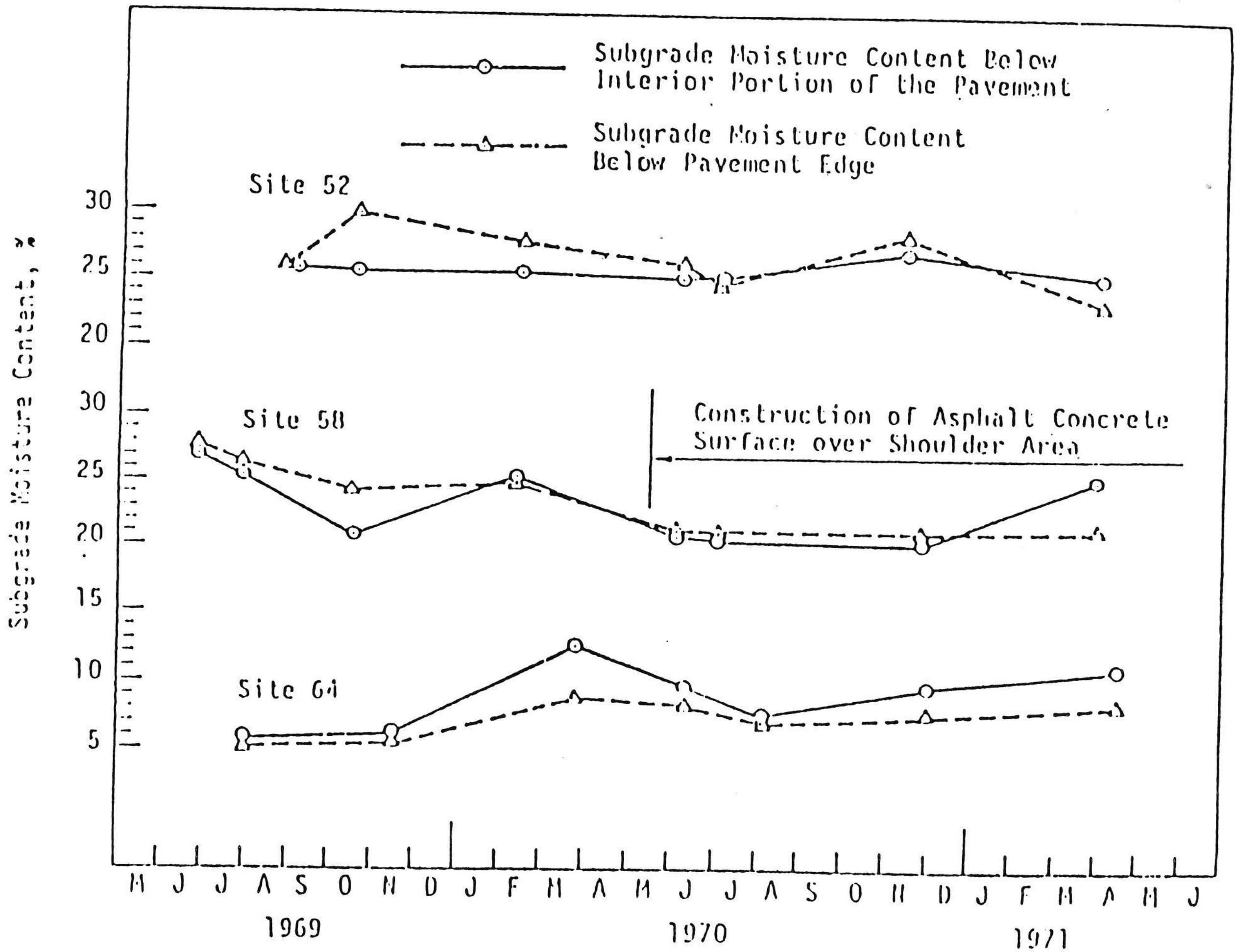

Figure 12. **Variations in Subgrade Moisture Contents With Time at Different Locations of the Pavement (27).**

constructed on a grade or in slight cut sections had smaller moisture variations. Also, fill sections may act as an obstruction to the natural flow of water, while a cut section in areas of high water tables may intersect the water table.

Other Factors

Compaction and soil density

Based on their observations Marks and Haliburton (16) indicated that moisture variations were reduced appreciably when initial moisture content of compacted subgrades were similar to natural moisture content of existing soil. Moisture variations were found to be smallest in subgrades where average moisture contents were below the plastic limit and greatest in soils where moisture contents were within the plastic range.

Mickel and Spangler (40) indicated that at relatively low moisture tension values soil density had a decided effect on equilibrium moisture contents, higher moisture contents being observed at lower soil densities. Vaswani (34) noted that the higher the compaction and dry density of the subgrade soil were, the lower the moisture content would be.

Depth

Guinnee and Thomas (37) reported that variations in moisture content were greater in the top levels than at deeper levels of subgrades beneath rigid pavements.

Kersten (41) conducted studies of subgrade moisture beneath several airfields in different states within the United States and observed that there was a slight increase in moisture content with an increase in depth. The average difference in moisture content between the surface of the subgrade and at a depth of 30 inches was between 1 and 1.5 percent. Mickel and Spangler (40) indicated that under normal field conditions, where increasing soil density was noted with increasing depth, it was possible to note increasing moisture contents with increasing height above the water table.

Soil Type

Cumberledge et al (22) reported that in the months of March and April the sand soils show the greatest increase in moisture (3 to 4 percent) as compared to increases of 2 to 3 percent for silt soils and only 1 percent for clay soils. The increased moisture content in the sands drops back to a base level by the months of September and October at a faster rate than the silty soils. Marks and Haliburton found no noticeable effect of soil type on subgrade moisture variations beneath Oklahoma highway pavements (16). They indicated that the absence of any observed correlation may result from the presence of fairly uniform deposits of Paleozoic clay soils in Oklahoma. Kersten (39) observed that the texture of the soil had a great impact on the ability of the soil to attain and retain water. Fine textured soils exhibited a greater tendency to attain moisture contents and moisture contents can be in excess of their plastic limit, as is often in the case of clayey soils. In contrast, coarse textured soils such as sandy loam rarely had moisture contents as great as their plastic limits as indicated in Table 2. Elzeftawy and Dempsey (42) noted that the drainability of a soil is a function of the soil's attraction for moisture. As shown in Figure 13, different soils exhibit different moisture attraction capacities at the same moisture content. For example, at a given moisture content, clayey soils have a higher attraction for water and consequently, drain slower compared to sandy soils. Bandyopadhyay and Frantzen (23) indicated that the extent of variation in modulus due to precipitation depended on the geotechnical properties of the subgrade soils.

Soil Type	Number of Tests	Average Saturation (%)	Tests 90% Saturation or Greater (%)	Average Air Voids (%)
Sandy Loam	6	59	0	12
Loam	12	77	8	7
Clay Loam	38	81	26	6
Clay	58	92	69	3

Table 2. Average Percent Saturation For Various Soil Types (39).

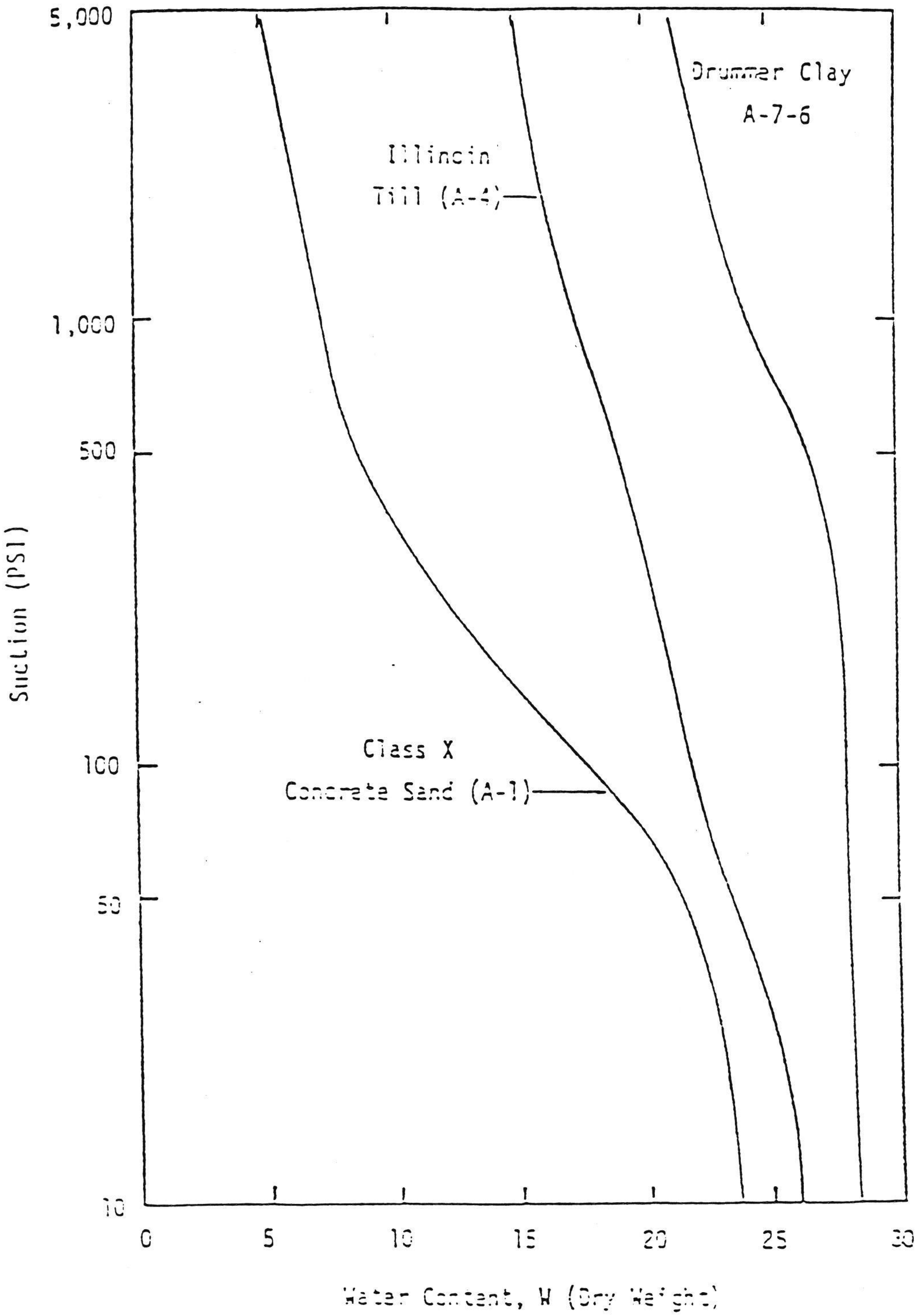

Figure 13. Soil Water Content - Suction Characteristic Relationship for Various Soils (42).

Prediction of Moisture in the Subgrade

Empirical Methods

Moisture migration in the subgrade from different sources and the interaction of this moisture movement with the different factors that affect subgrade moisture content makes the prediction of moisture in the subgrade a very complicated and difficult matter. Due to the complexity involved, many researchers have developed empirical methods which relate moisture contents to soil properties such as the Plastic Limit, PL.

In Minnesota, where the subgrades were mainly clayey silt soils with plastic limits ranging from 15 to 30 and densities between 90 and 105 percent of the Modified Procter maximum density, Swanberg and Hansen (43) found that the moisture contents of highway subgrades could be estimated in terms of the plastic limit using the following relationship:

$$W = 1.16PL - 7.4.$$

Moisture contents measured were about 1 percent higher in the spring than in the summer.

The American Navy (44) investigated sandy and clay subgrades at 70 airports where the groundwater table was greater than 60 cm below the surface and concluded that the water content of the subgrade exceeded the plastic limit by about 2 percent:

$$W \sim PL + 2.$$

Kersten (41) investigated subgrade moisture contents in the top 30 cm of subgrade soil beneath airport pavements in seven states, and concluded that the water content for sand and clay soils in damp regions was between 80 percent and 120 percent of the plastic limit of the soil:

$$0.8PL < W < 1.2PL.$$

The empirical formulas used to predict moisture in the subgrade cannot be used reliably because many of them are based on regression analysis, the standard deviations of which are considerably high. The Organization for Economic Cooperation and Development (OECD)(45) observed that these standard deviations can be as high as several percent of moisture content. Moreover, different researchers have proposed different empirical formulas. Large dispersions in moisture prediction using empirical formulas can be attributed to the omission of the influences of climatic factors, groundwater table, pavement edges, pavement type, soil compaction and fundamental properties of soil such as soil surface area and mineralogical composition.

Regional Classification

Subgrade Categories

Russam (46) divided subgrades into three categories based on the main factors that influence moisture conditions in the subgrade. These categories are:

(a) Subgrades where the water table is close to the surface and is the major influence on the moisture condition, i.e., the water table is within 20 ft. of the surface. The moisture content can be determined by laboratory suction tests on samples of soils which are representative of the subgrade condition at the time of construction of the pavement. The assumption is that the pore water tension is dependent solely on the position of the water table and the overburden pressure when the water table was within 10 ft. of the surface with sands, or within about 30 ft. of the surface with heavier soils.

(b) Subgrades where the water table is deeper than 20 ft. from the surface and the seasonal rainfall exceeds 10 inches. The major influence on the subgrade moisture content is the availability of this rainfall, supplemented by runoff. In such cases the ultimate suction of the subgrade can be estimated from the Thorntwaite Moisture Index and the soil texture. The plasticity index can be used as a guide to the soil texture and a practical finding is that within a given climatic environment the ratio of ultimate moisture content to the plastic limit tends to be constant. This ratio can be determined from data obtained by sampling beneath existing roads over five years old.

(c) Subgrades in areas where the climate is arid throughout the year, i.e., the rainfall is less than 10 inches per annum and there is no water table within 20 ft. of the surface. In this instance, the soil moisture is controlled by the atmospheric humidity and the ultimate moisture content differs little from the uncovered soil at the same depth. The small amount of rainfall has a negligible effect on the soil moisture content except immediately following rain. Soil suction tests of the uncovered soil can be used to determine the ultimate subgrade moisture content.

Climatic Regions

Based on the Thorntwaite Potential Evapotranspiration and Moisture Index (47), the United States is divided into nine climatic regions. These regions represent areas of similar moisture and temperature effects within the pavement structure. The nine regions are combinations of three moisture regions and three temperature regions. Figure 14 shows the different climatic zones; similar pavement performances are expected in similar climatic regions. Representative cities for the nine environmental regions are shown in Table 3.

Region I - High potential for moisture presence in the entire pavement structure throughout the year.

Region II - Seasonal variability in the presence of moisture in the pavement structure.

Region III - Very little moisture present in the pavement structure over the entire year.

Region A - Severe winters with a high potential for frost penetration to appreciable depths into the subgrade.

Region B - Surface and base course will be affected by freeze-thaw cycles. Long term freezing problems are minor but severe winters may produce frozen subgrades.

Region C - Low temperatures are not a problem, temperature stability problems should be considered.

In addition to the temperature and moisture regions, the seasonal variations of moisture in the United States were examined and were divided into the categories shown below.

d - Little or no water surplus in dry climates

r - Little or no water deficiency in moist climates

s - Moderate seasonal moisture variation, drier season occurs in summer, and wetter season occurs in winter

s2 - Large seasonal moisture variation, drier season occurs in summer, and wetter season occurs in winter.

The distribution of seasonal variation of moisture across the United States is shown in Figure 15.

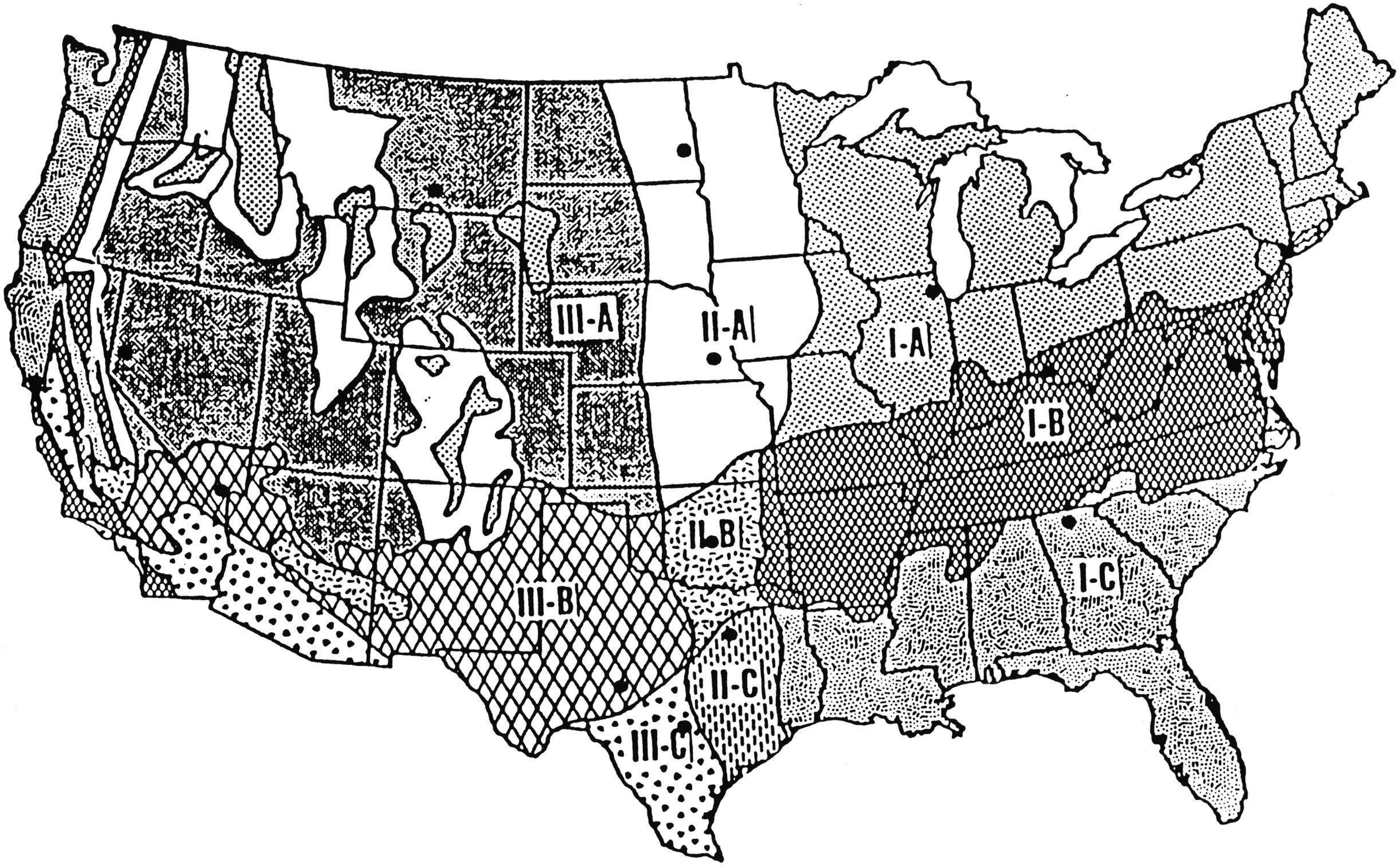

Figure 14. The Nine Climatic Regions in the U.S. and Representative Cities (47).

Moisture Region	Temperature Region		
	A	B	C
I	New York, NY Chicago, IL	Washington, D.C. Cincinnati, OH	San Francisco, CA Atlanta, GA
II	Fargo, ND Lincoln, NE	Oklahoma City, OK	Dallas, TX
III	Reno, NV Billings, MT	Las Vegas, NV San Angelo, TX	San Antonio, TX

Table 3. Representative Cities for the Nine Enviromental Regions (47).

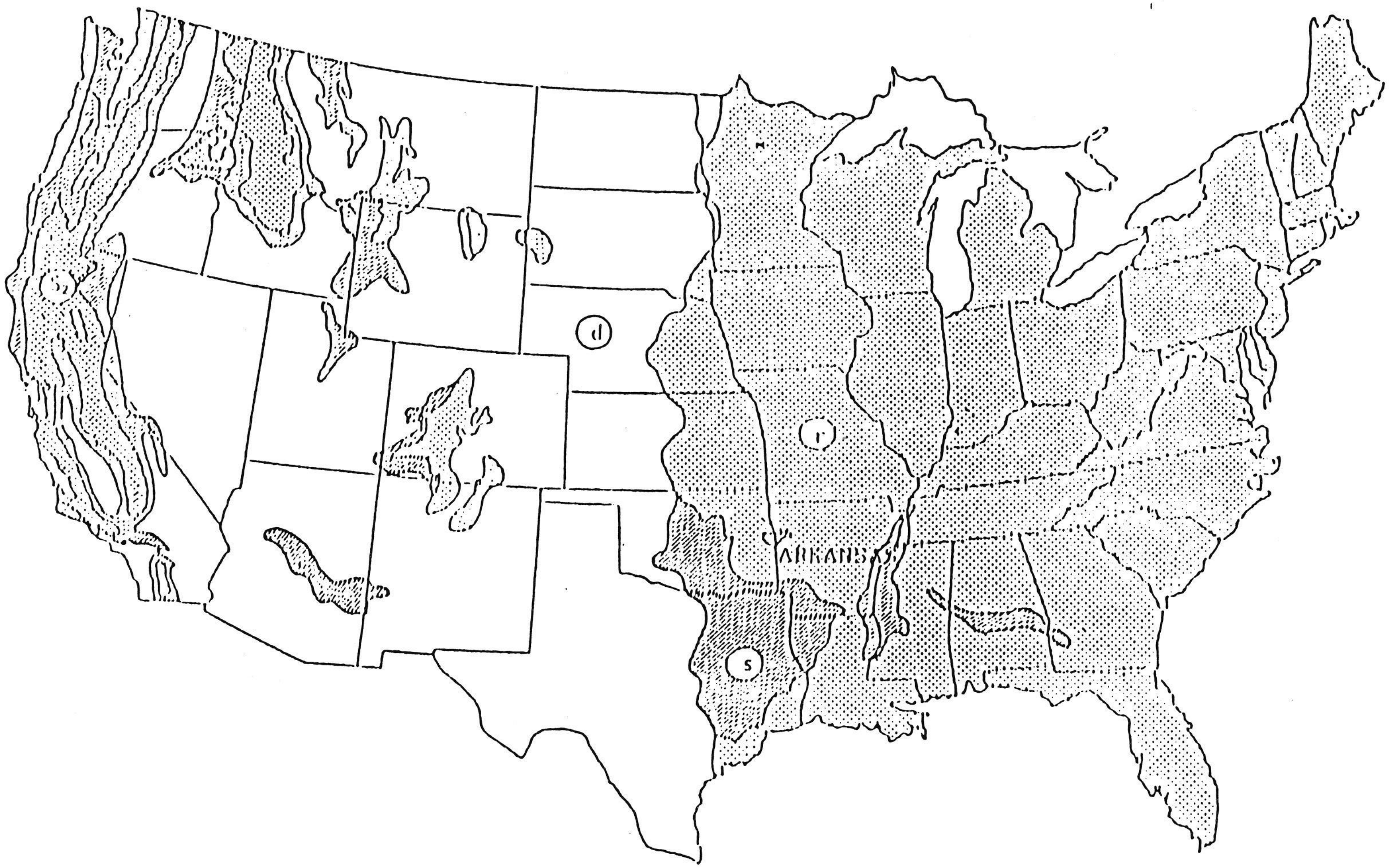

Figure 15. Distribution of Seasonal Moisture Variation Across the United States (47).

Integrated Model

Lytton et al (14) developed an Integrated Model by modifying and combining a precipitation model (Precip Model) with three separate models of climatic effects on pavements: the Climatic-Materials-Structures Model (CMS) developed at the University of Illinois; the Infiltration and Drainage Model (ID) developed at Texas A&M University, Texas Transportation Institute; and the CRREL Frost Heave and Thaw Settlement Model developed at the United States Army Cold Regions Research and Engineering Laboratory (CRREL). Within the Integrated Model Program, the weather patterns of rainfall, temperature, solar radiation, cloud cover, wind speed, and snow fall are simulated throughout an entire year using default data or the data input by the user. The program computes the pore water pressure, temperature, frost and thaw depth, frost heave, and layer materials elastic modulus with time. The computations are made in accordance with a numerical model of coupled heat and moisture flow in a medium with small volume changes. Because of the amount of detailed site data required and the complexity of the analysis, the Integrated Model is not practical for use as a tool to estimate subgrade moisture contents for resilient modulus testing. A schematic of the Integrated Model is shown in Figure 16.

Equilibrium Conditions

The Organization for Economic Cooperation and Development (45) outlined a procedure to predict moisture in the subgrade based on the thermodynamic theory of the equilibrium distribution of water in a porous body. This procedure which was developed by researchers at the British Road Research Laboratory is based on the fact that the trend in

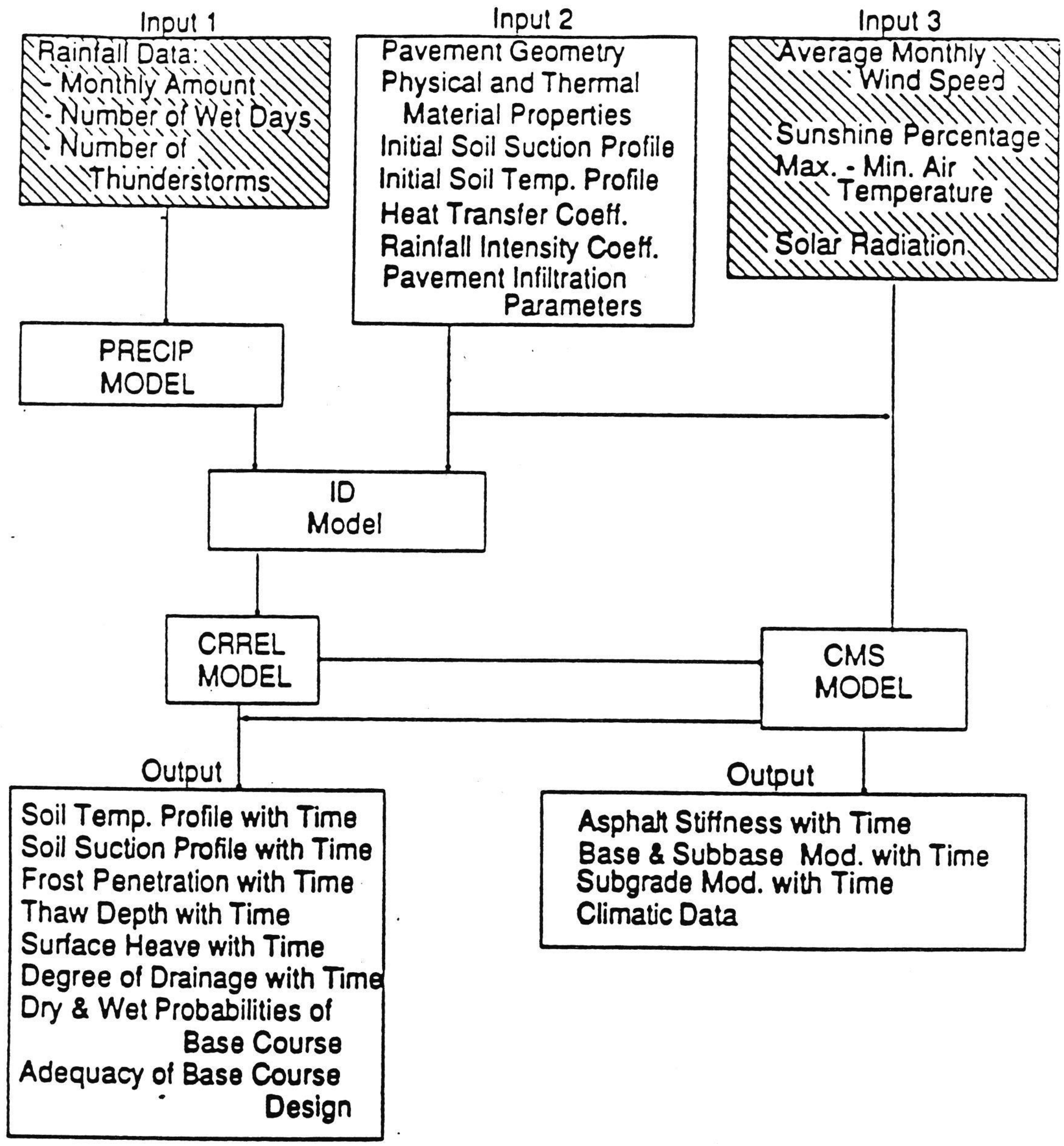

Figure 16. Integrated Pavement Model (14).

pore water pressure at a given level of the subgrade is toward an equilibrium value which under certain conditions depends solely on the height above the ground water level. Equilibrium conditions are established when the temperature within the subgrade is constant, uniform and above freezing; there is no infiltration of moisture into the subgrade through the pavement surface and no migration of moisture to and from adjacent soil masses. When an impervious pavement is constructed, rain is kept out of the soil and moisture is prevented from leaving the soil through evaporation and transpiration. The pavement also serves as an insulator which reduces the range as well as the rapidity of change of temperature in the underlying soil. Decrease in temperature of a soil increases its affinity for water. These artificial conditions created by engineering construction are conducive to the establishment of equilibrium with the water table below. The procedure also assumes the existence of a relationship between the pore water pressure in the soil at a given level and the soil suction, and a relationship between the soil suction and moisture content of the soil. Other researchers (48,49,50,51,52,53) have proposed mathematical formulas for predicting moisture movement in the subgrade based on thermodynamic principles. Lytton and Kher (54) illustrate the accuracy that can be achieved using mathematical models with accurate input data as illustrated in Figure 17.

Janssen and Dempsey (55) studied the relationship between soil suction - moisture content characteristic curve and moisture movement in subgrade soils for a number of Illinois soils. Their research indicated that soil-moisture characteristic curves can be used to predict the moisture content at various levels above the water table under equilibrium conditions. A typical curve of suction versus gravimetric water content for a homogeneous soil is shown in

Figure 18. The general shape of the soil suction curve suggests a method for approximating a soil suction curve. The lower portion of the curve can be approximated by a vertical straight line through the saturated water content whereas the mid portion of the curve can be approximated with a sloping straight line tangent to the curve. The suction value at the intersection of these two lines is termed as the break suction. W1000 is the water content at the intersection between the sloping line and a horizontal line at 1000 cm suction. Janssen and Dempsey performed a regression analysis and equations were developed to relate the break suction and W1000 to basic soil properties such as Plastic Index, Plastic Limit, Liquid Limit, Silt Content, Clay Content, Carbon Content and Saturated Water Content. The approximate soil-moisture characteristic curve may be drawn using the values of W1000 and break suction that are obtained from the regression equations.

Soil-suction curves can be used to plot sorption curves. Figure 19 shows typical sorption curves for two different soils, glacial till and loess. Some subgrades consist of several strata of different textured soils between the base of a pavement and the water table. In such cases the sorption curve will be a composite curve of the various soils encountered. Figure 20 shows actual capillary moisture contents of two texturally and geologically different soils plotted in comparison with the composite curves of the two materials. Since Janssen and Dempsey performed tests on soils under conditions that were representative of the soils in actual pavement subgrades, equilibrium moisture contents at any height above the groundwater table can be determined by using soil properties to plot soil suction curves and sorption curves for the site in question.

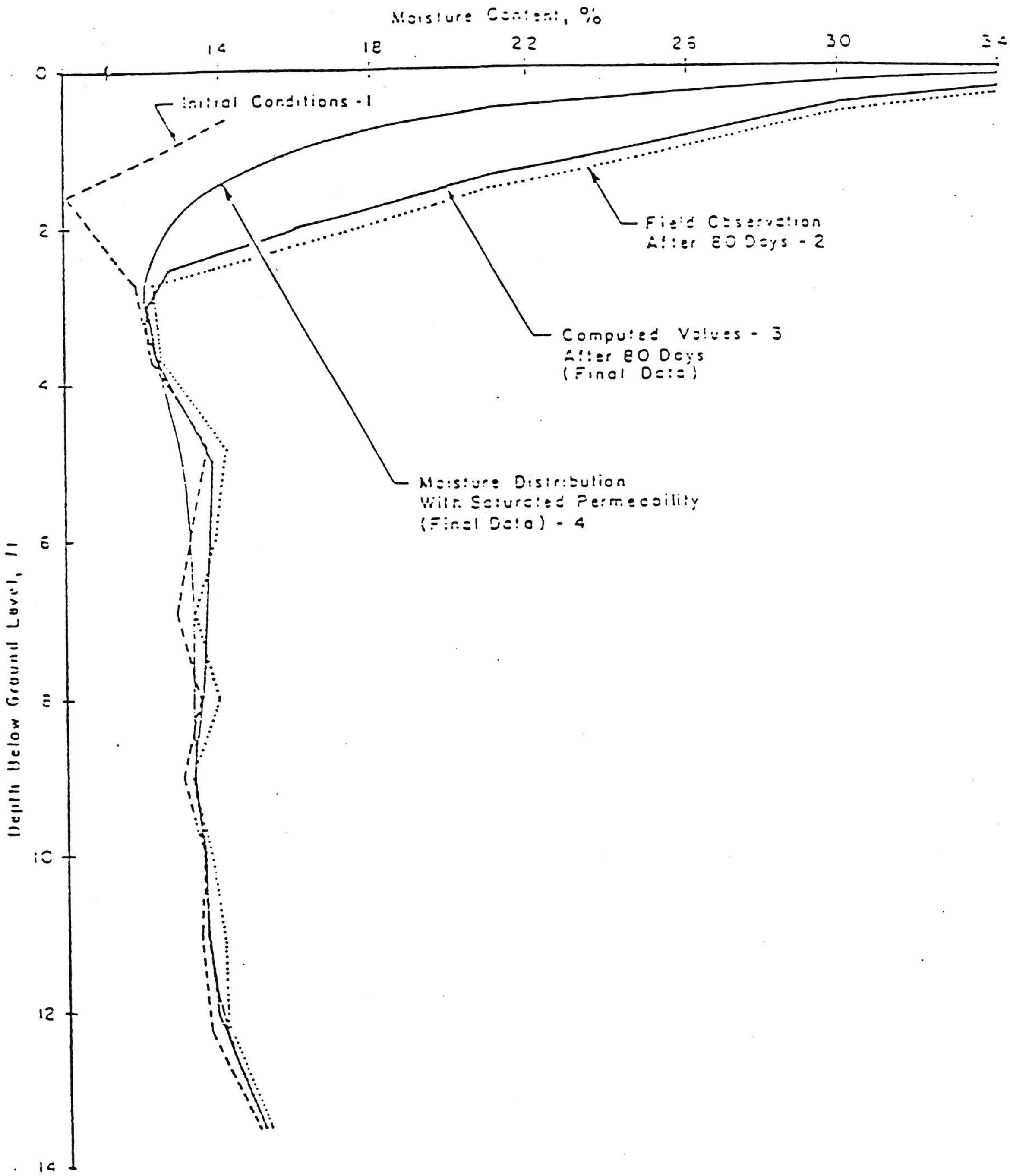

Figure 17. **Comparison Between Measured and Computed Moisture Contents at a Field Test Site in Wyoming (54).**

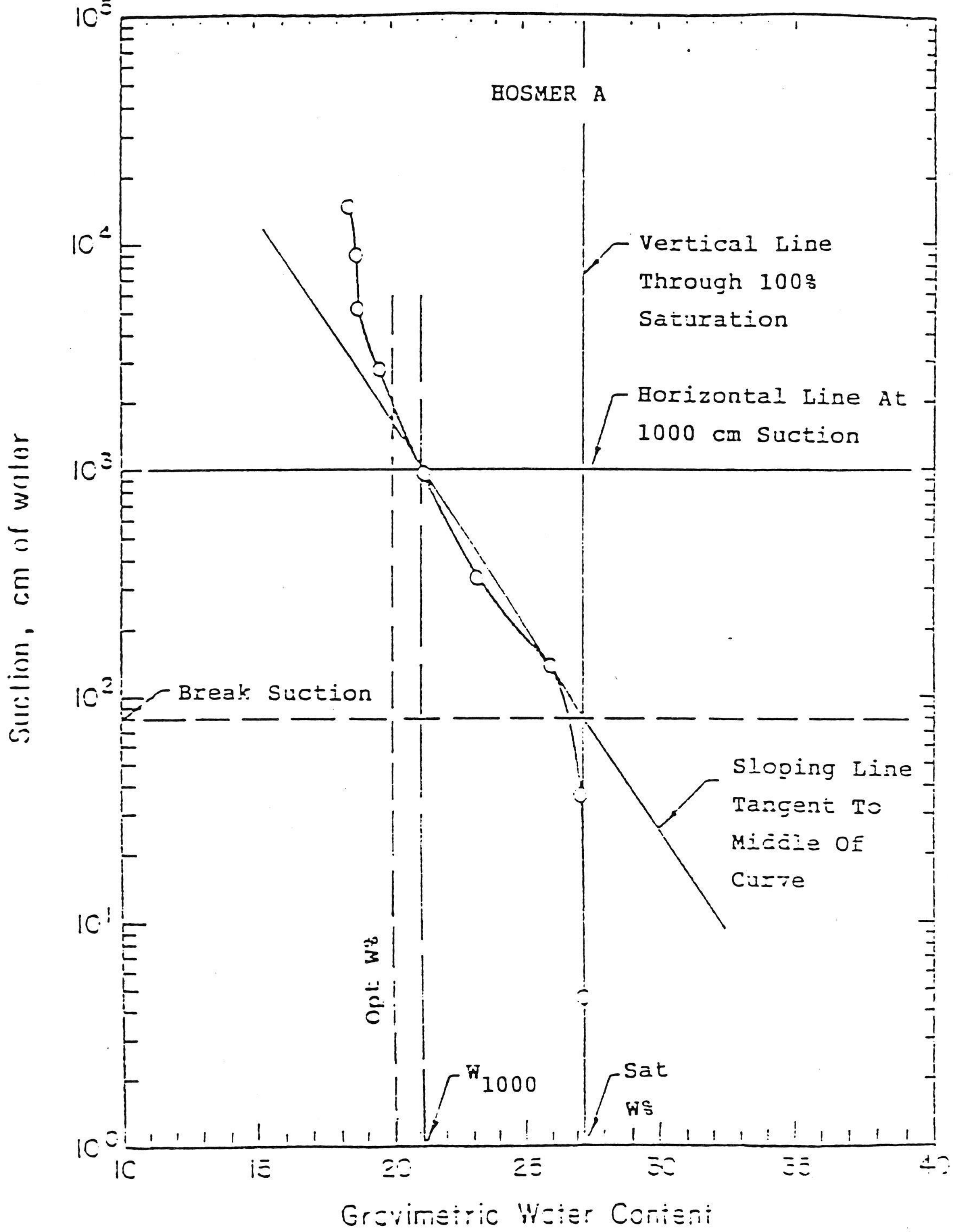

Figure 18. **Curve of Soil Suction Versus Gravimetric Water Content (55).**

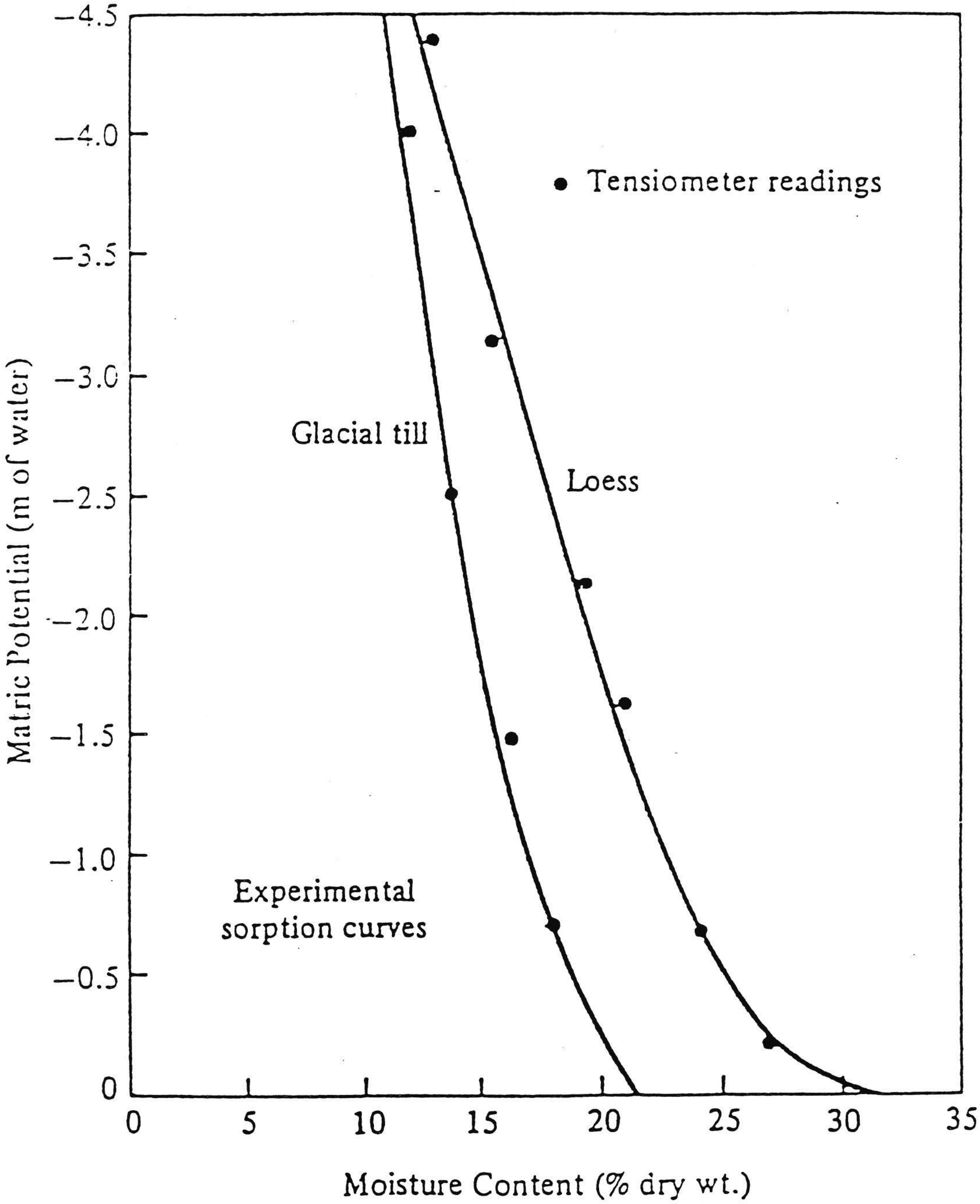

Figure 19. Typical Sorption Curves for Two Different Soils (55).

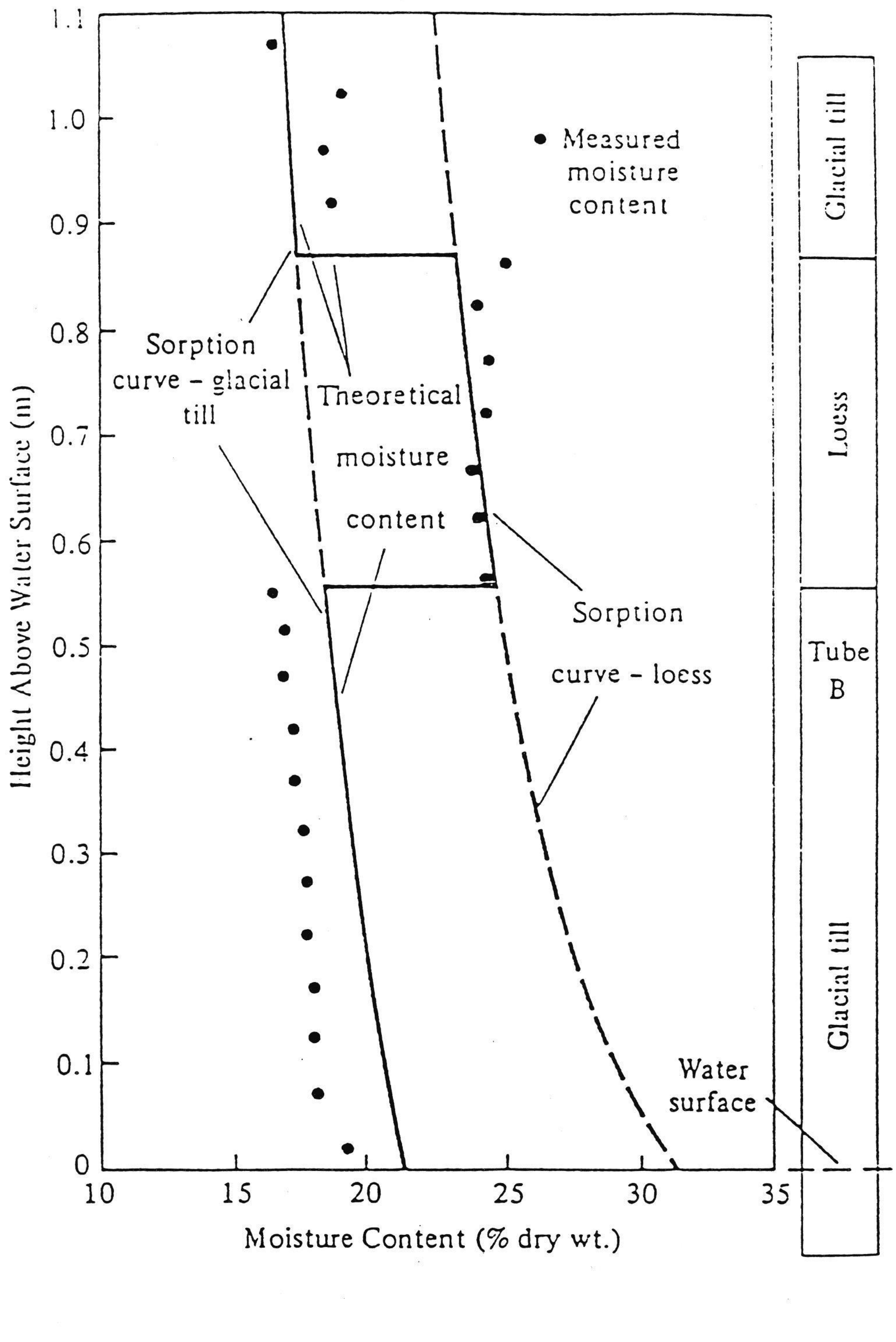

Figure 20. Composite Curves of Stratified Layers of Glacial Till, Loess, Glacial Till (55).

CHAPTER III

DATA COLLECTION

The collection of data was performed by the Planning and Research Division of the Arkansas Highway and Transportation Department (AHTD) in cooperation with the Federal Highway Administration. The data was published in Interim Report TRC-9104 (19) titled, "In-Situ Moisture Content of Arkansas Subgrades." The data collection was divided into three phases.

Phase I. Selection of Sites.

Soil type was one of the major considerations of the site selection. 18 sites from 14 counties were chosen for the collection of data. The soil types range from sandy loams and silty loams to silty clays and clays. The soil types of the sites consist of: Carnasaw, Sardis, Sacul, Amy, Jackport, Calloway, Perry, Smithton, Alligator, Sharkey, Foley, Cherokee, Sawyer, Leadvale. The soils selected represent the cases which had contributed to problems under Arkansas roadways and were also representative of many of the soils encountered in Arkansas. These soils typically have low permeability and vary from poorly drained to well drained. The soil types Smithton, Alligator and Sharkey were selected to have multiple sites; the difference in the sites being either a fill area as compared to natural ground level or a closer proximity to streams or rivers. Table 4 summarizes the location, soil type and soil classification of the test sites. The location of each of the test sites is shown in Figure 21.

Site	County	Location	Soil Series	AASHTO Class
1	Pulaski	Maumelle	Carnasaw	A-4
2	Grant	Sheridan	Sardis	A-7-6
3	Grant	Sheridan	Sacul	A-6
4	Grant	Sheridan	Amy	A-7-6
5	Monroe	Brinkley	Jackport	A-7-6
6	Ashley	Hamburg	Calloway	A-6
7	Lincoln	Fresno	Perry	A-7-5
8	Dallas	Holly Springs	Smithton	A-2-4
9	Dallas	Holly Springs	Smithton	A-2-4
10	Cross	Birdeye	Alligator	A-7-6
11	Cross	Birdeye	Alligator	A-7-6
12	Arkansas	Ethel	Sharkey	A-7-6
13	Jackson	Newport	Sharkey	A-7-6
14	Craighead	Jonesboro	Foley	A-7-6
15	Benton	Rogers	Cherokee	A-4,A-6
16	Hempstead	Hope	Sawyer	A-7-6
17	Mississippi	Lepanto	Sharkey	A-7-5
18	Yell	Blue Ball	Leadvale	A-6,A-4

Table 4. **Location, Soil Type and Classification of the 18 Sites.**

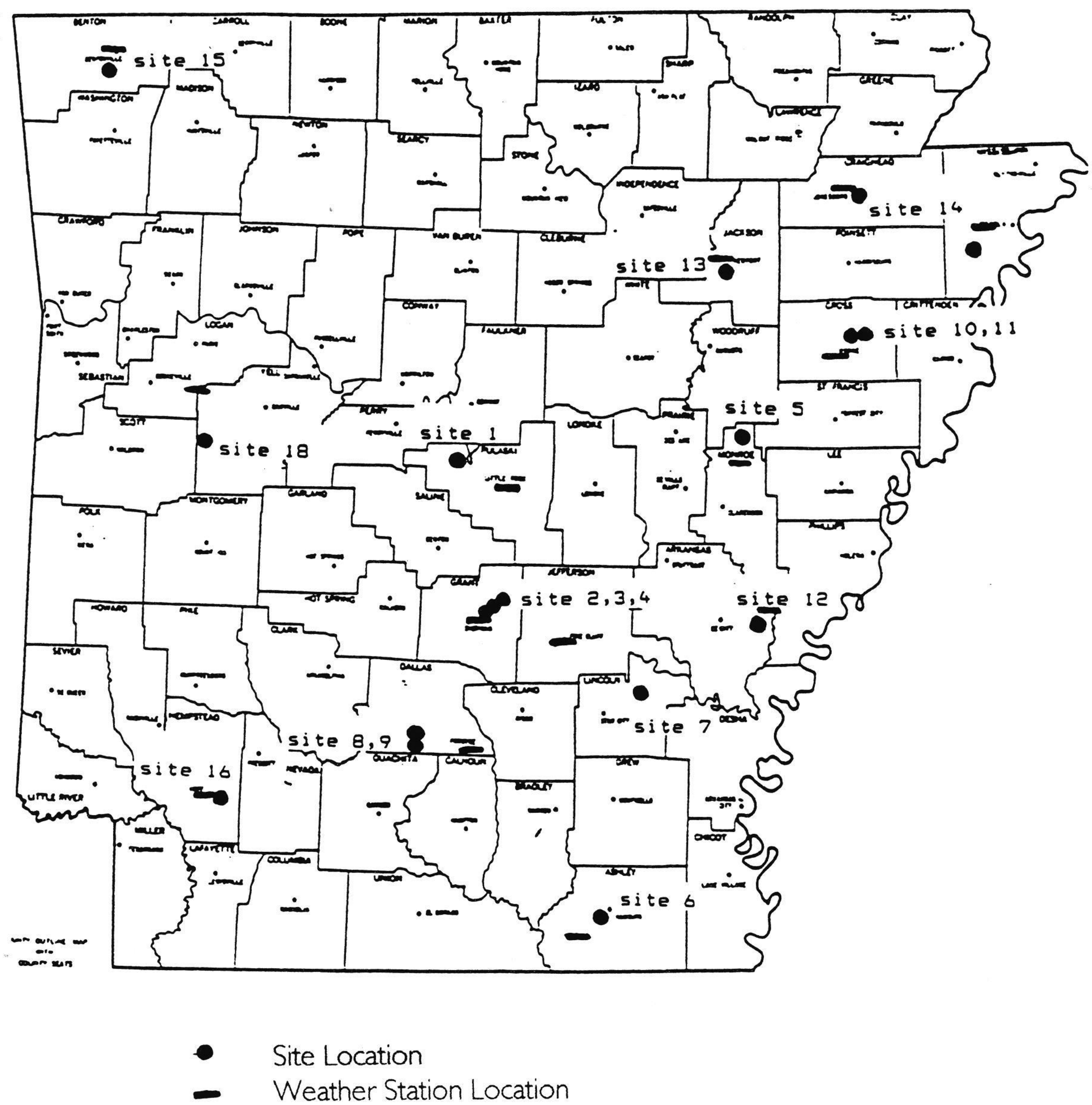

Figure 21. Location of the 18 Test Sites (19).

Phase II. Selection of Instrumentation, Development of Sampling Plan, Installation of Access Tubes.

The moisture contents and densities of the soil at the selected test sites were measured using a Campbell Pacific Nuclear Depth Probe Model 501. The probe measures the moisture and density of a sphere approximately 12 inches in diameter. A 64 second duration reading was used to achieve the necessary accuracy in the least amount of time. Based on an established sampling plan, some sites were read every month, some every two months, and the remainder every three months. The plan allowed for at least one reading per site per season. The frequency of testing on a per site basis is shown in Table 5. Not all sites were visited in strict accordance with the sampling plan due to problems like weather conditions, testing equipment malfunction, and scheduling problems.

2 inch aluminum access tubes were used with an inside diameter that allows only a minimum clearance between the tube wall and the nuclear probe. The tubes were 10 feet long. Care was taken to ensure that the installation of the tubes was performed without disturbing the surrounding soil. The tube was anchored by pouring concrete around the top of the tube. A 4 inch PVC pipe and PVC cap placed on top of the pipe was used as a protective covering for the tube. A rubber stopper was used to prevent moisture and dirt from entering the tube. Access tubes were installed on each shoulder and at the centerline of the pavement. Both asphalt and concrete pavements were monitored for this study. Figure 22 shows a typical section of the installation.

	91								92												93						
SITE	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**	**J**	**F**	**M**	**A**	**M**	**J**	**J**
1	3	1	1		1	3	1	1		1			1	1	1	1	1	1				1	1		3	3	
2,3,4	3	1	1	1	1	1	1	1		1			1	1	1	1	1	1				1	1		3	3	
5	2	3	2	3	2	3	2	3						1	2	3	2	3				2	3		3	3	
6	2	3	2	1	3		2	3						2	3	2	3			2	1	3			3	3	
7	2	3	2	3	2	3	2	3	2	3				2	1	3	2	3			2	3			3	3	
8,9	2	3	2	3	2	3	2	3	2	3				1	2	3	2	3	2		3	2	3		3	3	
10,11				1		1		1						3		3		3			2		1		3	3	
12	2	3	2	3			2	3						1	2	3	2	3				2	3		3	3	
13	2	3	2	3	2	3	2	3						1		2	3								3	3	
14			2	3	2	3	2	3						1	2	3	2	3			2	2	3		3	3	
15	2	3	2	3			2	3						1		2	3				2	3		3		3	
16	2	3	2	1	3		2	3						1		2	3				2	3		3		3	
17			2	3	2	3	2	3						2	3		1				2	3			3	3	
18			2	1	3									1		2	3					2	3		3	3	

1 = Proposed and Completed
2 = Proposed and not Completed
3 = Not Proposed but Completed

Table 5. Frequency of Testing.

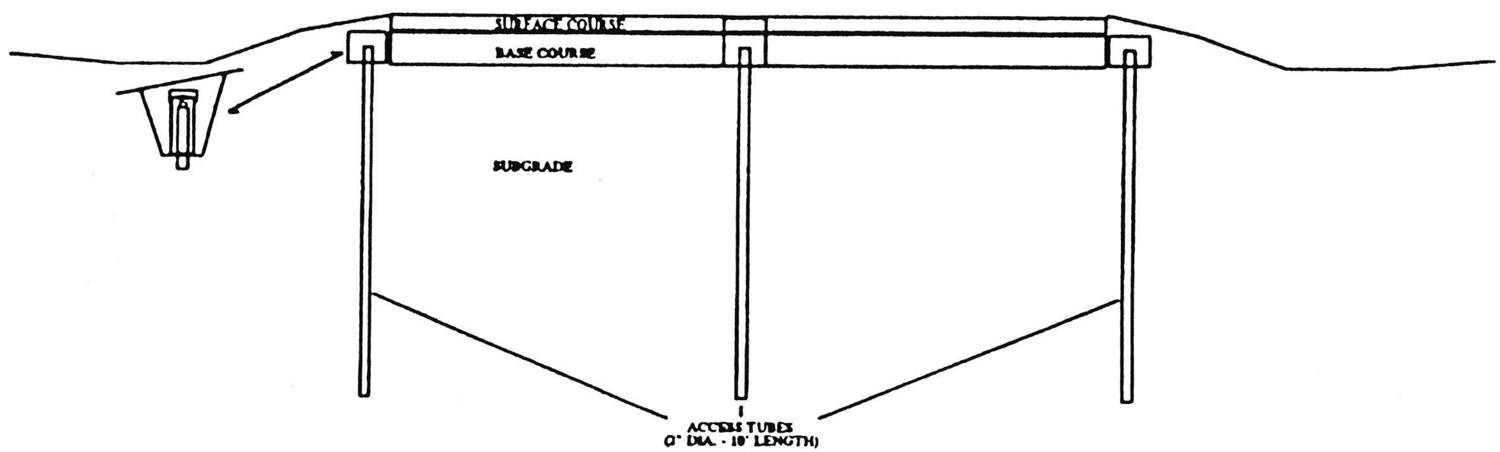

Figure 22. Typical Installation Section (19).

Phase III. Accumulation of Data.

Each site was visited and moisture/density data was taken at various times during the year, mostly according to the sampling plan. The readings were taken at one foot intervals from a depth of 1.5 feet to 9.5 feet below the surface. Falling Weight Deflectometer (FWD) was used to take deflection readings at the same time moisture/density readings were taken. The FWD loads were approximately 9,000 and 12,000 pounds. The FWD data was obtained in a pattern that covered the outside wheel paths of each lane and the centerline of the road. The readings were taken every 25 feet starting 10 feet from the tubes in each direction. The FWD pattern is shown in Figure 23. Rainfall data gathered by the National Weather Service as obtained from the closest reporting station was used in this project. This rainfall data is assumed to represent a reasonable approximation of the rainfall in the area under consideration.

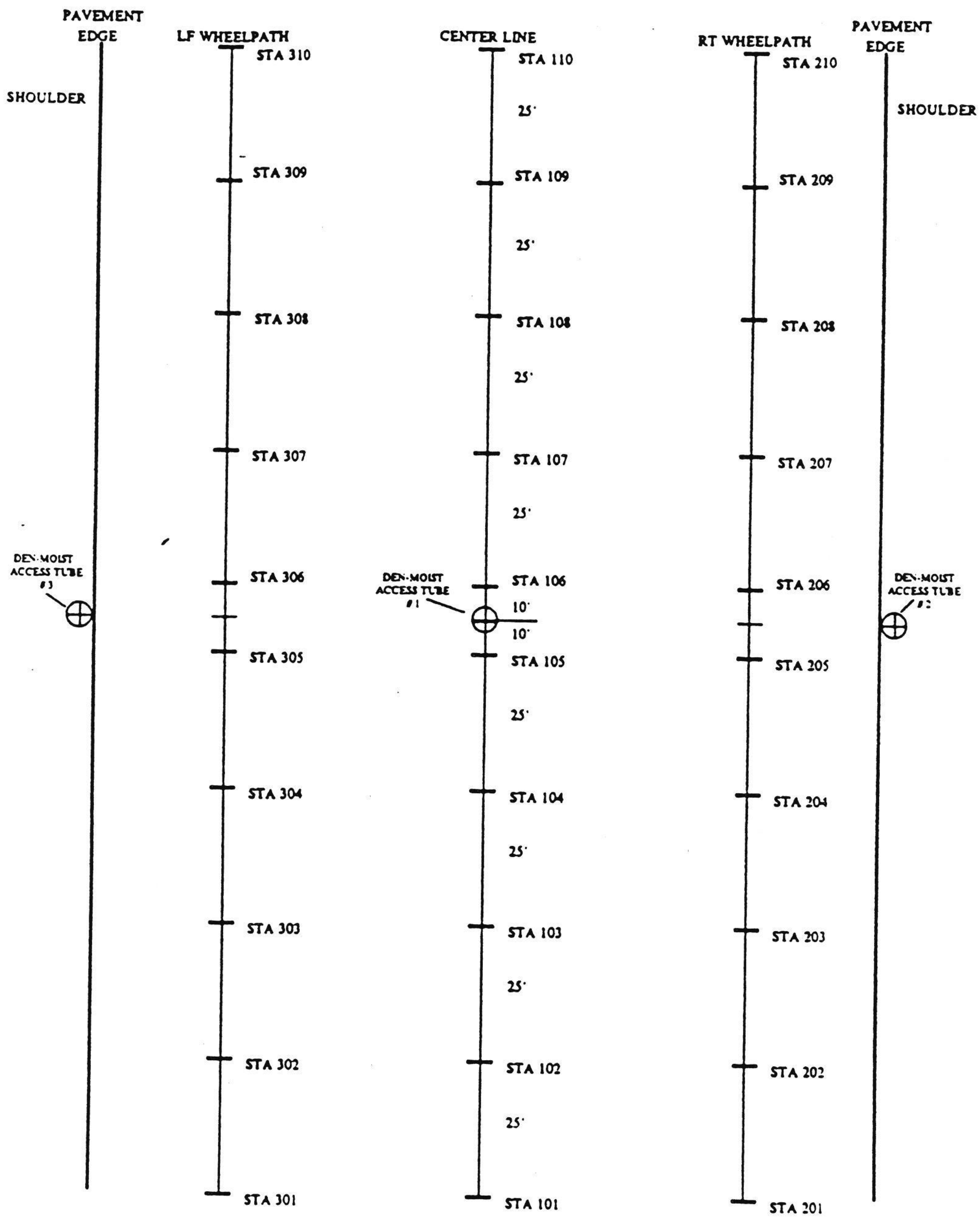

Figure 23. FWD Test Locations at Density/Moisture Sites (19).

CHAPTER IV

ANALYSIS OF DATA

Preparing the Data

A relational database was created for a thorough analysis of the different types of data. The tables in the database included: (a) A "Moisture Data" table containing moisture content information for the 18 sites measured at different depths at different times between May 1991 and July 1993. The data which was obtained from the Arkansas Highway Department was in hard copy form and only data relevant to the project was used. (b) Two site information tables - A "General Site Information" table containing general site information like County, Soil Type etc. and a "Specific Site Information" table containing specific site information like pavement layer thickness' etc. (c) Two soil information tables - A "Soil Series Information" table and a "Soil Profile Information" table containing soil information obtained from the County Soils Reports. (d) Two tables containing precipitation data - A "Precipitation Data" table containing actual monthly precipitation and average monthly temperature data obtained from the Arkansas Climatological Records measured at the nearest weather station and a "Weather Data CSR" table containing average monthly precipitation and temperature data for the different counties obtained from the county soils reports.

Information from these tables were queried and transferred to spreadsheets for graphical, statistical and visual analysis of the data. The results of the analysis follow.

Correlation With Precipitation and Temperature

A shallow depth of 30 inches below the pavement surface and a deep depth of 90 inches below the pavement surface were used for a correlation analysis between subgrade moisture content and monthly precipitation and also between subgrade moisture content and average monthly temperature. Table 6 shows the correlation analysis results considering moisture beneath the edges and the center of the pavement.

The following general conclusions can be drawn from the correlation analyses. Correlation coefficients at very few sites are statistically significant. The subgrade moisture at some sites are more likely to be correlated with monthly precipitation or average monthly temperature than others.

1. The correlation coefficients are not very high indicating the influence of other factors on the moisture in the subgrade.
2. Correlation at the shallow depth may or may not be indicative of correlation at the deeper depth.
3. Correlation of subgrade moisture with precipitation is predominantly positive and may even be delayed by one or two months.
4. Correlation of subgrade moisture with temperature at most sites is predominantly negative indicating lower moisture contents in the subgrade during the winter months. A typical plot of average monthly temperature versus time of year is shown in Figure 24.
5. Moisture contents at the shallow depths are more likely to be correlated with temperature than moisture contents at the deep depths.

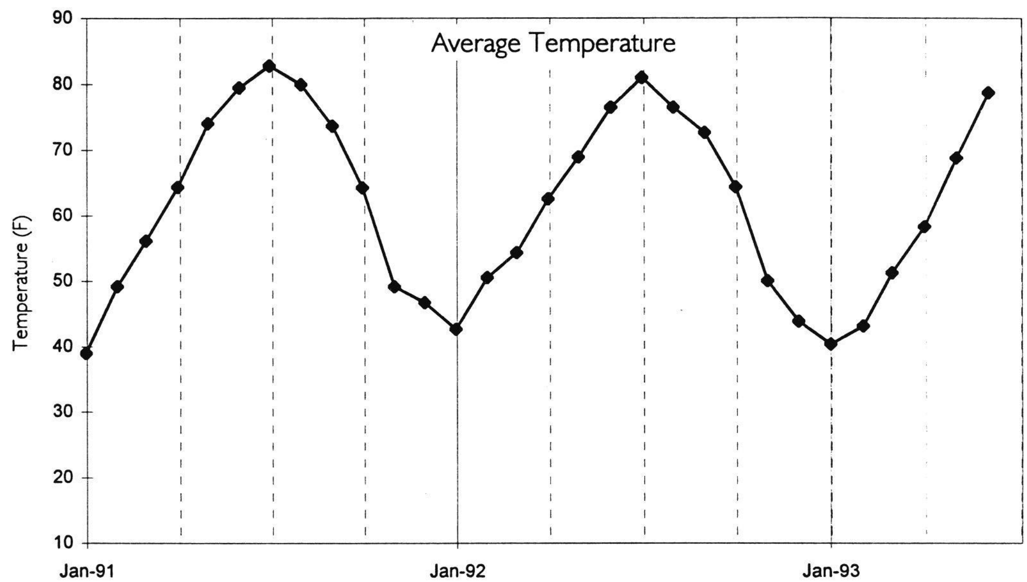

Figure 24. Average Monthly Temperature Versus Time For A Typical Site in Arkansas.

Site No.	Precipitation(Shallow)			Precipitation(Deep)			Temperature(Shallow)			Temperature(Deep)		
	Month(0)	Month(-1)	Month(-2)	Month(0)	Month(-1)	Month(-2)	Month(0)	Month(-1)	Month(-2)	Month(0)	Month(-1	Month(-2)
1	-0.09	-0.04	0.03	0.50	-0.11	0.18	-0.58	-0.65	-0.49	-0.10	0.10	0.28
2	-0.16	-0.15	0.07	-0.08	-0.09	0.05	-0.28	-0.34	-0.24	-0.39	-0.45	-0.29
3	-0.11	-0.19	0.29	0.32	-0.01	-0.08	-0.22	-0.22	-0.11	-0.23	-0.10	0.08
4	-0.06	0.31	-0.04	0.03	0.19	0.19	-0.28	-0.37	-0.35	-0.19	-0.35	-0.37
5	0.00	0.23	0.29	0.06	0.22	0.17	-0.19	-0.26	-0.22	0.01	-0.05	-0.05
6	-0.22	0.19	-0.31	-0.15	0.39	0.10	-0.06	0.21	0.42	0.04	0.27	0.43
7	0.13	-0.09	-0.51	-0.12	-0.27	0.26	0.21	0.44	0.40	-0.23	-0.29	-0.23
8	0.27	-0.24	0.18	0.45	-0.19	0.64	-0.51	-0.64	-0.60	-0.76	-0.96	-0.96
9	0.36	-0.27	0.20	0.40	-0.42	0.38	-0.51	-0.67	-0.69	-0.65	-0.79	-0.67
10	0.34	0.21	0.12	0.06	-0.11	-0.05	-0.48	-0.39	-0.12	-0.18	-0.01	0.15
11	-0.46	0.41	0.30	-0.01	-0.22	-0.15	-0.03	-0.22	-0.31	-0.06	0.06	0.16
12	0.09	0.27	0.15	0.61	0.29	-0.18	0.14	0.21	0.28	-0.20	-0.02	0.50
13	0.23	0.43	0.24	0.26	0.36	0.26	-0.67	-0.73	-0.32	-0.74	-0.68	-0.17
14	-0.18	0.34	0.31	0.02	0.14	0.14	-0.47	-0.51	-0.32	-0.43	-0.37	-0.08
15	0.37	0.63	0.56	0.50	0.14	0.01	-0.30	-0.43	-0.51	0.08	-0.03	-0.29
16	0.04	-0.03	0.00	0.18	-0.39	-0.22	0.12	0.20	0.21	0.19	0.36	0.39
17	0.48	-0.17	0.50	0.47	0.23	0.70	-0.67	-0.60	-0.14	-0.36	-0.54	-0.46
18	-0.16	-0.11	0.01	-0.10	-0.32	-0.28	0.01	0.20	0.25	-0.13	0.15	0.28

Table 6. **Correlation Between Subgrade Moisture Content and Precipitation and Temperature At the Shallow Depth of 30 Inches and the Deep Depth of 90 Inches Below the Surface of the Pavement for the 18 Sites.**

The following specific observations can be made from the correlation analyses and the subgrade moisture graphs.

1. The soils at sites 1,3,16 and 18 are moderately well drained to well drained soils and these sites show no correlation between subgrade moisture and precipitation at the shallow depth.
2. The moisture content at the shallow depth at site 15 is strongly correlated with precipitation. The water table at site 15 is deep (at least 114 inches) and with the silty loam soil, capillary action may not be a significant factor and hence the higher influence of precipitation on subgrade moisture at site 15 at the shallow depth.
3. The moisture content at site 2 shows no correlation with the precipitation at both the shallow and deep depths. The permeability of the soil at site 2 is moderate and does not change with depth. The moisture content at site 17 is well correlated with precipitation at both the shallow and deep depths. The permeability of the soil at site 17 is very slow and does not change with depth.
4. Sites 8 and 9 are both in Dallas county with Smithton soil series while sites 10 and 11 are both in Cross county with Alligator soil series. Although the correlation behavior at the shallow depth may differ due to construction or other factors the correlation coefficients at the deep depth seems to agree between the two pairs of sites.
5. Although moisture contents in the subgrade are inversely correlated to temperature (and hence time of year) to some extent at some sites, there is no indication that soil properties may dictate the degree of correlation.

Equilibrium

The moisture contents in the subgrade were plotted as a function of time for the 18 sites and for each of the 9 depths ranging from 18 inches to 114 inches below the surface of the pavement. The actual monthly precipitation was also plotted as a function of time. Appendix A shows the subgrade moisture graphs and the corresponding precipitation graphs at two depths - the shallow depth of 30 inches below the pavement surface and the deep depth of 90 inches below the pavement surface.

The subgrade moisture graphs indicate that moisture in the subgrade for each site and at each depth is limited to a range of values. The upper and lower limits of this range can be considered as the upper and lower equilibrium values for the moisture content in the subgrade. The spread, median, upper and lower limits depend on site and soil characteristics and also vary with depth. They are however independent of precipitation, temperature or time of the year. Table 7 shows the upper equilibrium value, the lower equilibrium value, the spread and the median values of subgrade moisture contents at the two depths of 30 inches and 90 inches below the surface of the pavement for the 18 test sites.

The following general conclusions can be drawn from the graphs and from Table 7.

1. The lower equilibrium values for the subgrade moisture contents at the deeper depths are typically higher and on the average more than 3 percent higher than the corresponding values at the shallow depths.
2. The upper equilibrium values for the moisture at the deeper depths are comparable to those at the shallow depth with an average difference of less than 1 percent.

Site No.	Shallow (Depth=30 inches)				Deep (Depth=90 inches)			
	Minimum	Median	Maximum	Spread	Minimum	Median	Maximum	Spread
1	14.0	17.5	24.0	10.0	17.0	20.0	21.5	4.5
2	12.0	13.5	17.5	5.5	20.0	23.5	29.5	9.5
3	8.0	21.0	36.0	28.0	24.0	29.5	38.0	14.0
4	12.0	15.0	21.0	9.0	20.5	24.0	28.0	7.5
5	24.0	27.0	34.0	10.0	19.5	26.0	34.0	14.5
6	16.5	20.5	30.0	13.5	17.0	21.0	27.0	10.0
7	17.5	22.5	30.5	13.0	25.0	29.5	36.5	11.5
8	7.5	11.5	15.5	8.0	18.0	18.5	24.0	6.0
9	12.0	16.0	20.0	8.0	17.0	19.0	23.0	6.0
10	15.0	19.0	21.0	6.0	10.0	17.0	23.0	13.0
11	23.5	31.0	34.5	11.0	21.5	24.0	28.0	6.5
12	13.5	16.0	21.8	8.0	16.0	18.0	23.5	7.5
13	12.5	16.0	26.0	13.5	16.0	20.5	22.5	6.5
14	7.5	13.5	21.0	13.5	16.0	21.5	24.0	8.0
15	19.0	23.0	29.0	10.0	13.0	15.5	17.0	4.0
16	18.0	21.5	28.0	10.0	17.5	24.0	27.5	10.0
17	26.0	36.0	39.0	13.0	25.5	34.5	39.0	13.5
18	12.5	15.5	22.0	9.5	13.5	16.0	22.5	9.0
Ave	15.1	19.8	26.2	11.1	18.2	22.3	27.1	9.0

Table 7. **Equilibrium Constants at Depths of 30 Inches and 90 Inches Below the Surface of the Pavement For the 18 Sites.**

3. Median values for the moisture contents in the subgrade are typically higher by an average of 2 percent at the deeper depths than the shallow depths.
4. The difference between the upper and lower equilibrium values (the spread of the moisture range) are higher at the shallow depth than at the deep depth by an average of more than 2 percent. The average spread of moisture contents at the shallow depth is 11.1 percent while the average spread of moisture contents at the deep depths is 9 percent.

A correlation analysis was performed between the equilibrium values, the median moisture contents and spreads with several soil and site properties. The soil and site properties used in this analysis are based on data obtained from County Soils Reports for the sites in question. The correlation tables obtained from this analysis for six depths are shown in Appendix B. The following conclusions can be drawn from the correlation analysis.

1. At the shallow depth of 18 inches, the lower equilibrium value, the higher equilibrium value, the median and the spread are strongly correlated with Liquid Limit, Plasticity Index, Permeability and percent passing sieve #200.
2. Factors like surface course thickness, average daily temperatures, average total yearly precipitation, average depth to water table and average daily traffic do not seem to be strongly correlated with the equilibrium values.
3. At the depth of 30 inches below the surface of the pavement, the upper and lower equilibrium values have a stronger correlation with soil properties 12 inches above than soil properties at the same depth.

4. As the depth increases to 78 inches below the surface of the pavement, the equilibrium values, median values and the spreads are almost independent of soil factors.
5. Other factors like slopes, surface course thickness, depth to water table, average daily temperatures, average total precipitation, and average daily traffic seem to have a stronger correlation with the equilibrium values at the deeper depth than the soil properties.

Based on these observations a Visual Basic program was written to develop regression equations for the upper and lower equilibrium values from soil properties obtained from the County Soils Reports. Since the County Soils Reports for sites 10,11,12,13 and 17 did not contain all the soil information needed, these sites were not included in developing the regression equations for the depths of 18 inches and 30 inches below the pavement surface. Also sites 5,10,11,12 and 16 were not used in developing the regression equations for the depth of 78 inches below the pavement surface because of insufficient information. The regression equations are shown below:

18 inches below the pavement surface:

$$\text{Lower Limit} = 2.86 + 0.174(\#200_L)^{1.08} - 0.173(LL_U + 5)^{1.11} + 0.021(PI_L)^{2.12} - 0.089(\text{Log}(\text{Perm}_U))^{-3}$$

Correlation Coefficient = 0.89, R-Square = 0.79

$$\text{Upper Limit} = 6.45 + 0.221(\#200_L)^{1.08} - 0.134(LL_U + 5)^{1.11} + 0.024(PI_L)^{2.12} - 0.071(\text{Log}(\text{Perm}_U))^{-3}$$

Correlation Coefficient = 0.89, R-Square = 0.80

30 inches below the pavement surface:

$$\text{Lower Limit} = -1.25 + 0.313(\#200_{LA})^{1.08} - 0.292(LL_{UA} + 5)^{1.11} + 0.028(PI_{LA})^{2.13} - 0.075(\text{Log}(\text{Perm}_{UA}))^{-3}$$

Correlation Coefficient = 0.78, R-Square = 0.61

$$\text{Upper Limit} = 9.66 + 0.212(\#200_{LA})^{1.08} - 0.118(LL_{UA} + 5)^{1.14} + 0.023(PI_{LA})^{2.13} - 0.059(\text{Log}(\text{Perm}_{UA}))^{-3}$$

Correlation Coefficient = 0.86, R-Square = 0.74

78 inches below the pavement surface:

$$\text{Lower Limit} = -1.29 + 5.85(\text{Log}(AWTD)+1.2)^{1.19} + 5.72E\text{-}7(ADMinT)^{4.31} - 6.80E\text{-}7(ATP - 13)^{3.94} - 12.1E\text{-}7(ADT+11000)^{1.68}$$

Correlation Coefficient = 0.77, R-Square = 0.59

Upper Limit - Not well defined

Where

#200 = Percent passing sieve #200

LL = Liquid Limit

PI = Plasticity Index

Perm = Permeability

AWTD = Average Water Table Depth from USGS Quad Maps

ADMinT = Average Daily Minimum Temperature for a year

ATP = Average Total Precipitation for a year

ADT = Average Daily Traffic

Suffix L = Lower Limit from the County Soils Reports

Suffix U = Upper Limit from the County Soils Reports

Suffix A = Soil Properties 12 inches Above

These equations should be used with caution and engineering judgment should be exercised with the knowledge that the equations have been developed using upper and lower limits of soil properties from County Soils Reports and predict upper and lower equilibrium values that have been established for the 18 sites based on visual and statistical analysis. Also as evident from the correlation analysis, the actual upper and lower equilibrium values depend on many other factors especially at the deeper depths. The correlation between the predicted values and the actual moisture equilibrium values is poor at the deeper depths. Another factor to be considered is that two sites may have identical soil properties as obtained from the County Soils Reports but may have different equilibrium values due to factors not considered in the regression equations.

Figures 25 through 30 shows the plots of the predicted upper and lower equilibrium values versus the actual upper and lower equilibrium values for the depths of 18, 30 and 78 inches below the pavement surface.

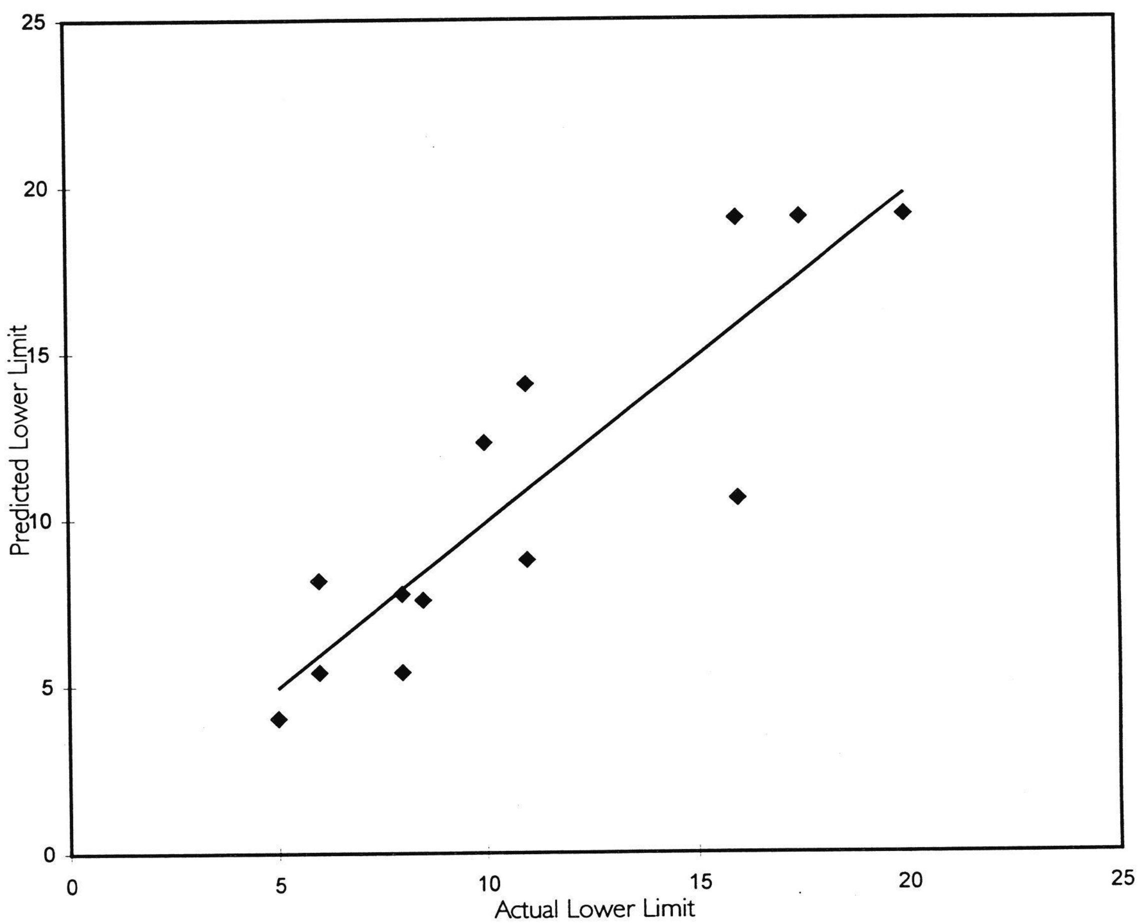

Figure 25. **Predicted Lower Equilibrium Values Versus Actual Lower Equilibrium Values at Depth of 18 Inches Below the Pavement Surface.**

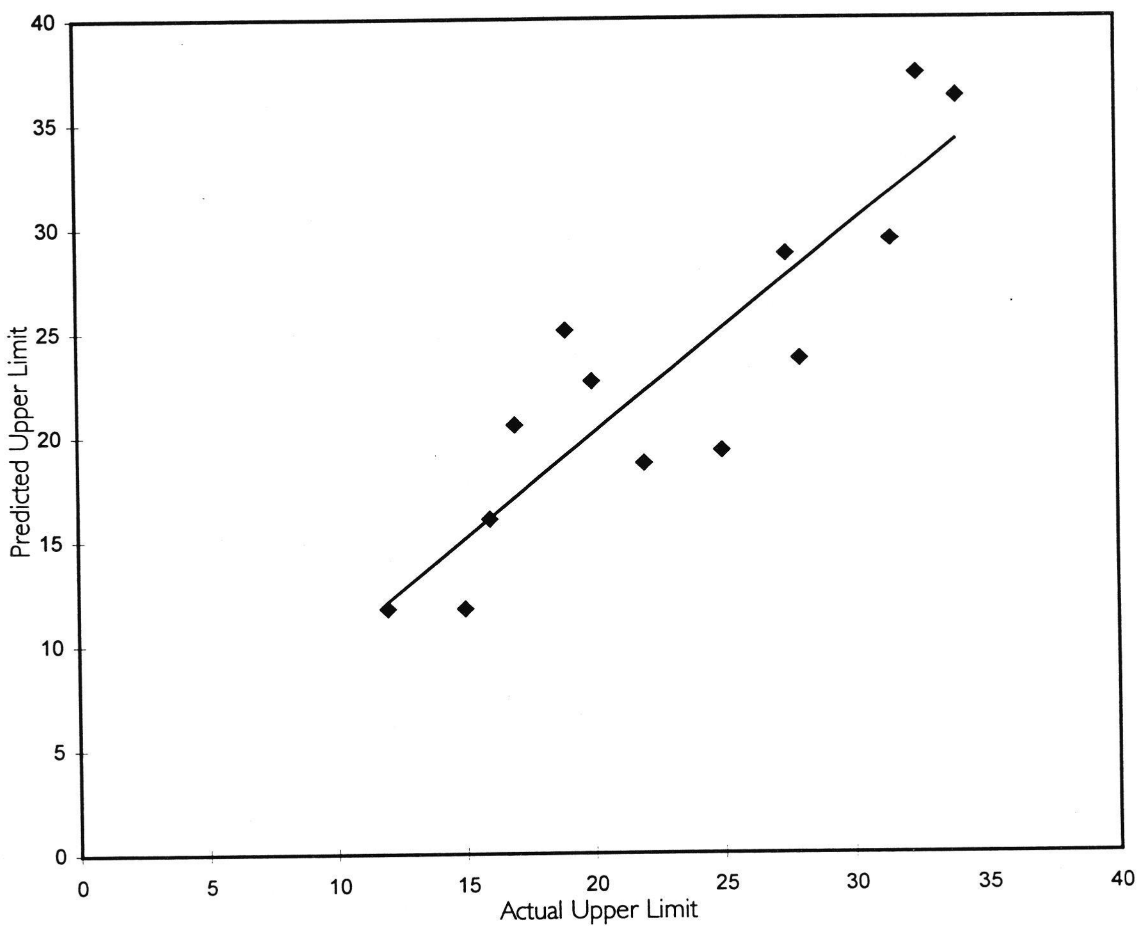

Figure 26. **Predicted Upper Equilibrium Values Versus Actual Upper Equilibrium Values for the Depth of 18 Inches Below the Pavement Surface.**

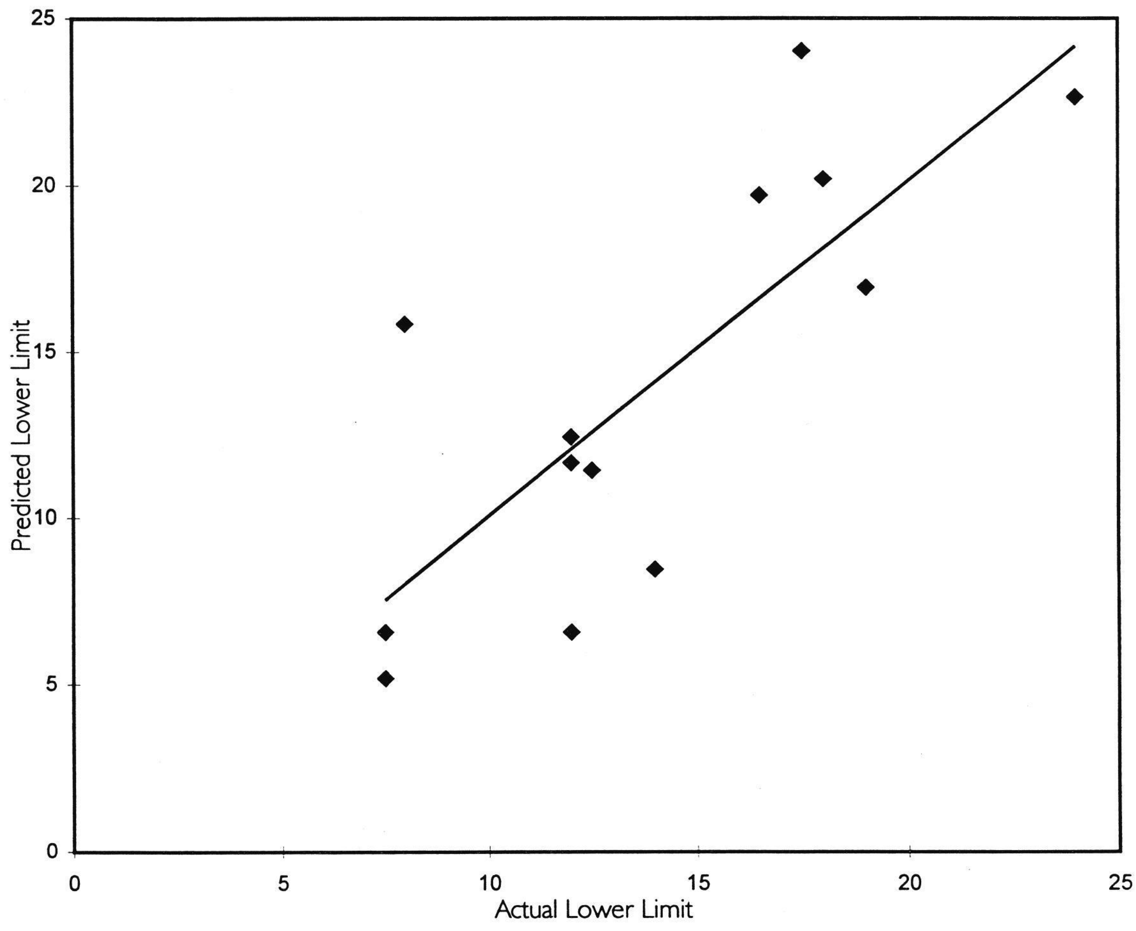

Figure 27. Predicted Lower Equilibrium Values Versus Actual Lower Equilibrium Values for the Depth of 30 Inches Below the Pavement Surface.

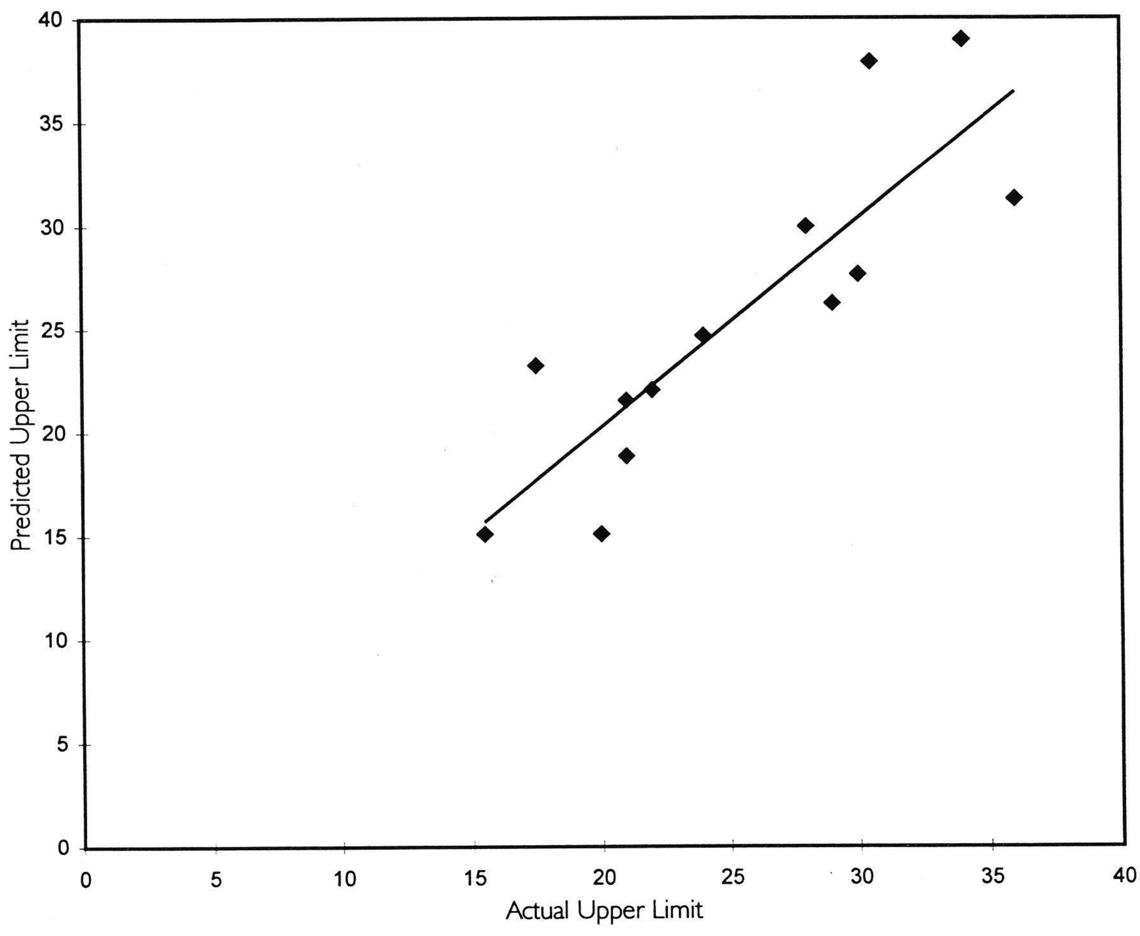

Figure 28. Predicted Upper Equilibrium Values Versus Actual Upper Equilibrium Values for the Depth of 30 Inches Below the Pavement Surface.

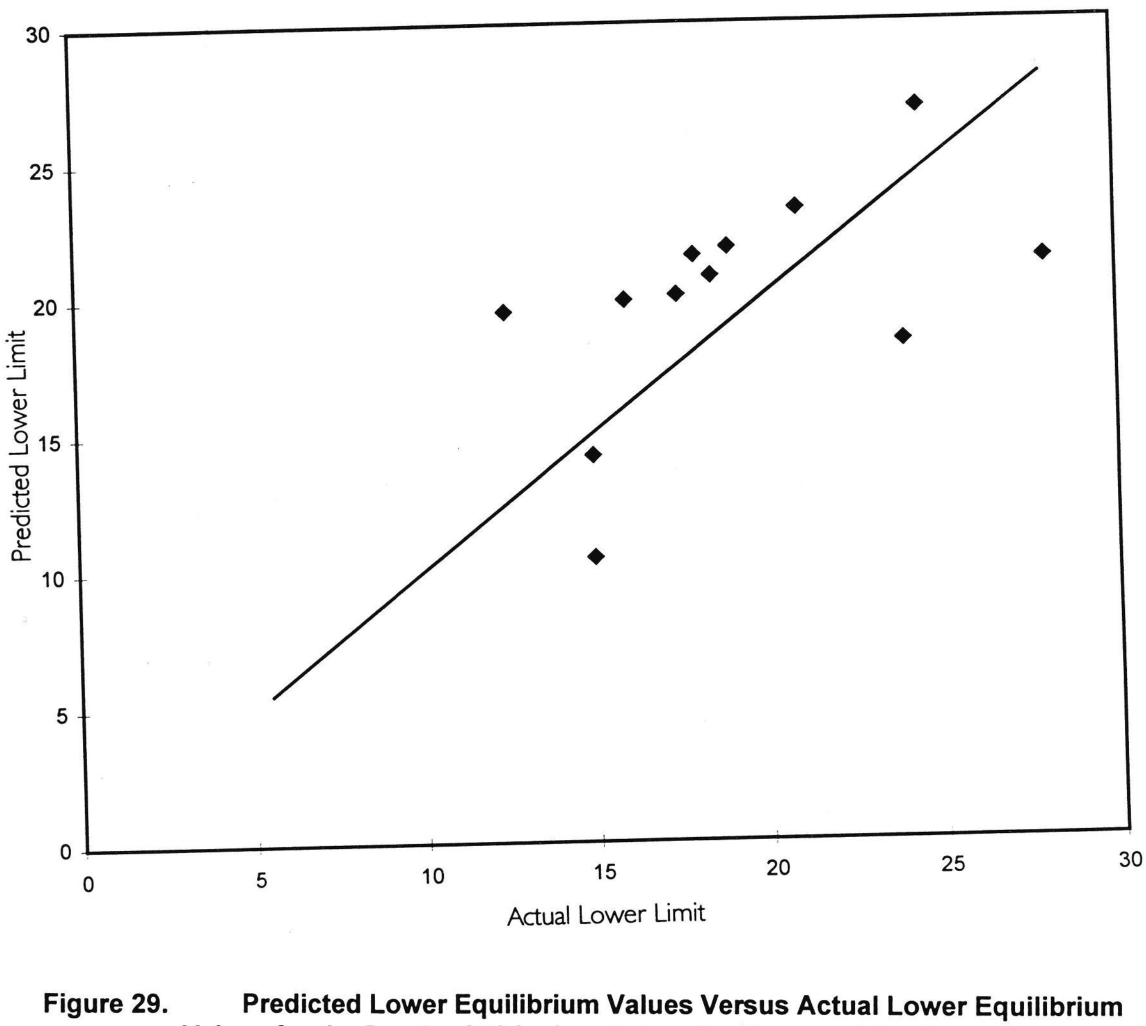

Figure 29. **Predicted Lower Equilibrium Values Versus Actual Lower Equilibrium Values for the Depth of 78 Inches Below the Pavement Surface.**

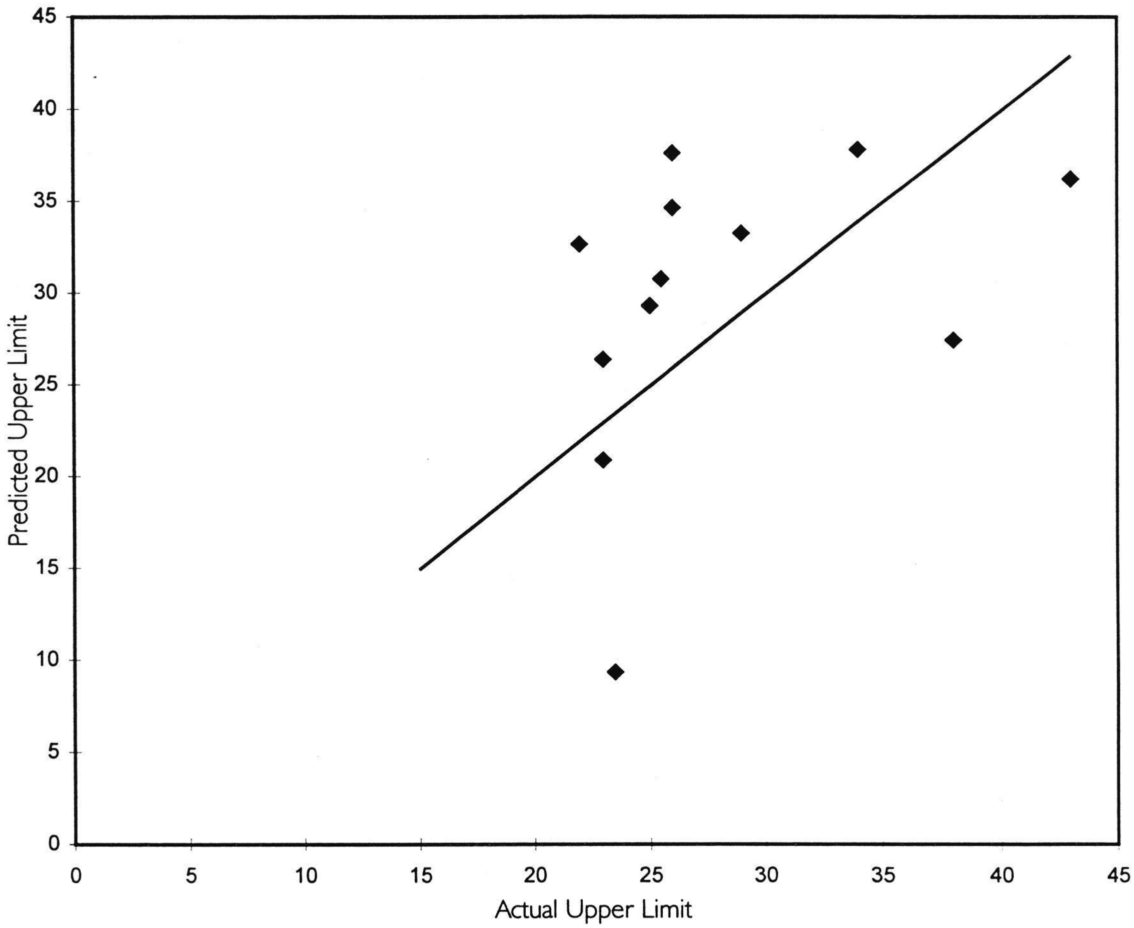

Figure 30. Predicted Upper Equilibrium Values Versus Actual Upper Equilibrium Values for the Depth of 78 Inches Below the Pavement Surface.

Changes with Depth

The variation of the equilibrium values, median values and spreads with depth for the 18 sites is shown in Appendix C. Typical variation of the actual subgrade moisture content with depth at different times of the year for the 18 sites are shown in Appendix D.

The variations of subgrade moisture content with depth show similarities in patterns with the variations of the median equilibrium values. The following general patterns are observed with respect to variation of subgrade moisture with respect to depth.

1. Sites 4, 12 and 14 show a general and gradual increase in subgrade moisture content with depth.
2. The subgrade moisture content at site 15 decreases with depth till about 60 inches below the pavement surface. The subgrade moisture content increases beyond that depth.
3. At sites 1,5 and 11, the subgrade moisture content gradually increase with depth at the shallow depth and then decrease with increasing depth at the deeper depth.
4. The moisture contents of the soils at sites 10, 16, 17 and 18 remain constant at all depths beneath the pavement.
5. The rest of the sites - sites 2,3,6,7,8,9 and 13 indicate a quick increase in subgrade moisture content with depth, the moisture content then remains constant beyond that depth.

The above 5 modes of variation of subgrade moisture content with depth are indicated both in the plots of the actual moisture contents and in the plots of the equilibrium and median values.

CHAPTER V

CONCLUSION

Many factors need to be considered in the analysis of moisture beneath a pavement and the collection of data need to reflect these factors. The following are some of the factors that need to be considered in the collection of data for analysis of moisture in the subgrade.

Resolution of Data

The minimum resolution of moisture data collected by the Arkansas State Highway and Transportation Department was one month. The subgrade moisture data at many sites were collected only a few times a year. This resolution is poor for the study of the effects of precipitation on sites because the time difference between major precipitation events and the days when the data is collected can be months.

Insufficient Data

A complete study of subgrade moisture content should involve all the information about factors that affect moisture in the subgrade. Soil properties such as Liquid Limit, Plastic Limit, Clay Content etc. should be determined at every depth. Precise site information including description of section, terrain, closeness to sources of water should be documented. Water table depth measurements should be made at the sites each time moisture data is collected.

Number of Variables

Many variables affect the moisture in the subgrade and each of these variables need to be studied individually, keeping other factors constant. Examples of variables that could be studied individually are precipitation, time of year and depth to water table. Soil properties affect how these variables interact with subgrade moisture content. These individual factors need to be considered when data is collected. For example, if the purpose of the study is to determine the affect of time of year on subgrade moisture, then data should be collected each month for many years. If data is collected only for a few months for two or three years the results of such data may be unreliable.

The Theory of Chaos

Despite all the above factors, soil moisture beneath the pavement may never be able to be predicted with any certain degree of accuracy because of the number of factors that affect subgrade moisture and their interaction with each other. Many systems exist in nature whose behavior cannot be predicted solely on present conditions because of complexities involved in the formation of the system. Such systems are called "Chaotic Systems." A property of chaotic systems is the significant effect of slight changes in initial conditions on the final result. Soil moisture not only incorporates the intricacies of a weather system (which is a chaotic system) but also the added effects of soil properties. A good way to study chaotic systems is to look for trends, ranges and equilibrium values, and not try to come up with exact solutions.

Factors Affecting Subgrade Moisture

Many factors act together to affect subgrade moisture content. The following are some observations with respect to these factors.

- Although the correlation between precipitation and subgrade moisture content is predominantly positive, the extent to which precipitation affects subgrade moisture varies from one site to another. When the subgrade soil has good drainage and permeability characteristics, and the water table is not close to the subgrade, water leaves the subgrade quickly and the correlation between precipitation and subgrade moisture content is small. On the other hand, when the drainage of the soil is poor, pavement surface and edge conditions dictate how much water enters the subgrade, and the correlation between precipitation and subgrade moisture content could be high beneath pavements in poor conditions.

- The correlation between temperature and subgrade moisture content is predominantly negative indicating higher moisture content beneath the pavement during the winter months. However influence of other factors such as precipitation and pavement conditions could minimize this effect
- When close to the surface, the groundwater table plays a major role in determining subgrade moisture content. The presence of the water table is not only a source of water, but also establishes an equilibrium condition between soil moisture and the water table, especially beneath newly constructed pavements which act as impermeable surfaces and minimize the affects of precipitation and temperature on subgrade moisture.
- Pavement related factors like pavement and edge conditions affect moisture beneath the pavement indirectly by controlling the effect of precipitation and temperature on subgrade moisture.
- Soil type is the single most important factor that affects subgrade moisture content. The

type of soil affects drainage characteristics and the water capacity of the soil. Soil type controls the extent to which all other factors affect subgrade moisture content. While other factors affect how moisture enters the subgrade, soil factors decide how much water the subgrade will hold and how quickly moisture will leave the subgrade.

In developing equilibrium values, the effects of precipitation and temperature on subgrade moisture are eliminated. Also because pavement factors affect subgrade moisture through their effects on precipitation and temperature, the effects of pavement related factors on subgrade moisture are also reduced. Since soil type is the only other major factor affecting subgrade moisture content at the shallow depths, soil properties correlate well with equilibrium values at these depths.

Recommendations for Future Data Collection

- A majority of the sites selected by the Arkansas Highway and Transportation Department were from the southeast part of the state. These soils in this region are clayey and are wet throughout the year. Although 18 to 20 sites are sufficient for a thorough analysis of the effects of soil type on subgrade moisture, sites selected should be uniformly distributed throughout different regions of the state, with the soils at these sites comprising of the different soil types found throughout the state. At least 4 to 5 sites with rigid pavements should also be considered.
- Soil samples at each depth of moisture measurement (1 ft intervals) should be collected at each site. Sieve analysis should be performed and properties such as clay contents, liquid limits, plasticity indices, optimum moisture contents and permeabilities should be

measured for all soil samples.

- Depth to the ground water table should be recorded with the collection of moisture content data for each and every site.
- Site information should be collected and should include pavement conditions, type of section (fill, cut etc.), surface course and base course thickness', type and slopes of terrain and other pertinent information. Site photographs could also provide good visual help.
- Data should be collected for some of the sites every month of the year for a number of years to study the effects of precipitation, temperature and time of year on subgrade moisture content. To truly study the effects of precipitation, temperature and time on subgrade moisture content data may need to be collected for as many as ten years.

Recommended Procedure for Estimating Subgrade Moisture Content

The following procedure is recommended for estimating the subgrade moisture content. As explained in the results and conclusions, engineering judgment should be exercised every step of this procedure.

Step 1. Determine the general pattern of moisture variation with depth. This could be one of five patterns as discussed in Chapter IV.

Step 2. Establish upper and lower equilibrium values at the shallow depth of 18 inches below the surface of the pavement and 30 inches below the surface of the pavement using the regression equations developed. The information to be used in these regression equations can be obtained from the County Soils Reports. These equations cannot be used if the combined thickness of the pavement and base course is greater than 18 inches.

Step 3. Establish equilibrium values at the depth of 78 inches below the pavement surface.

Step 4. Based on the pattern of moisture variation with depth and the equilibrium values at the shallow depth, a general plot of the variation of equilibrium values with depth can be developed.

Step 5. Determine if the subgrade moisture content at the site is affected by precipitation and temperature. Some of the factors that can be used to determine this is discussed in Chapter IV.

Step 6. If the subgrade moisture content is affected by precipitation and temperature, the upper equilibrium values can be used as the subgrade moisture content during times of high precipitation and low temperatures, while the lower equilibrium values can be used during times of low precipitation and high temperatures.

Step 7. If the subgrade moisture content is not significantly affected by precipitation or temperature, median values can be used as typical moisture values for the site. Note that median moisture values tend to be closer to the lower equilibrium values than the upper equilibrium values.

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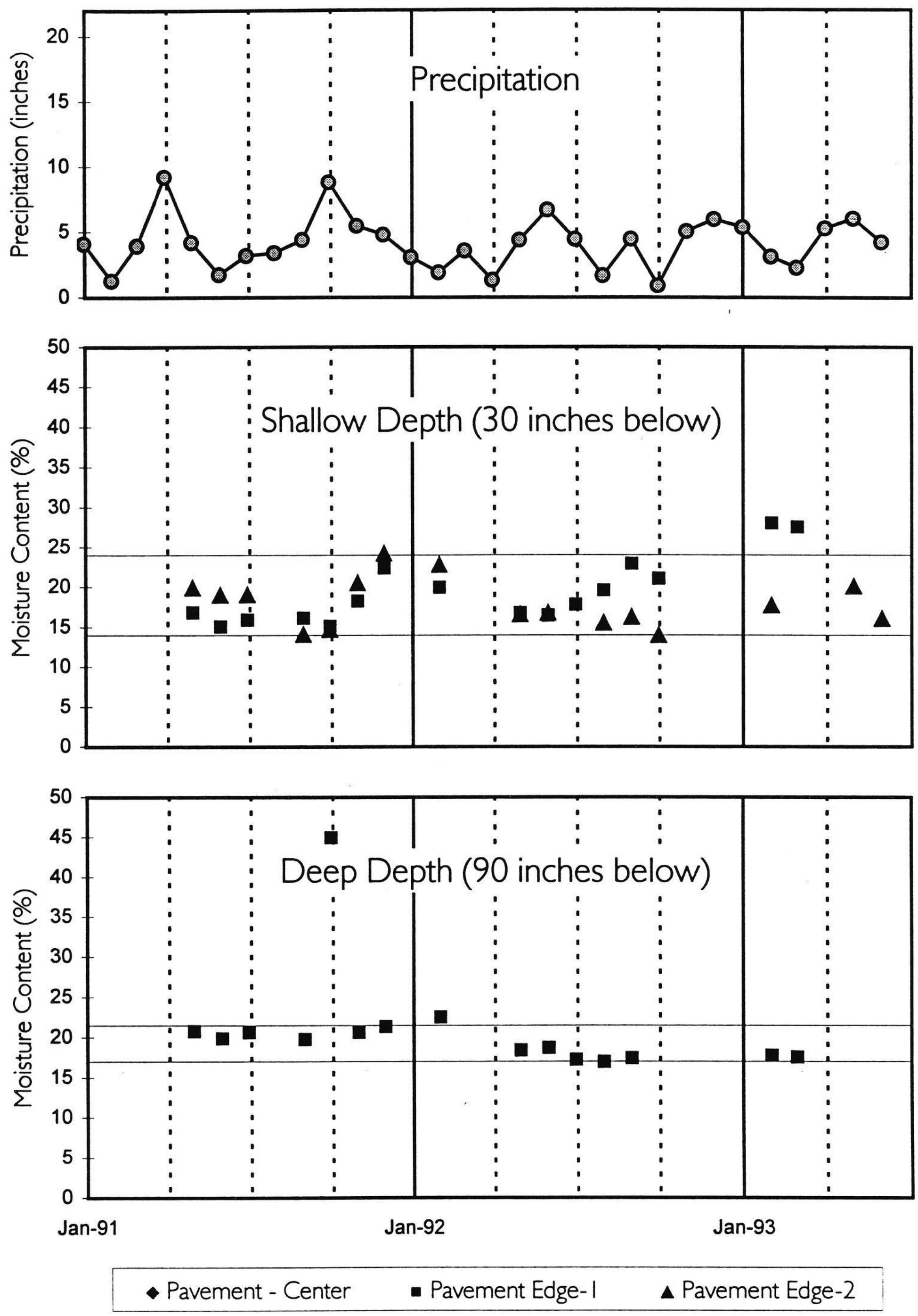
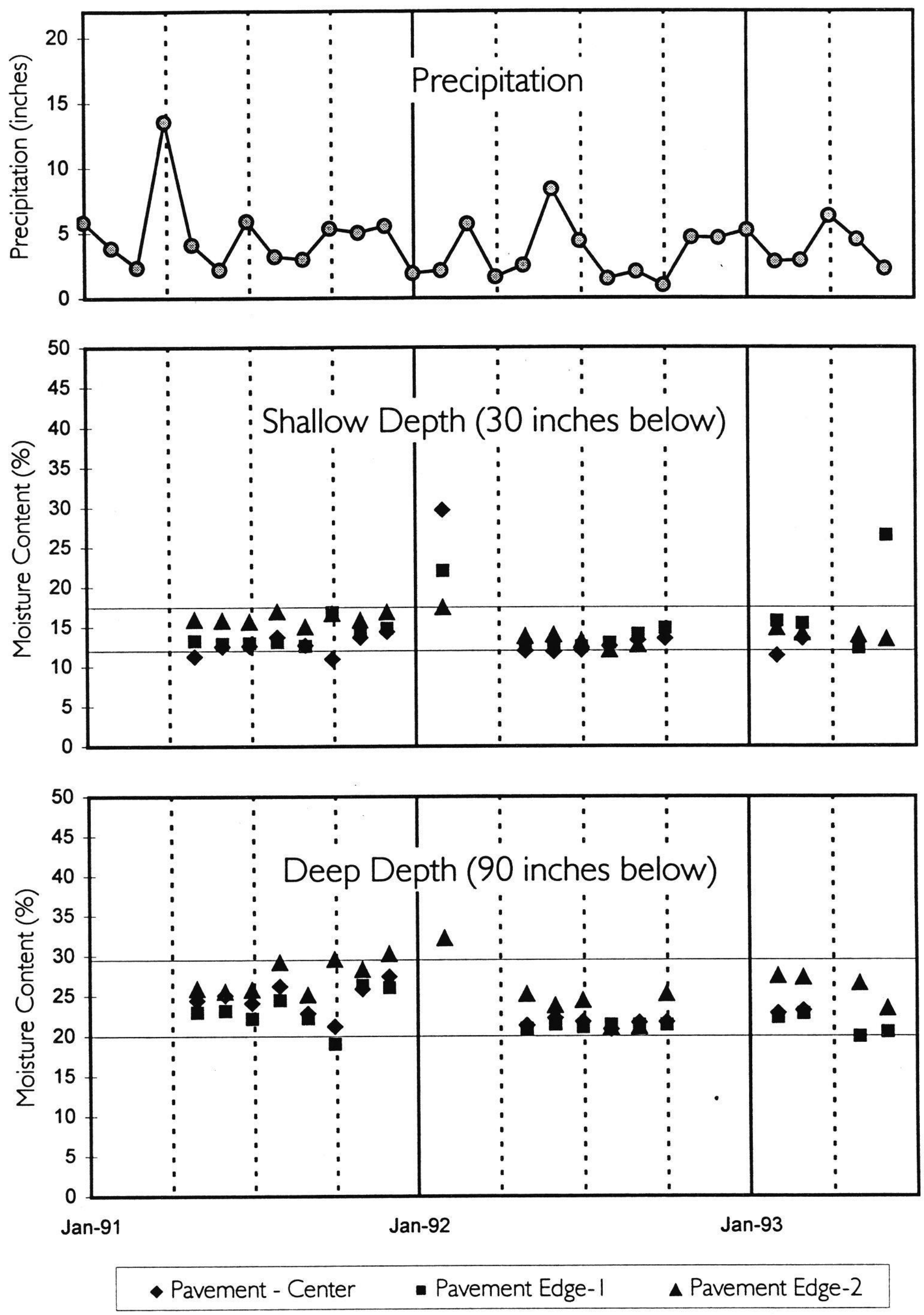
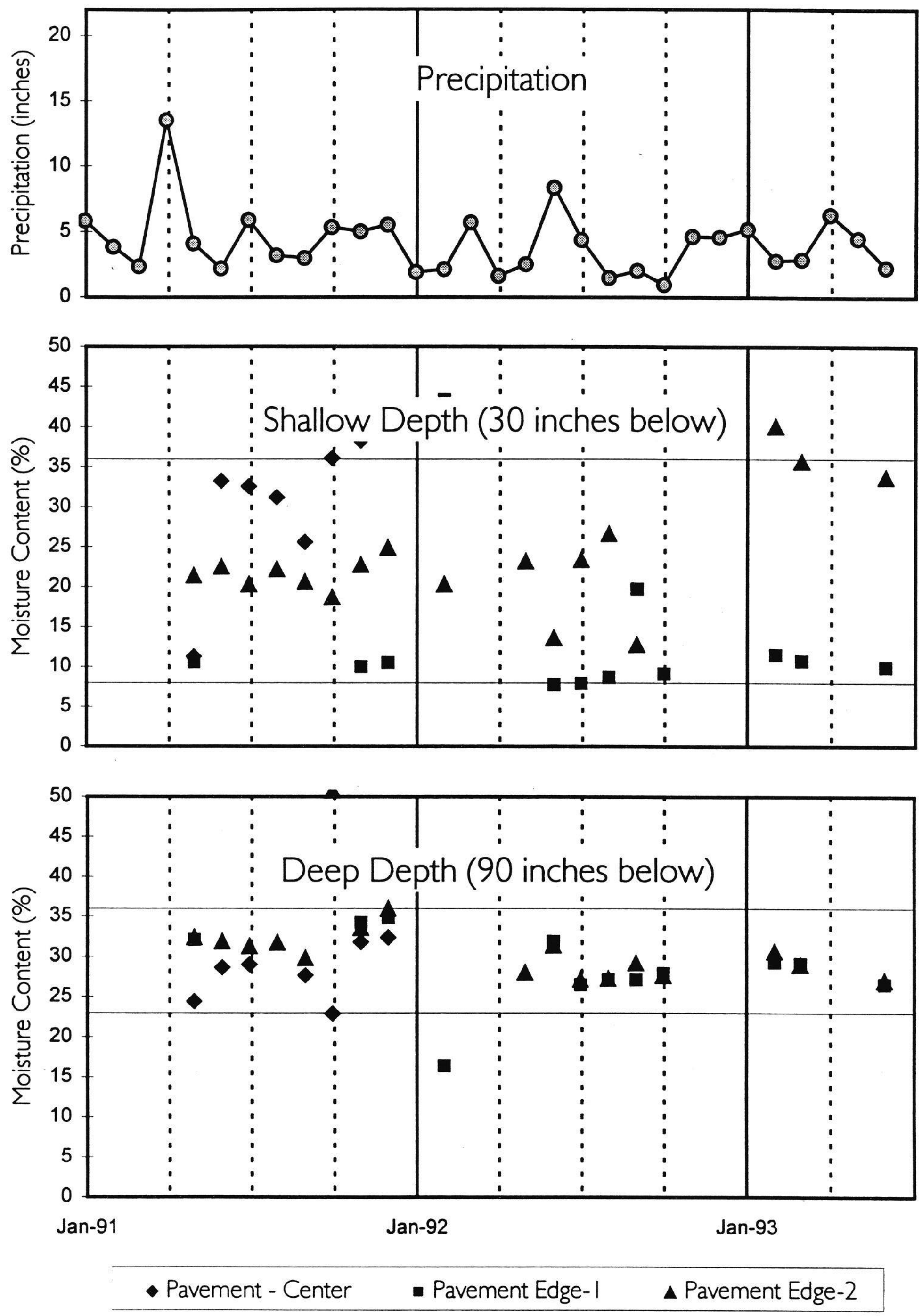
APPENDIX A



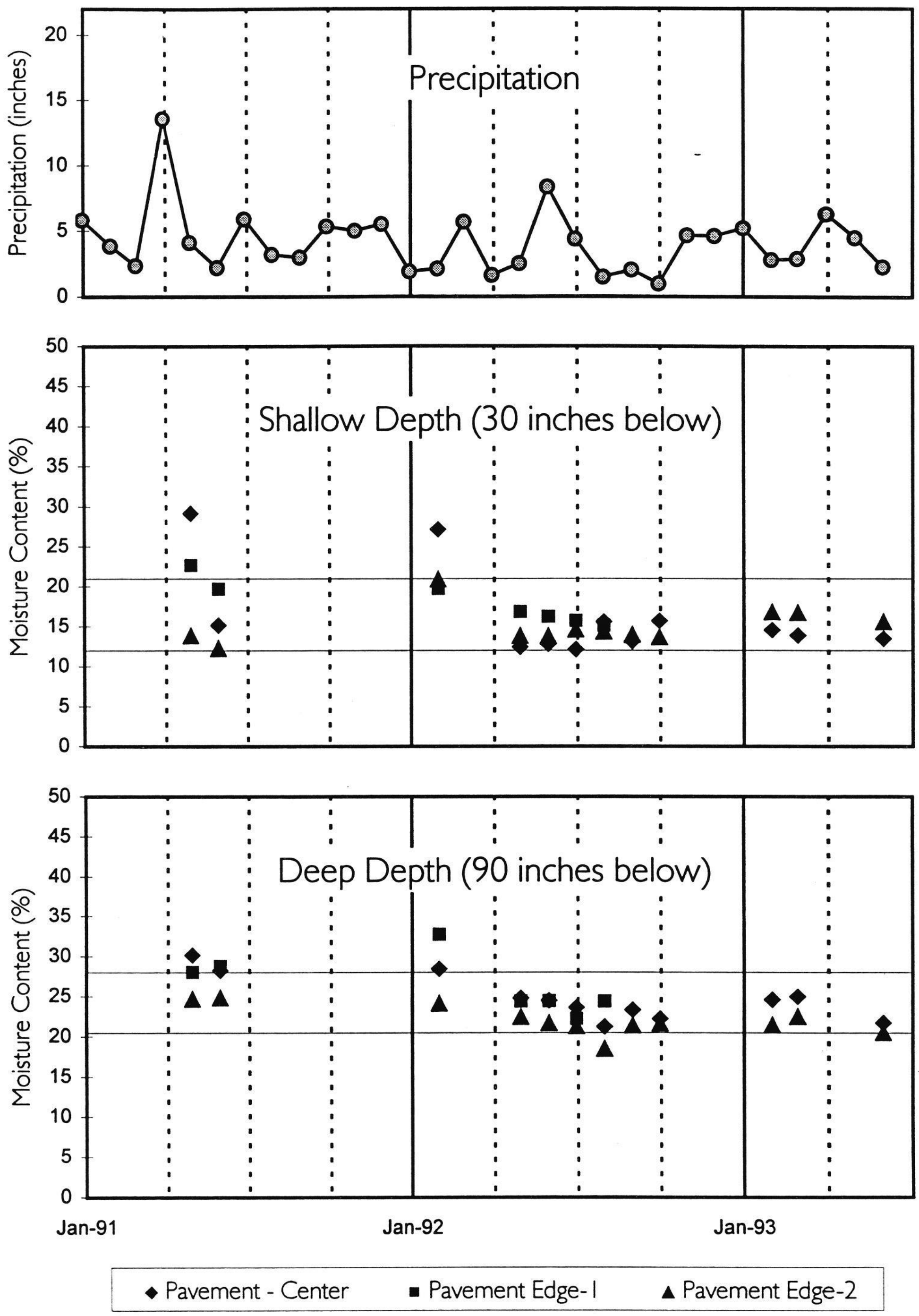
Appendix A - SITE 1. Subgrade Moisture Content Variation with Time at Depths of 30 and 90 Inches Below the Surface of the Pavement.



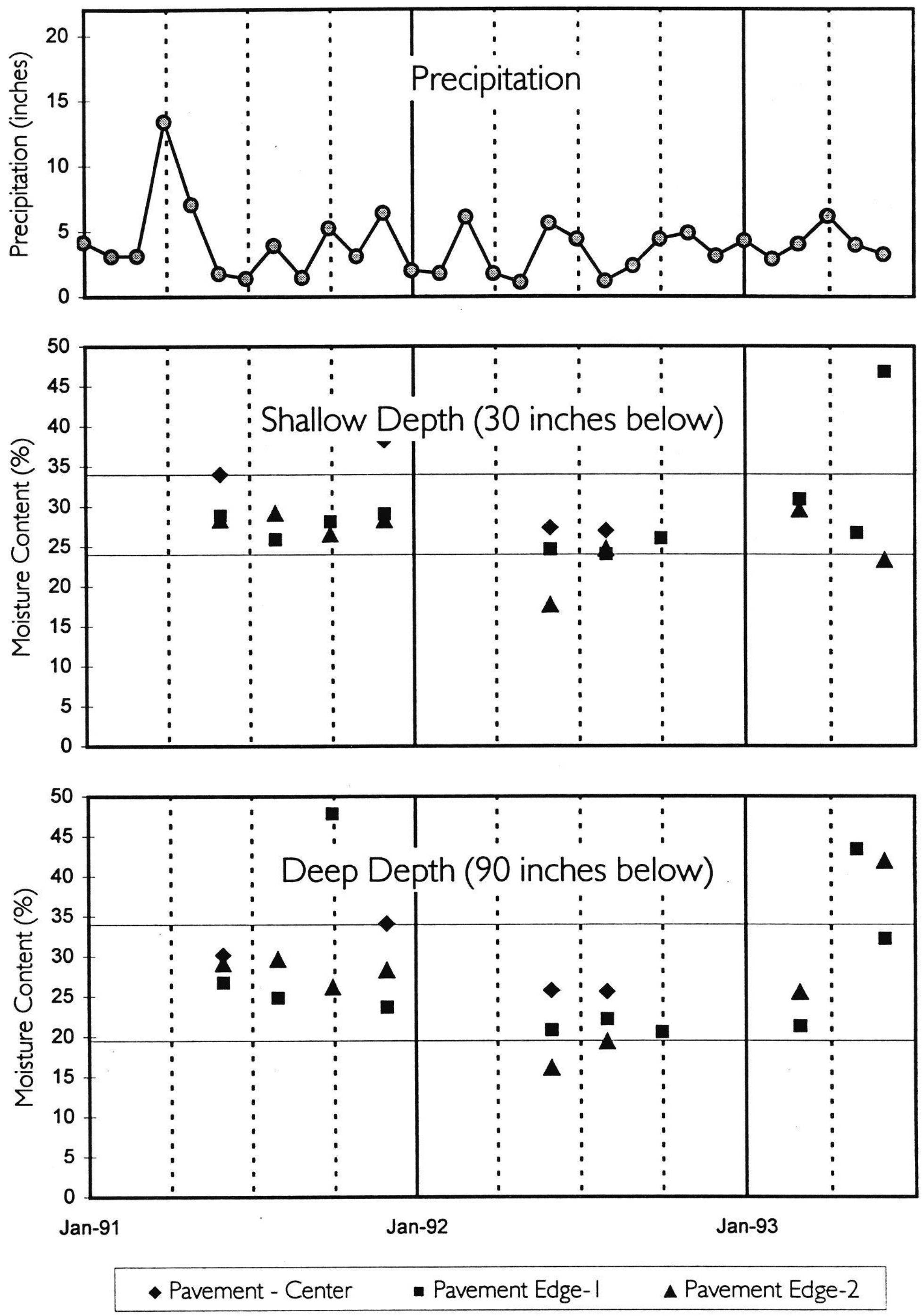
Appendix A - SITE 2. Subgrade Moisture Content Variation with Time at Depths of 30 and 90 Inches Below the Surface of the Pavement.



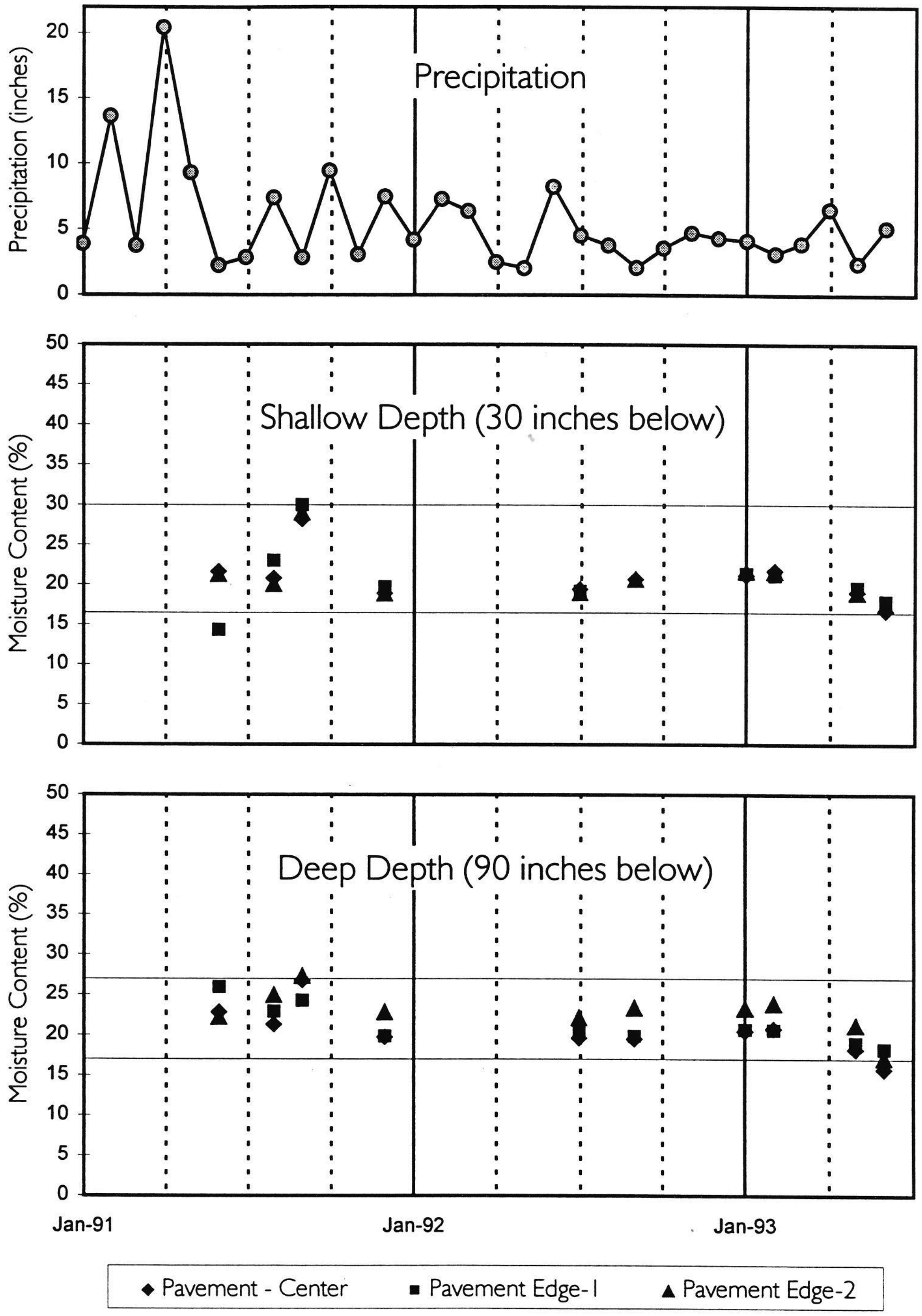
Appendix A - SITE 3. Subgrade Moisture Content Variation with Time at Depths of 30 and 90 Inches Below the Surface of the Pavement.



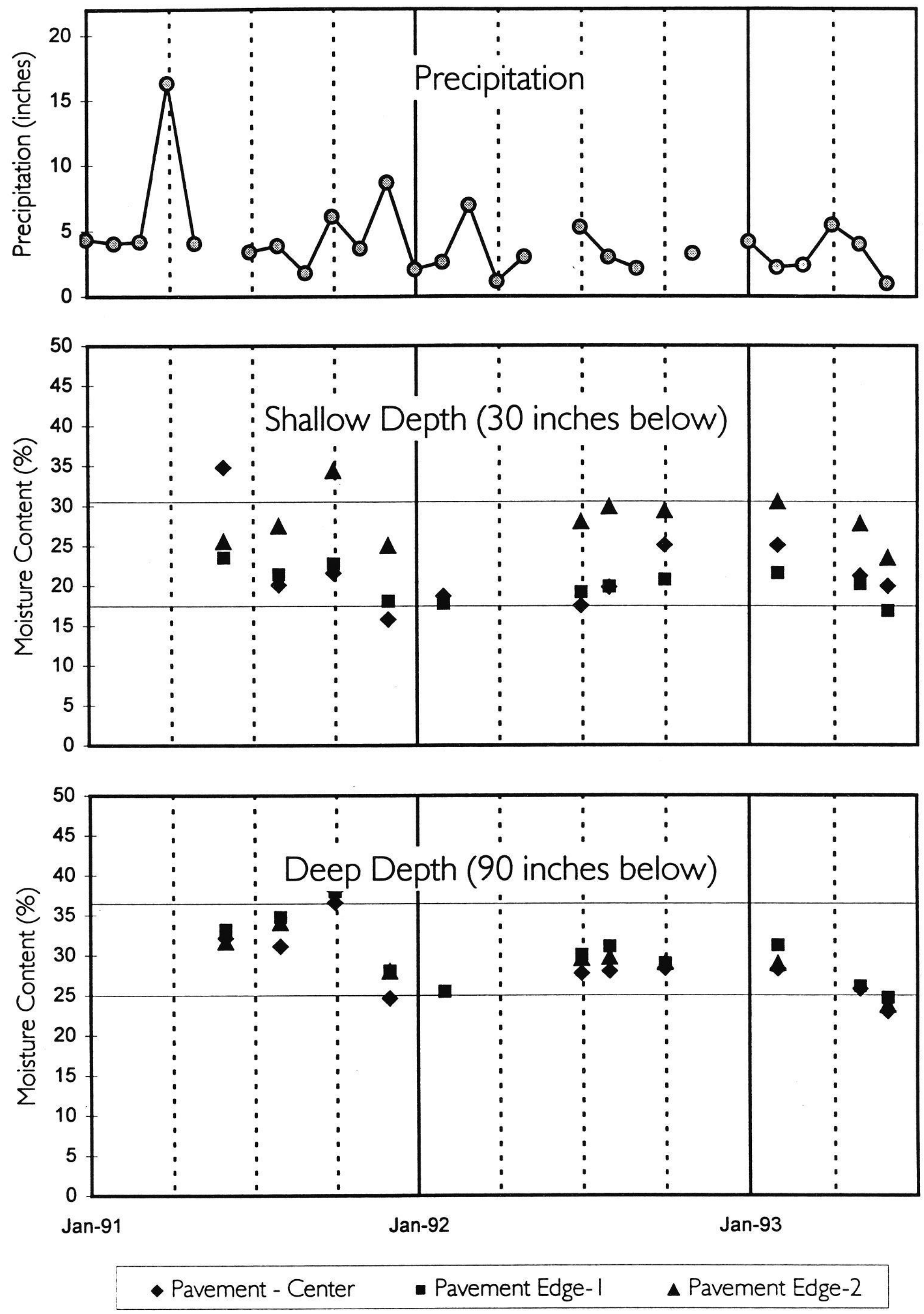
Appendix A - SITE 4. Subgrade Moisture Content Variation with Time at Depths of 30 and 90 Inches Below the Surface of the Pavement.



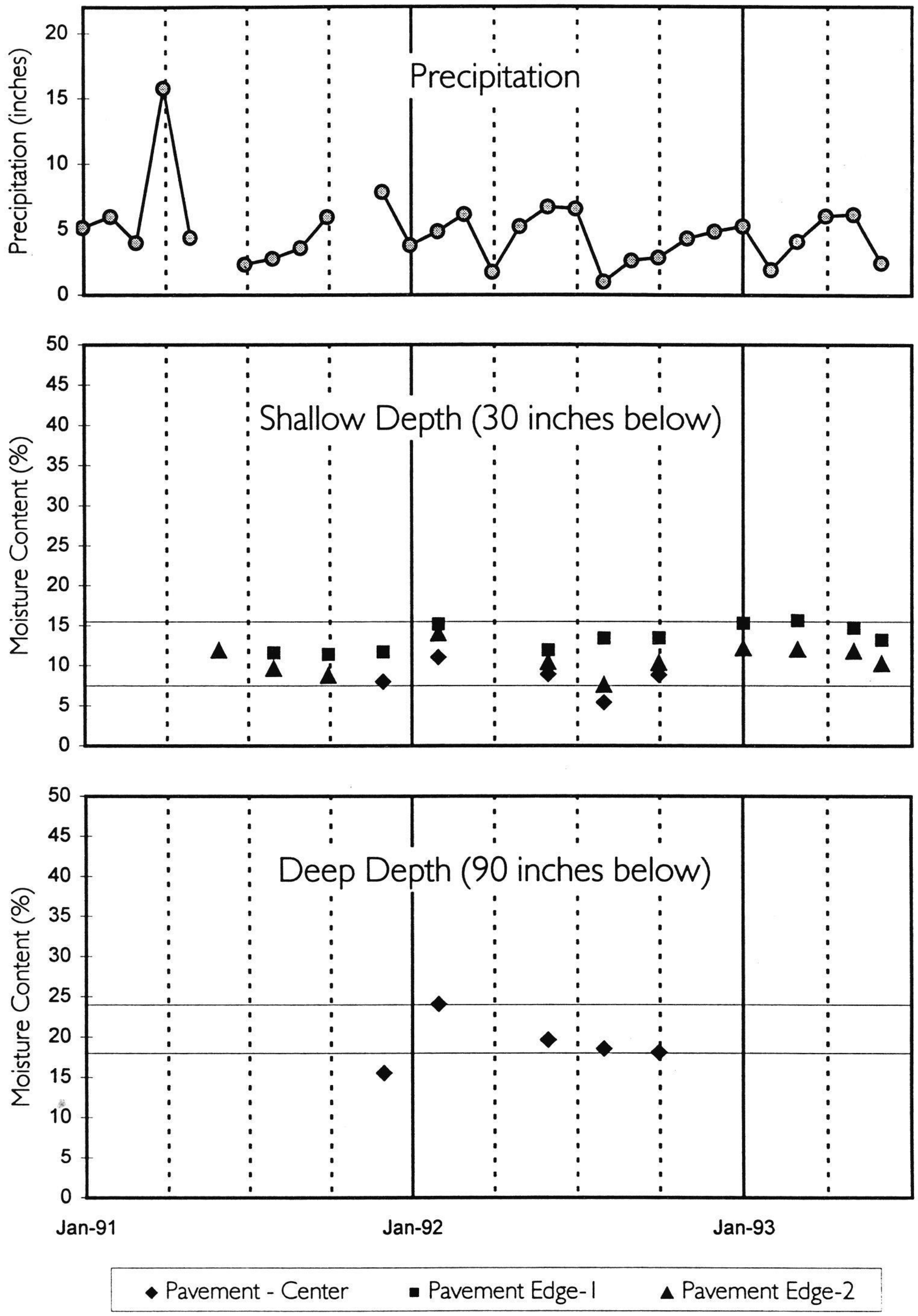
Appendix A - SITE 5. Subgrade Moisture Content Variation with Time at Depths of 30 and 90 Inches Below the Surface of the Pavement.



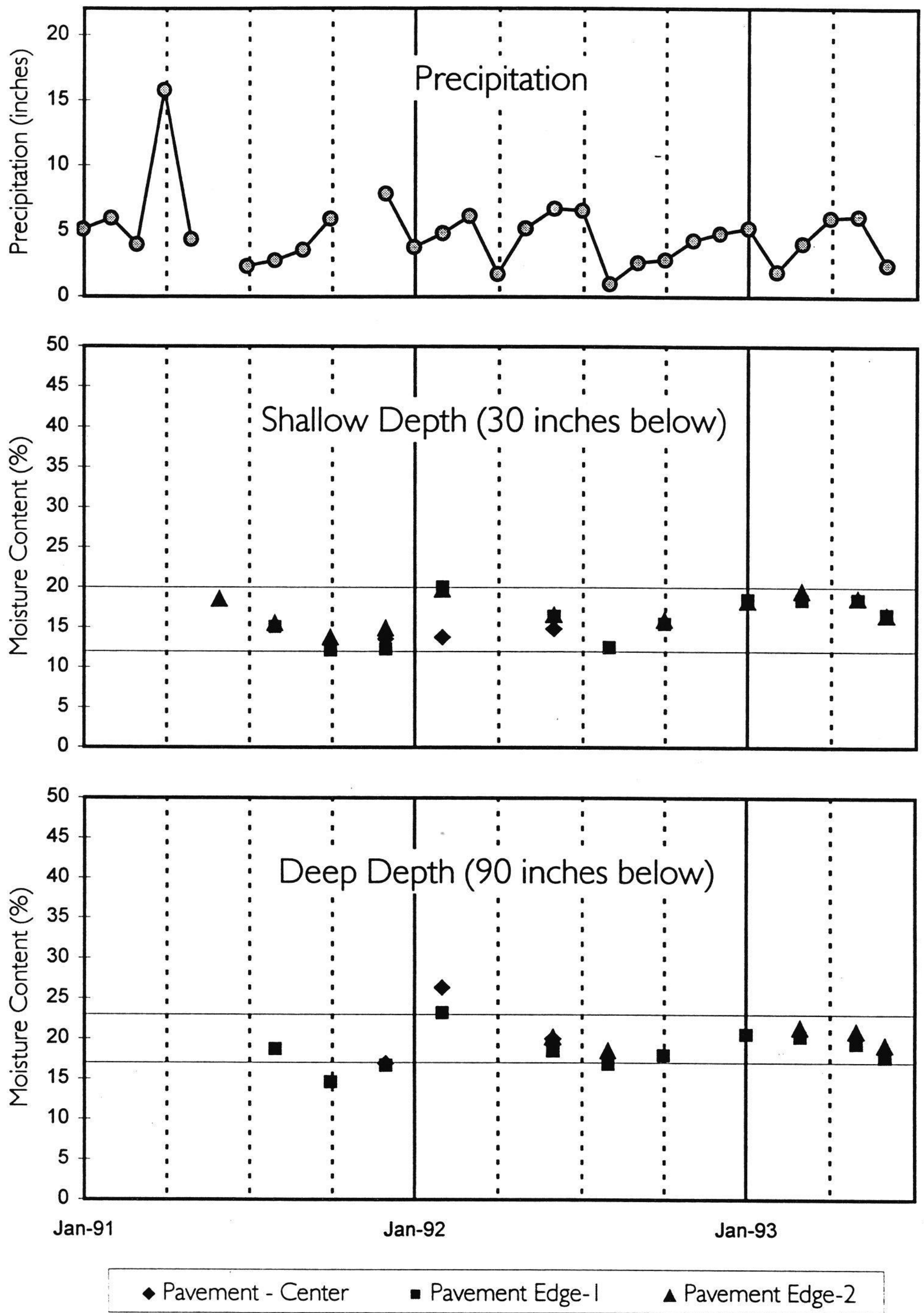
Appendix A - SITE 6. Subgrade Moisture Content Variation with Time at Depths of 30 and 90 Inches Below the Surface of the Pavement.



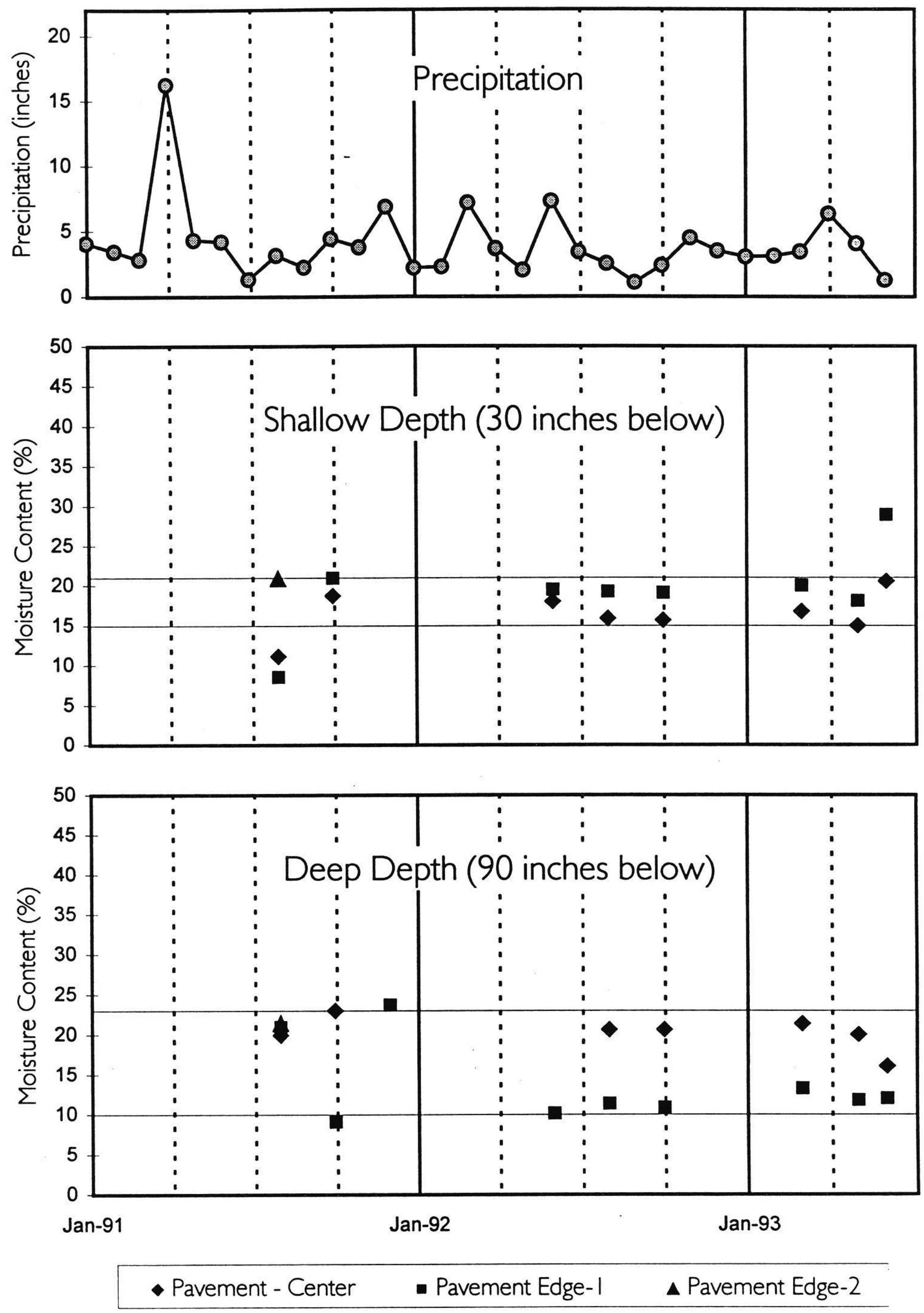
Appendix A - SITE 7. Subgrade Moisture Content Variation with Time at Depths of 30 and 90 Inches Below the Surface of the Pavement.



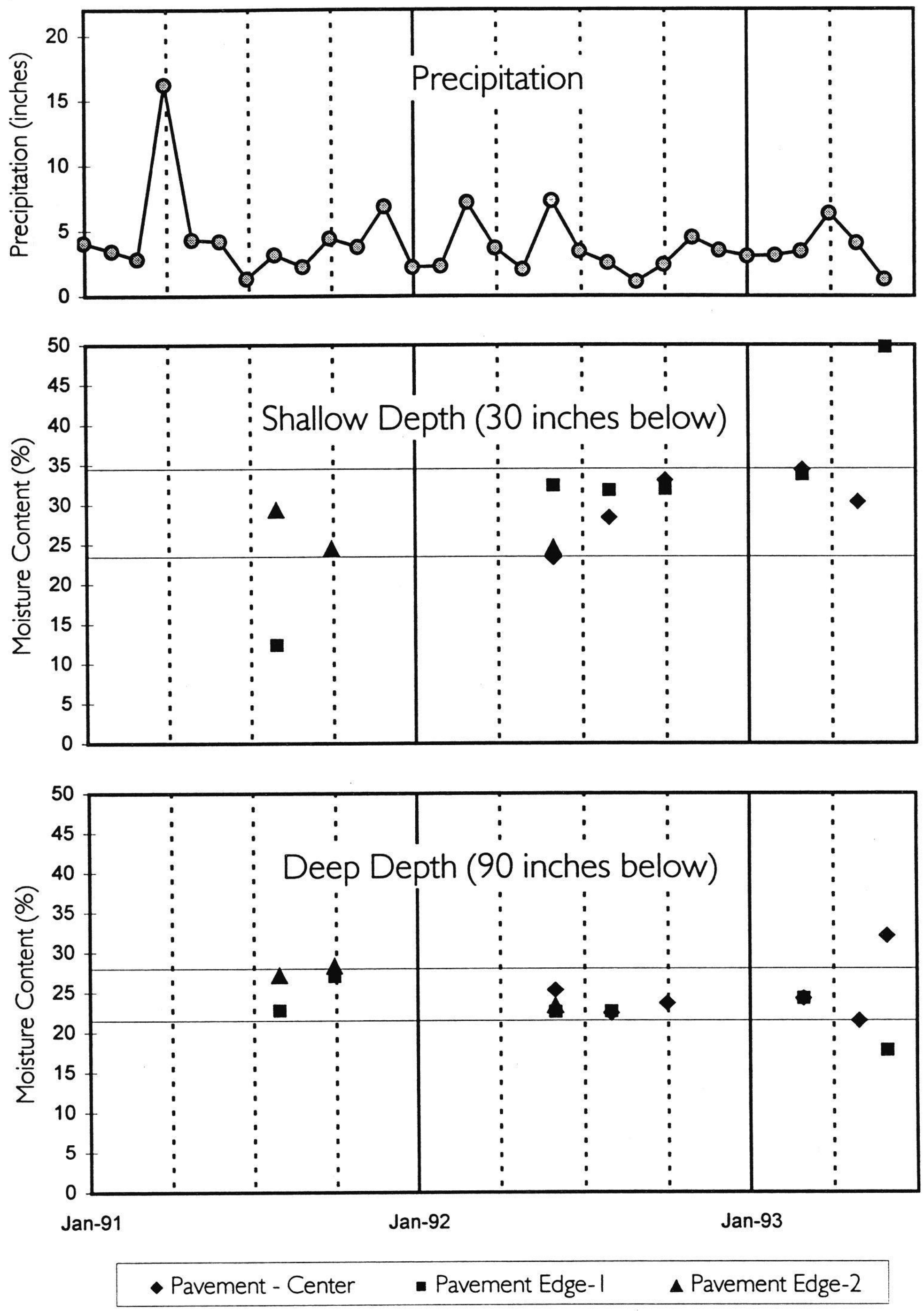
Appendix A - SITE 8. Subgrade Moisture Content Variation with Time at Depths of 30 and 90 Inches Below the Surface of the Pavement.



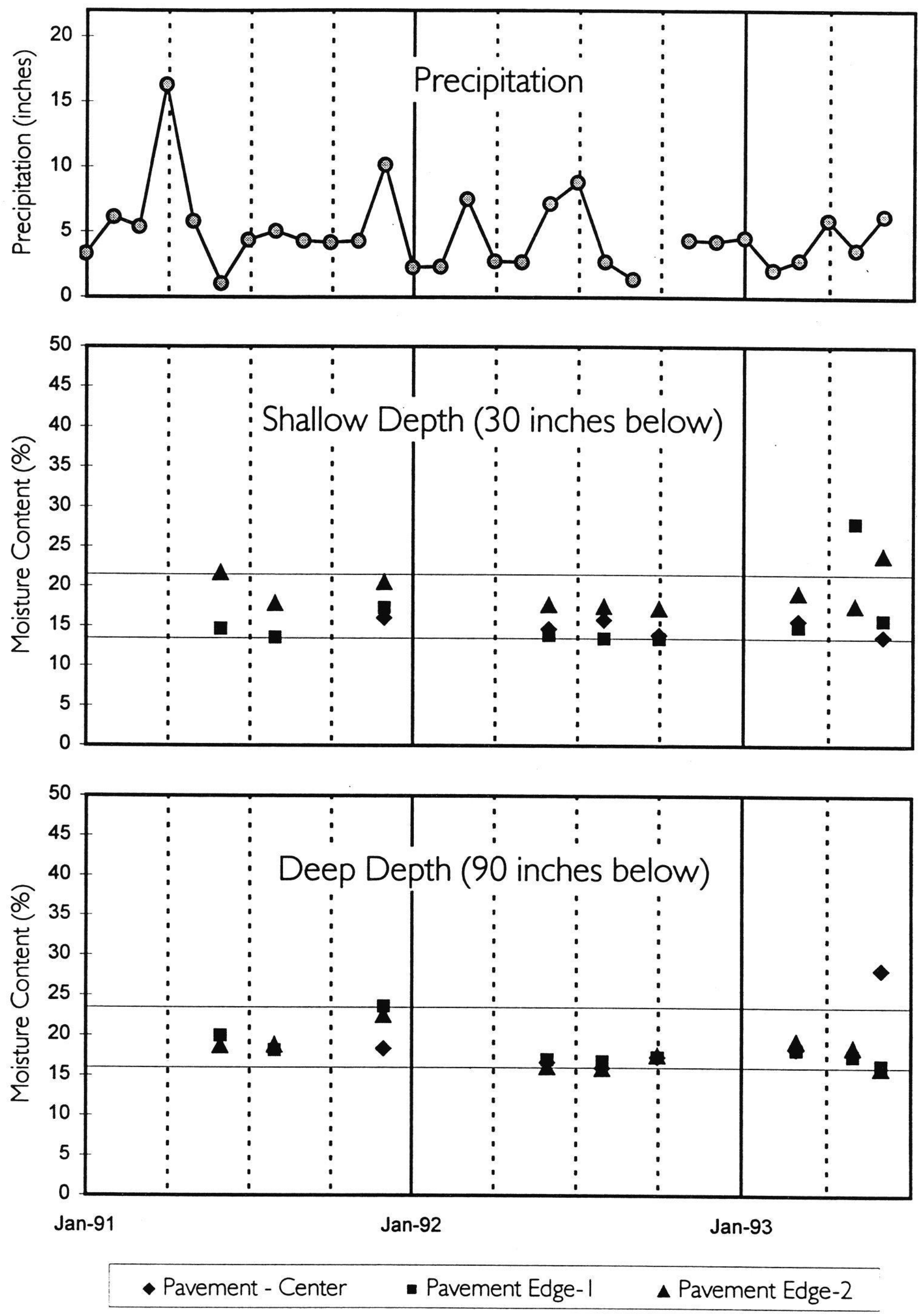
Appendix A - SITE 9. **Subgrade Moisture Content Variation with Time at Depths of 30 and 90 Inches Below the Surface of the Pavement.**



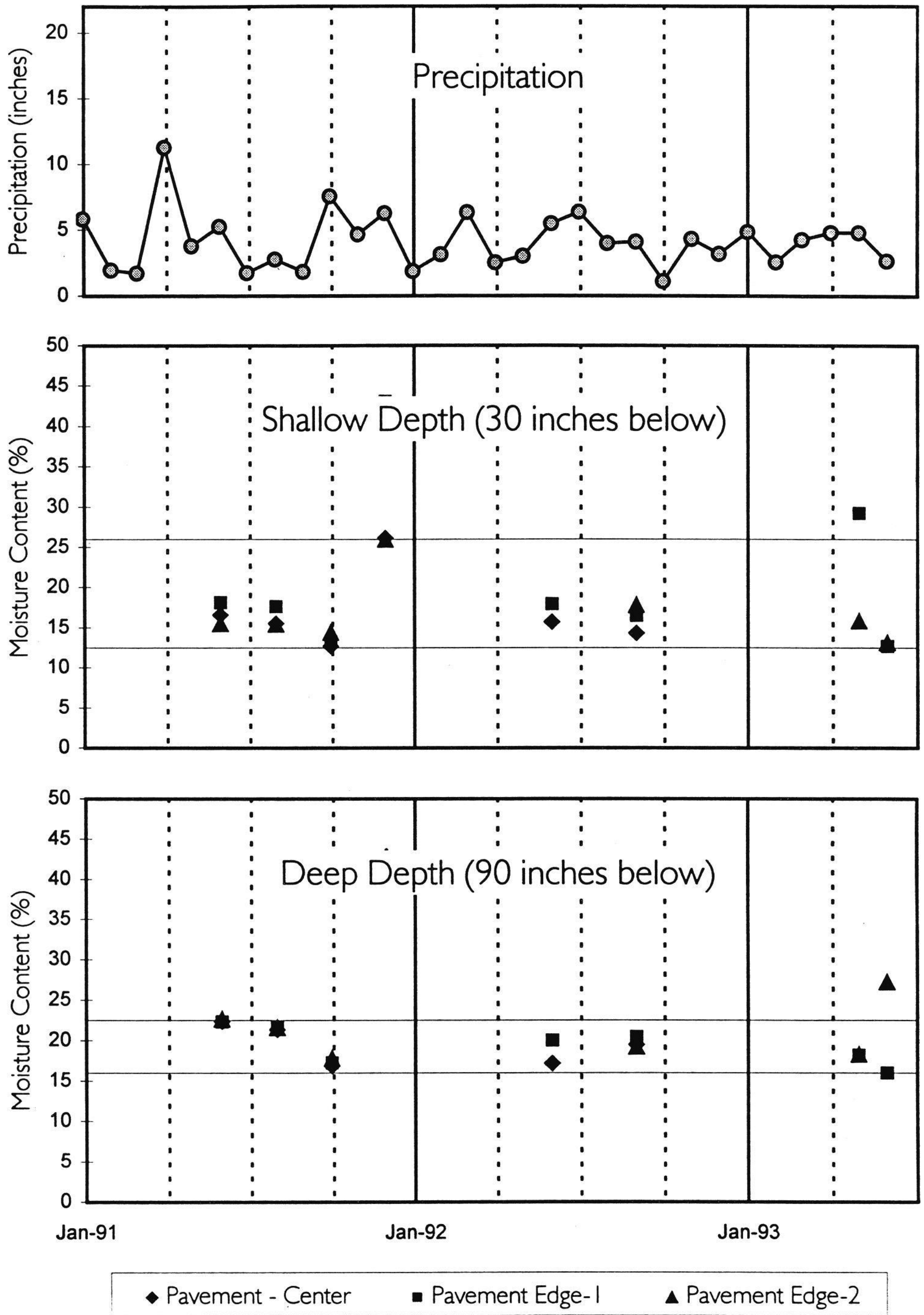
Appendix A - SITE 10. Subgrade Moisture Content Variation with Time at Depths of 30 and 90 Inches Below the Surface of the Pavement.



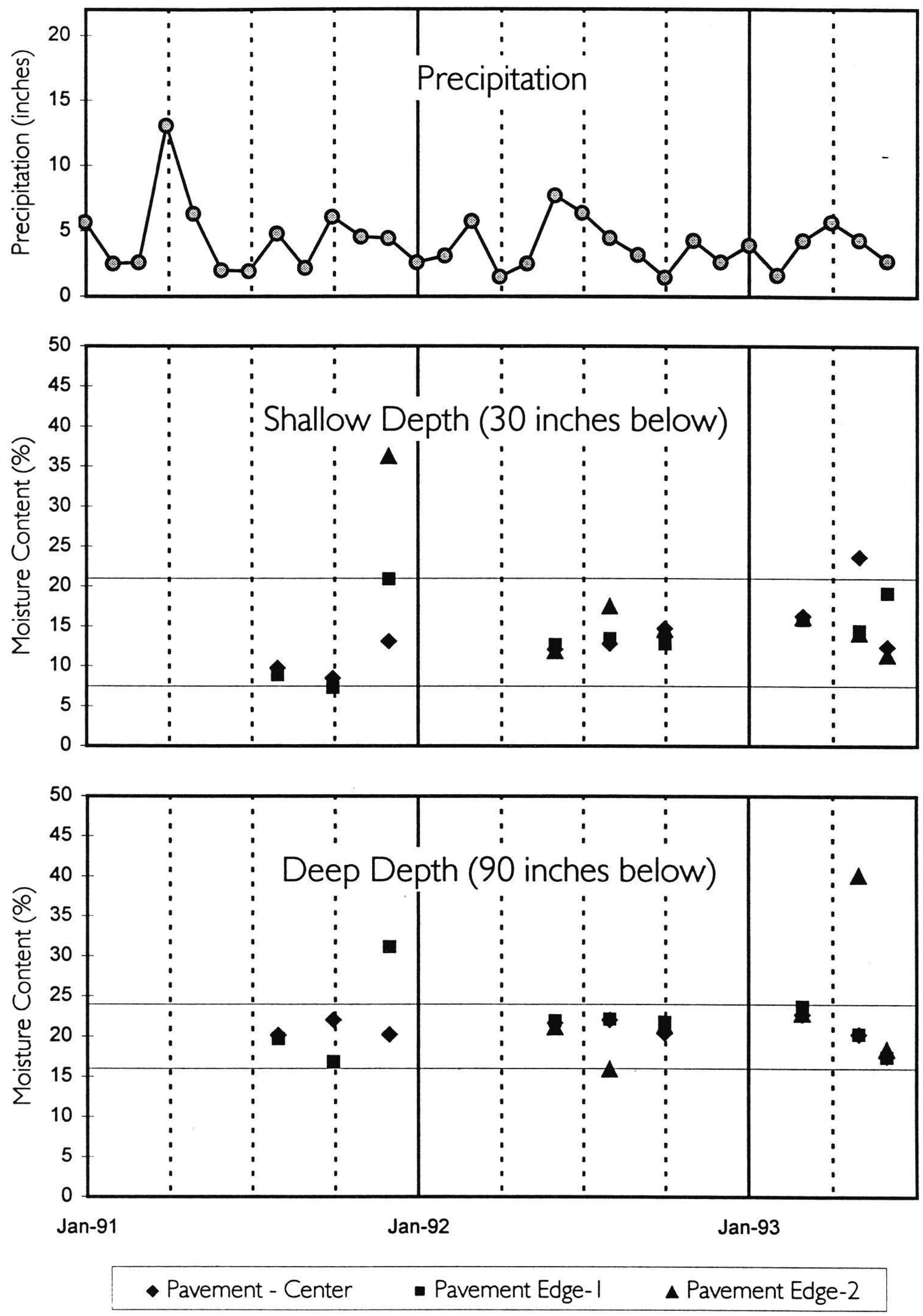
Appendix A - SITE 11. Subgrade Moisture Content Variation with Time at Depths of 30 and 90 Inches Below the Surface of the Pavement.



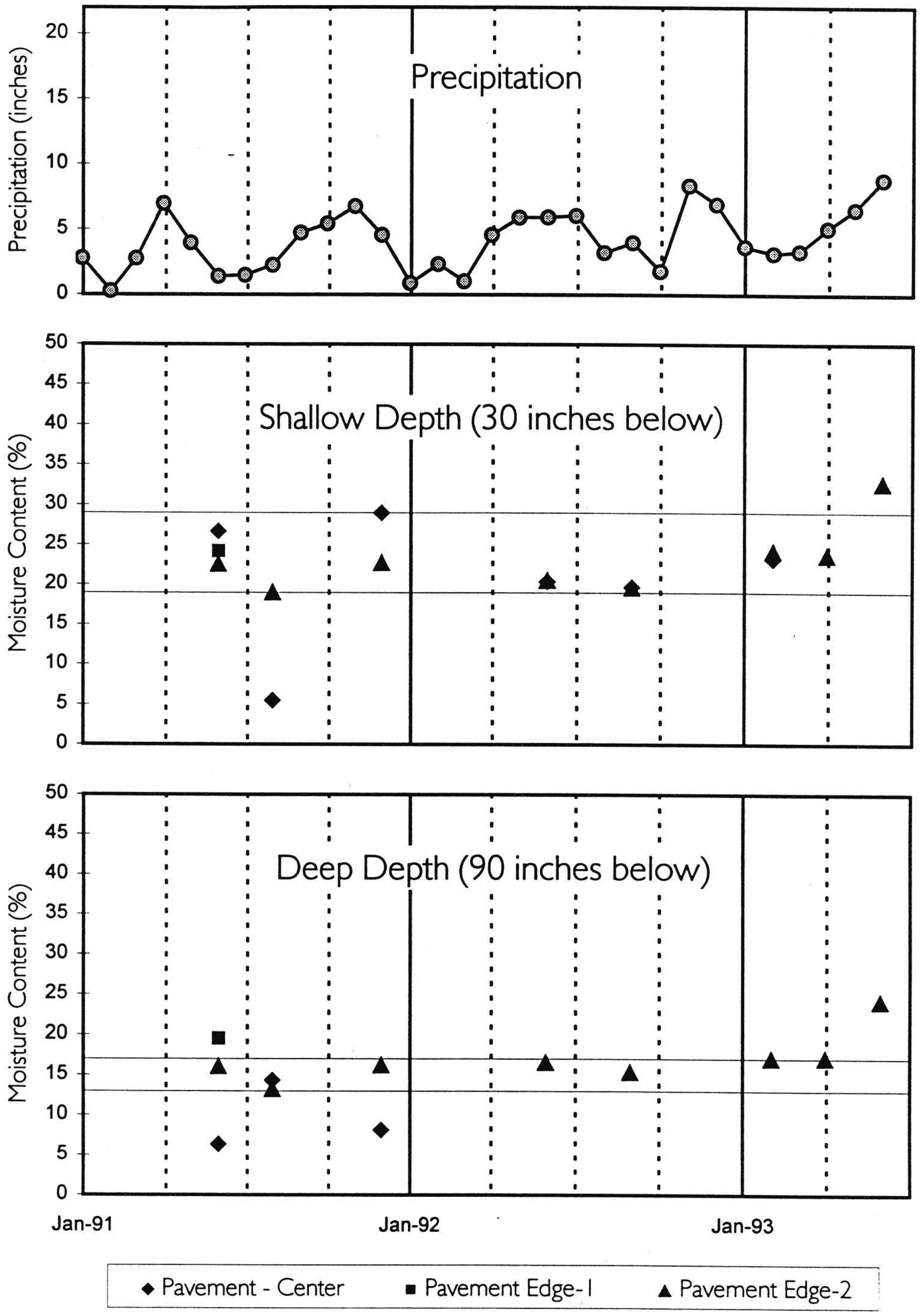
Appendix A - SITE 12. Subgrade Moisture Content Variation with Time at Depths of 30 and 90 Inches Below the Surface of the Pavement.



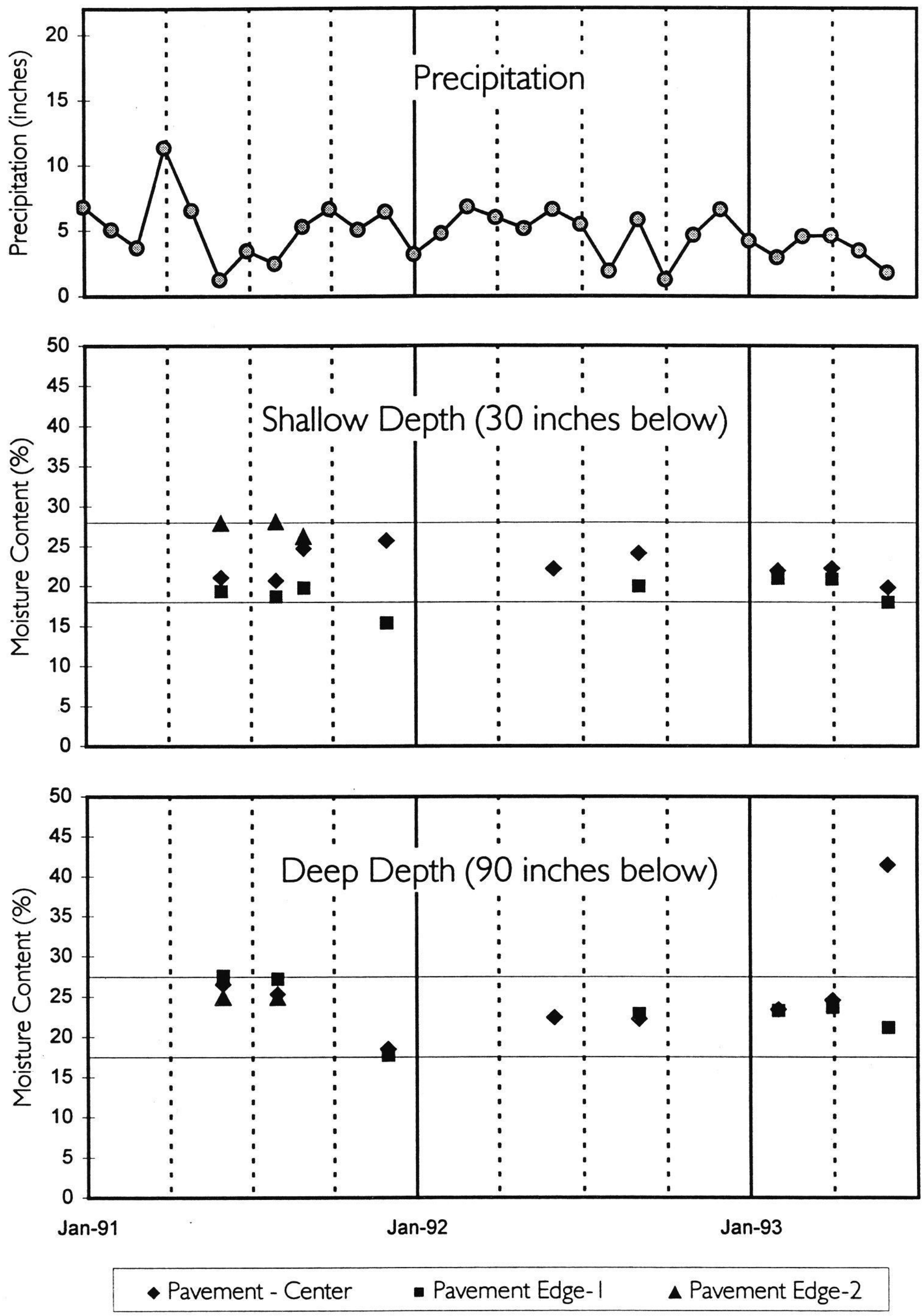
Appendix A - SITE 13. Subgrade Moisture Content Variation with Time at Depths of 30 and 90 Inches Below the Surface of the Pavement.



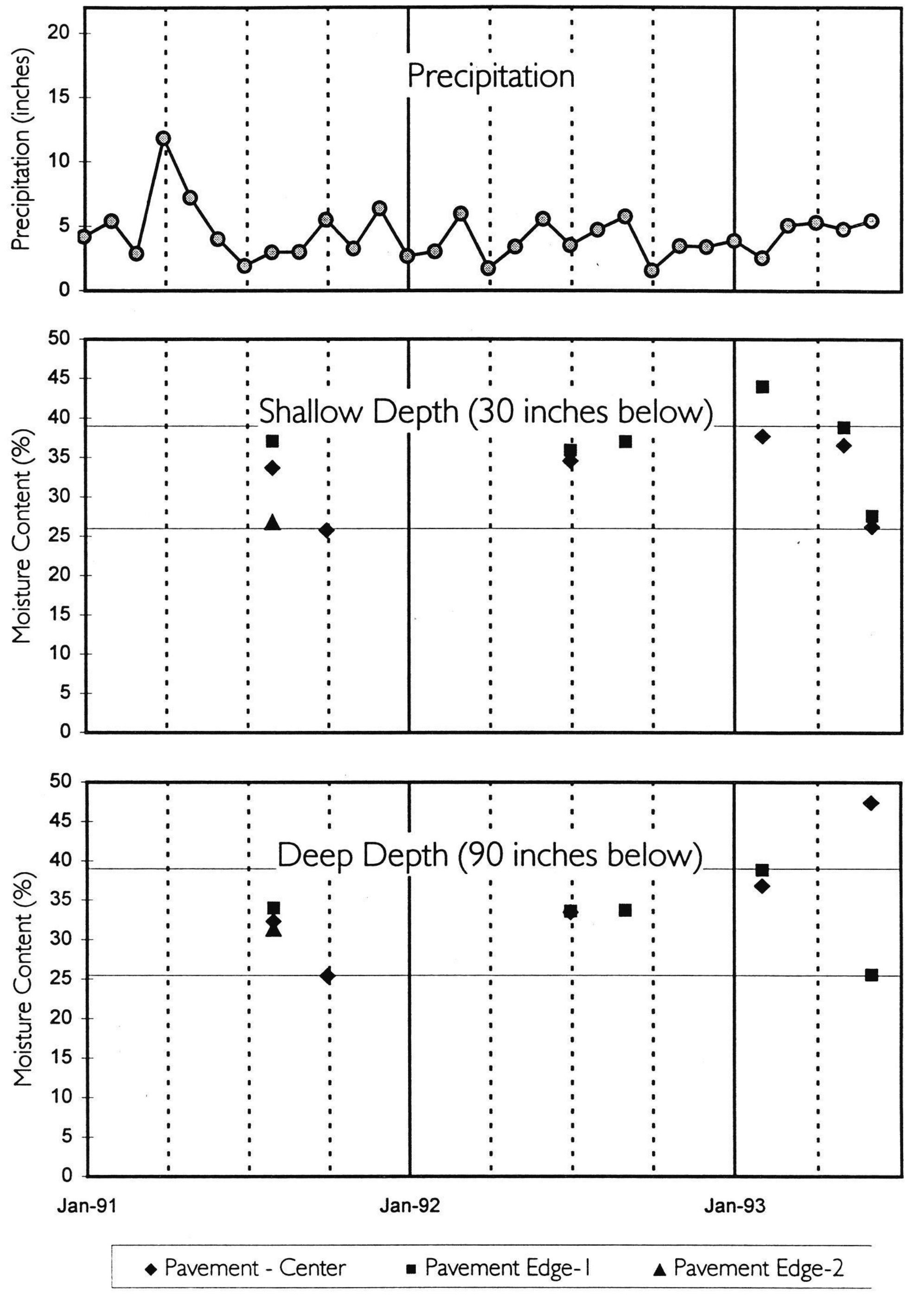
Appendix A - SITE 14. Subgrade Moisture Content Variation with Time at Depths of 30 and 90 Inches Below the Surface of the Pavement.



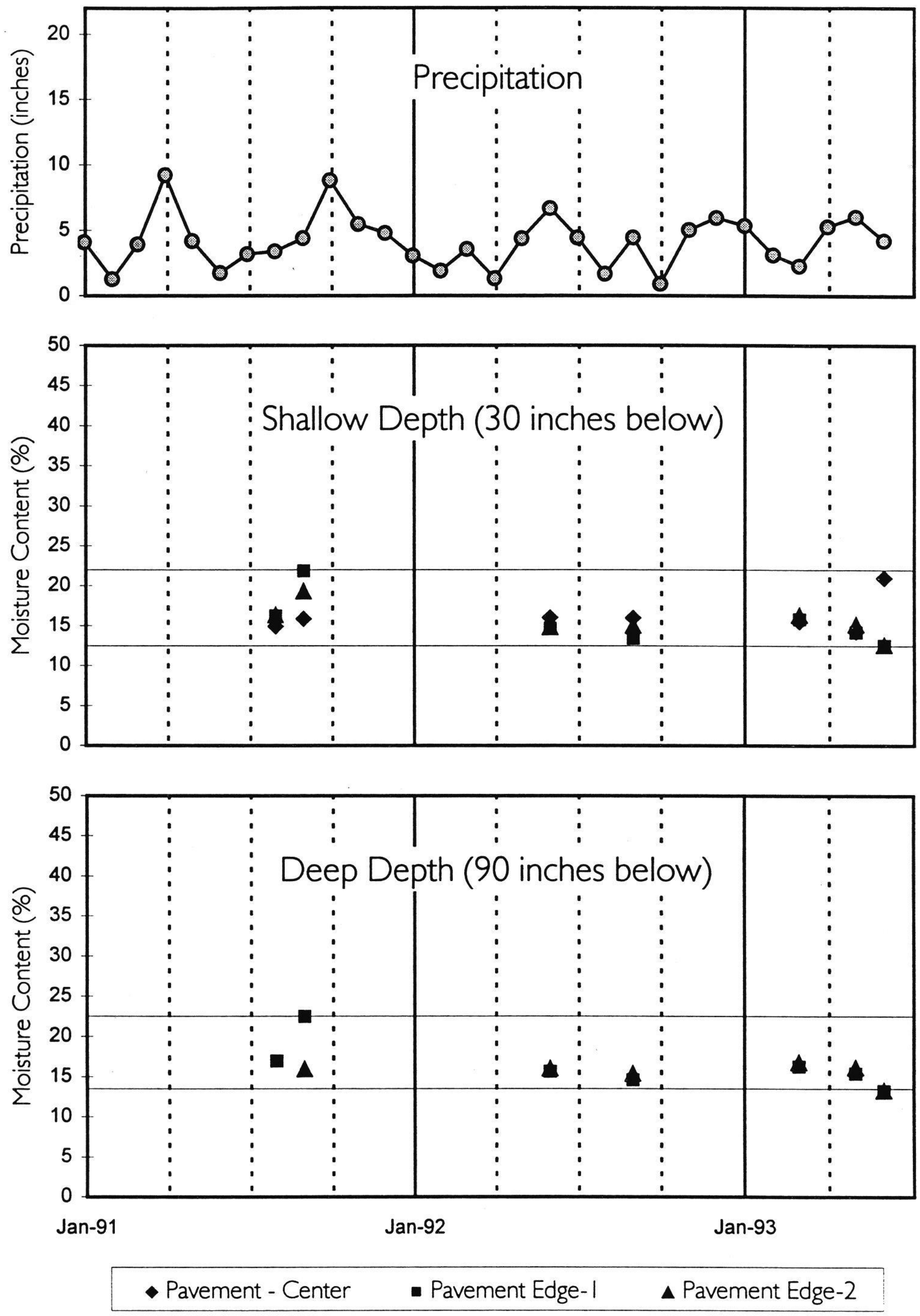
Appendix A - SITE 15. Subgrade Moisture Content Variation with Time at Depths of 30 and 90 Inches Below the Surface of the Pavement.



Appendix A - SITE 16. Subgrade Moisture Content Variation with Time at Depths of 30 and 90 Inches Below the Surface of the Pavement.



Appendix A - SITE 17. Subgrade Moisture Content Variation with Time at Depths of 30 and 90 Inches Below the Surface of the Pavement.



Appendix A - SITE 18. Subgrade Moisture Content Variation with Time at Depths of 30 and 90 Inches Below the Surface of the Pavement.

APPENDIX B

	Same Depth Properties				Properties 12 Inches Above			
	MinRange	Median	MaxRange	Spread	MinRange	Median	MaxRange	Spread
# 40 (lower)	0.37	0.57	0.59	0.56				
# 40 (upper)	0.06	0.21	0.14	0.16				
# 200 (lower)	0.50	0.62	0.69	0.49				
# 200 (upper)	0.35	0.45	0.50	0.38				
LL (lower)	0.61	0.61	0.71	0.51				
LL (upper)	0.63	0.68	0.79	0.54				
PI (lower)	0.68	0.69	0.76	0.52				
PI (upper)	0.63	0.66	0.75	0.45				
Perm (lower)	-0.68	-0.72	-0.76	-0.38				
Perm (upper)	-0.61	-0.66	-0.71	-0.37				
Water cap (lower)	0.17	0.27	0.27	0.25				
Water cap (upper)	-0.30	-0.30	-0.38	-0.24				
pH (lower)	0.40	0.45	0.34	0.03				
pH (upper)	0.31	0.38	0.25	0.01				
Slopes (lower)	-0.07	-0.14	0.05	0.18				
Slopes (upper)	-0.12	-0.17	0.10	0.32				
Top layer thickness	-0.23	-0.35	-0.34	-0.26				
Base course thickness	-0.25	-0.23	-0.20	0.00				
Depth to water table	-0.09	-0.03	0.02	0.14				
Ave daily max temp	-0.34	-0.28	-0.26	0.04				
Ave daily min temp	-0.24	-0.16	-0.22	-0.03				
Ave daily temp	-0.35	-0.27	-0.29	0.01				
Ave total prec	-0.33	-0.30	-0.28	-0.03				
ADT	0.02	-0.03	-0.05	-0.11				

Appendix B - 1. Depth 18 - Correlation Coefficients.

	Same Depth Properties				Properties 12 Inches Above			
	MinRange	Median	MaxRange	Spread	MinRange	Median	MaxRange	Spread
# 40 (lower)	0.39	0.36	0.36	0.07	0.47	0.49	0.52	0.20
# 40 (upper)	0.35	0.11	0.05	-0.25	0.37	0.14	0.05	-0.27
# 200 (lower)	0.49	0.50	0.52	0.17	0.59	0.57	0.58	0.16
# 200 (upper)	0.45	0.37	0.37	0.01	0.45	0.40	0.43	0.09
LL (lower)	0.45	0.63	0.68	0.39	0.46	0.69	0.75	0.47
LL (upper)	0.54	0.66	0.75	0.43	0.55	0.68	0.77	0.45
PI (lower)	0.36	0.51	0.60	0.38	0.47	0.73	0.77	0.48
PI (upper)	0.46	0.55	0.67	0.40	0.54	0.67	0.75	0.43
Perm (lower)	-0.35	-0.46	-0.43	-0.20	-0.59	-0.67	-0.63	-0.23
Perm (upper)	-0.31	-0.43	-0.41	-0.22	-0.50	-0.60	-0.58	-0.26
Water cap (lower)	0.11	0.08	0.03	-0.07	0.38	0.32	0.18	-0.15
Water cap (upper)	-0.31	-0.41	-0.39	-0.20	-0.20	-0.33	-0.32	-0.22
pH (lower)	0.11	0.15	0.14	0.07	0.30	0.34	0.22	-0.03
pH (upper)	0.15	0.21	0.17	0.06	0.22	0.31	0.19	0.01
Slopes (lower)	-0.26	-0.05	0.18	0.55	-0.28	-0.07	0.18	0.57
Slopes (upper)	-0.34	-0.03	0.29	0.78	-0.36	-0.04	0.29	0.81
Top layer thickness	-0.18	-0.19	-0.15	-0.01	-0.14	-0.12	-0.21	-0.14
Base course thickness	-0.28	-0.28	-0.10	0.17	-0.27	-0.27	-0.10	0.16
Depth to water table	0.04	-0.04	0.03	0.00	0.02	-0.07	0.03	0.03
Ave daily max temp	-0.27	-0.28	-0.20	0.00	-0.29	-0.31	-0.20	0.02
Ave daily min temp	-0.23	-0.22	-0.19	-0.03	-0.25	-0.24	-0.19	-0.01
Ave daily temp	-0.30	-0.30	-0.24	0.00	-0.32	-0.33	-0.24	0.02
Ave total prec	-0.25	-0.26	-0.12	0.12	-0.25	-0.27	-0.12	0.12
ADT	0.06	0.00	0.06	0.02	0.07	0.01	0.06	0.01

Appendix B - 2. Depth 30 - Correlation Coefficients.

	Same Depth Properties				Properties 12 Inches Above			
	MinRange	Median	MaxRange	Spread	MinRange	Median	MaxRange	Spread
# 40 (lower)	0.40	0.18	0.17	-0.14	0.34	0.07	0.14	-0.11
# 40 (upper)	0.41	0.00	-0.05	-0.39	0.25	-0.13	-0.08	-0.30
# 200 (lower)	0.41	0.34	0.35	0.07	0.41	0.32	0.39	0.12
# 200 (upper)	0.35	0.20	0.21	-0.06	0.37	0.21	0.24	-0.04
LL (lower)	0.37	0.49	0.53	0.31	0.38	0.47	0.58	0.36
LL (upper)	0.49	0.64	0.65	0.34	0.54	0.67	0.71	0.39
PI (lower)	0.32	0.40	0.46	0.27	0.30	0.39	0.48	0.30
PI (upper)	0.45	0.55	0.58	0.29	0.48	0.57	0.63	0.35
Perm (lower)	-0.24	-0.28	-0.29	-0.15	-0.34	-0.38	-0.37	-0.16
Perm (upper)	-0.24	-0.31	-0.31	-0.18	-0.31	-0.36	-0.36	-0.17
Water cap (lower)	0.11	0.04	-0.04	-0.14	0.00	-0.18	-0.09	-0.12
Water cap (upper)	0.04	0.03	-0.10	-0.17	-0.21	-0.33	-0.38	-0.29
pH (lower)	0.04	-0.03	0.04	0.01	0.04	-0.03	0.04	0.01
pH (upper)	0.00	-0.10	-0.02	-0.03	0.12	0.01	0.08	-0.01
Slopes (lower)	-0.19	0.28	0.35	0.65	-0.19	0.28	0.35	0.65
Slopes (upper)	-0.27	0.37	0.47	0.88	-0.27	0.37	0.47	0.88
Top layer thickness	-0.21	-0.26	-0.18	-0.04	-0.21	-0.26	-0.18	-0.04
Base course thickness	-0.25	-0.15	-0.14	0.06	-0.25	-0.15	-0.14	0.06
Depth to water table	-0.12	-0.18	-0.10	-0.01	-0.12	-0.18	-0.10	-0.01
Ave daily max temp	0.06	0.14	0.08	0.05	0.06	0.14	0.08	0.05
Ave daily min temp	0.23	0.15	0.11	-0.05	0.23	0.15	0.11	-0.05
Ave daily temp	0.07	0.09	0.07	0.02	0.07	0.09	0.07	0.02
Ave total prec	-0.02	0.10	0.08	0.12	-0.02	0.10	0.08	0.12
ADT	-0.18	-0.28	-0.20	-0.08	-0.18	-0.28	-0.20	-0.08

Appendix B - 3. Depth 42 - Correlation Coefficients.

	Same Depth Properties				Properties 12 Inches Above			
	MinRange	Median	MaxRange	Spread	MinRange	Median	MaxRange	Spread
# 40 (lower)	-0.02	-0.13	-0.09	-0.11	0.29	0.12	0.11	-0.10
# 40 (upper)	0.16	-0.03	-0.02	-0.17	0.06	-0.16	-0.21	-0.36
# 200 (lower)	0.13	0.14	0.11	0.04	0.24	0.25	0.21	0.09
# 200 (upper)	0.22	0.14	0.13	-0.02	0.17	0.12	0.10	-0.02
LL (lower)	0.04	0.24	0.27	0.35	0.04	0.24	0.27	0.35
LL (upper)	0.33	0.50	0.52	0.44	0.28	0.46	0.48	0.44
PI (lower)	0.09	0.22	0.26	0.29	0.08	0.22	0.25	0.29
PI (upper)	0.34	0.44	0.47	0.36	0.28	0.41	0.43	0.36
Perm (lower)	0.00	-0.12	-0.09	-0.14	0.00	-0.12	-0.09	-0.14
Perm (upper)	-0.07	-0.17	-0.16	-0.17	-0.04	-0.16	-0.14	-0.17
Water cap (lower)	0.18	0.10	-0.04	-0.22	0.18	0.10	-0.03	-0.22
Water cap (upper)	0.22	0.12	0.03	-0.18	0.27	0.15	0.06	-0.18
pH (lower)	0.22	0.19	0.17	0.05	0.04	0.04	0.02	-0.01
pH (upper)	0.25	0.18	0.19	0.04	0.09	0.05	0.05	-0.01
Slopes (lower)	-0.20	0.16	0.27	0.62	-0.20	0.16	0.27	0.62
Slopes (upper)	-0.11	0.30	0.48	0.85	-0.11	0.30	0.48	0.85
Top layer thickness	-0.29	-0.28	-0.29	-0.16	-0.29	-0.28	-0.29	-0.16
Base course thickness	-0.04	-0.10	0.05	0.11	-0.04	-0.10	0.05	0.11
Depth to water table	-0.45	-0.40	-0.33	-0.06	-0.45	-0.40	-0.33	-0.06
Ave daily max temp	0.38	0.25	0.27	0.06	0.38	0.25	0.27	0.06
Ave daily min temp	0.50	0.31	0.31	0.01	0.50	0.31	0.31	0.01
Ave daily temp	0.35	0.24	0.25	0.04	0.35	0.24	0.25	0.04
Ave total prec	0.25	0.17	0.24	0.13	0.25	0.17	0.24	0.13
ADT	-0.51	-0.47	-0.40	-0.11	-0.51	-0.47	-0.40	-0.11

Appendix B - 4. Depth 54 - Correlation Coefficients.

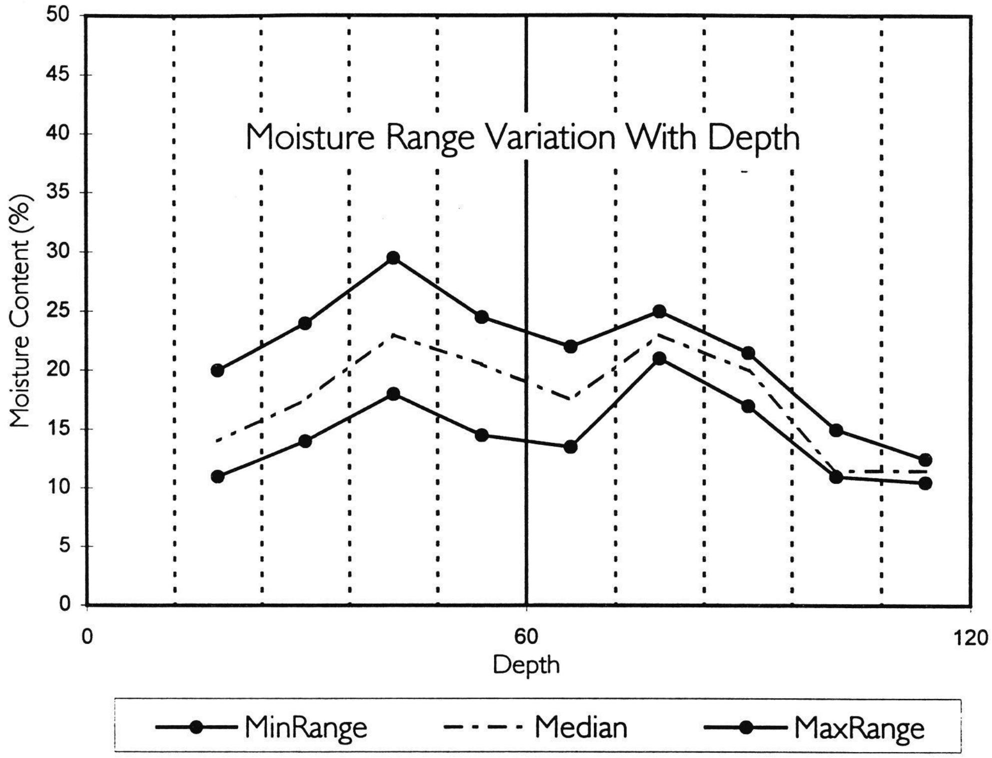
	Same Depth Properties				Properties 12 Inches Above			
	MinRange	Median	MaxRange	Spread	MinRange	Median	MaxRange	Spread
# 40 (lower)	-0.40	-0.40	-0.39	-0.23	-0.05	-0.08	-0.09	-0.14
# 40 (upper)	0.25	0.27	0.20	0.01	0.08	0.06	0.05	-0.03
# 200 (lower)	-0.24	-0.20	-0.26	-0.23	0.14	0.17	0.10	-0.03
# 200 (upper)	0.05	0.08	0.07	0.09	0.15	0.15	0.11	-0.01
LL (lower)	-0.02	0.02	-0.01	0.02	0.07	0.15	0.10	0.12
LL (upper)	0.20	0.26	0.26	0.31	0.35	0.41	0.39	0.34
PI (lower)	-0.01	0.03	-0.02	-0.03	0.11	0.17	0.10	0.04
PI (upper)	0.24	0.29	0.26	0.20	0.35	0.40	0.36	0.24
Perm (lower)	0.10	0.03	0.03	-0.14	-0.02	-0.08	-0.07	-0.15
Perm (upper)	0.03	-0.02	-0.01	-0.08	-0.09	-0.14	-0.12	-0.13
Water cap (lower)	0.22	0.20	0.03	-0.39	0.25	0.20	-0.03	-0.62
Water cap (upper)	0.32	0.24	0.09	-0.46	0.21	0.14	-0.01	-0.48
pH (lower)	0.20	0.24	0.17	0.06	0.13	0.18	0.13	0.08
pH (upper)	0.28	0.29	0.29	0.22	0.13	0.16	0.14	0.10
Slopes (lower)	0.07	0.13	0.18	0.37	0.03	0.09	0.16	0.38
Slopes (upper)	0.28	0.32	0.37	0.47	0.23	0.27	0.35	0.47
Top layer thickness	-0.35	-0.35	-0.40	-0.38	-0.24	-0.25	-0.35	-0.44
Base course thickness	0.08	0.01	0.08	0.05	-0.03	-0.07	0.05	0.18
Depth to water table	-0.43	-0.42	-0.43	-0.29	-0.45	-0.43	-0.41	-0.17
Ave daily max temp	0.50	0.36	0.42	0.11	0.50	0.36	0.42	0.11
Ave daily min temp	0.47	0.35	0.39	0.09	0.47	0.35	0.39	0.09
Ave daily temp	0.44	0.33	0.37	0.09	0.44	0.33	0.37	0.09
Ave total prec	0.41	0.30	0.32	0.02	0.35	0.25	0.30	0.07
ADT	-0.60	-0.56	-0.58	-0.35	-0.61	-0.56	-0.56	-0.22

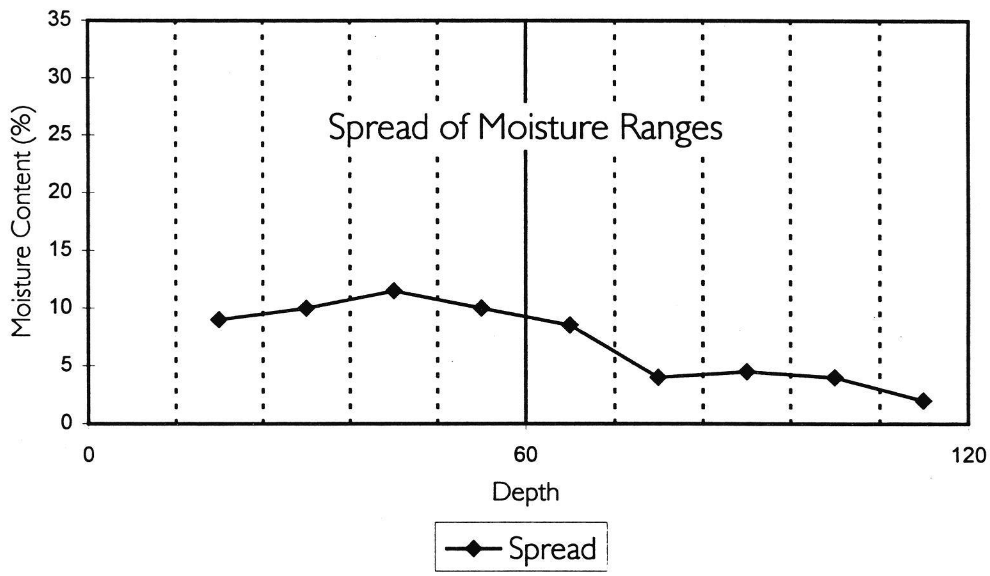
Appendix B - 5. Depth 66 - Correlation Coefficients.

	Same Depth Properties				Properties 12 Inches Above			
	MinRange	Median	MaxRange	Spread	MinRange	Median	MaxRange	Spread
# 40 (lower)	-0.34	-0.26	-0.21	0.20	-0.43	-0.36	-0.35	0.04
# 40 (upper)	0.12	0.30	0.24	0.42	0.19	0.36	0.25	0.28
# 200 (lower)	-0.34	-0.15	-0.25	0.06	-0.37	-0.19	-0.34	-0.13
# 200 (upper)	-0.06	0.10	0.07	0.34	-0.02	0.12	0.04	0.16
LL (lower)	-0.17	0.01	-0.05	0.23	-0.19	-0.01	-0.10	0.11
LL (upper)	0.10	0.26	0.21	0.33	0.09	0.23	0.18	0.27
PI (lower)	-0.13	0.02	-0.07	0.08	-0.15	-0.01	-0.10	0.03
PI (upper)	0.14	0.28	0.21	0.26	0.13	0.27	0.19	0.20
Perm (lower)	0.17	0.03	0.05	-0.22	0.17	0.03	0.05	-0.22
Perm (upper)	0.10	-0.04	0.00	-0.23	0.10	-0.04	0.00	-0.23
Water cap (lower)	0.22	0.23	0.18	-0.04	0.26	0.25	0.17	-0.15
Water cap (upper)	0.32	0.27	0.15	-0.31	0.32	0.27	0.15	-0.31
pH (lower)	0.08	0.13	0.07	0.01	0.18	0.25	0.16	0.07
pH (upper)	0.23	0.28	0.22	0.16	0.23	0.28	0.22	0.16
Slopes (lower)	0.39	0.29	0.34	0.07	0.39	0.29	0.34	0.07
Slopes (upper)	0.52	0.42	0.55	0.38	0.52	0.42	0.55	0.38
Top layer thickness	-0.33	-0.32	-0.36	-0.25	-0.33	-0.32	-0.36	-0.25
Base course thickness	-0.19	-0.16	-0.02	0.32	-0.19	-0.16	-0.02	0.32
Depth to water table	-0.48	-0.39	-0.38	0.01	-0.48	-0.39	-0.38	0.01
Ave daily max temp	0.47	0.28	0.36	0.02	0.47	0.28	0.36	0.02
Ave daily min temp	0.61	0.37	0.35	-0.27	0.61	0.37	0.35	-0.27
Ave daily temp	0.54	0.32	0.35	-0.15	0.54	0.32	0.35	-0.15
Ave total prec	0.41	0.27	0.32	0.06	0.41	0.27	0.32	0.06
ADT	-0.71	-0.54	-0.54	0.03	-0.71	-0.54	-0.54	0.03

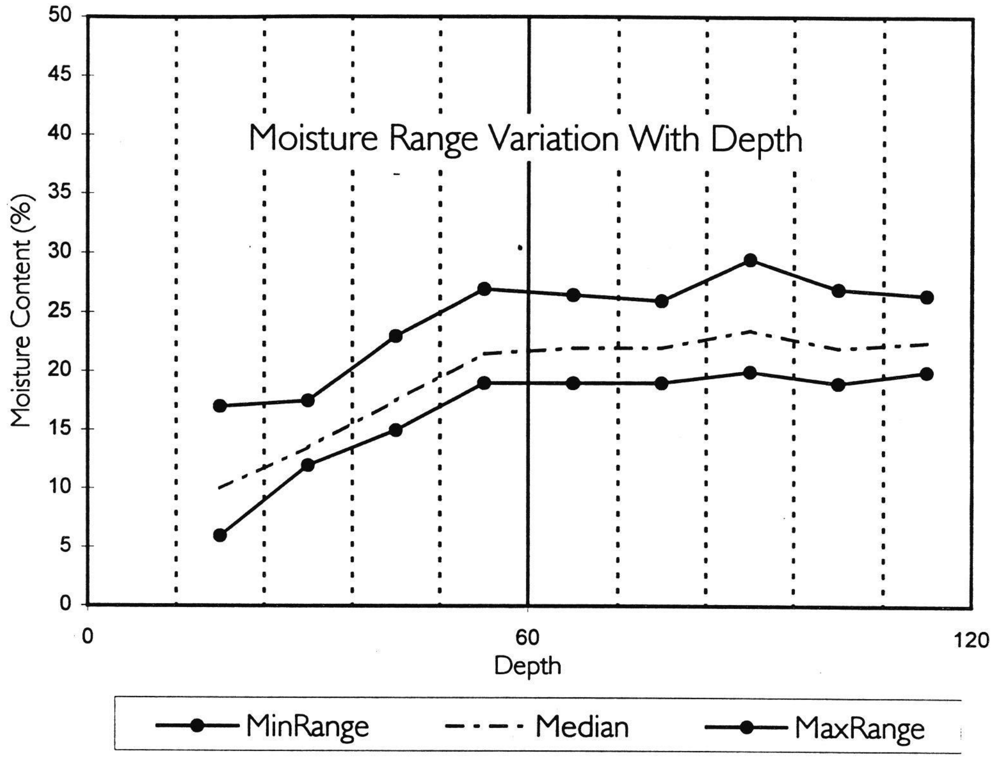
Appendix B - 6. Depth 78 - Correlation Coefficients.

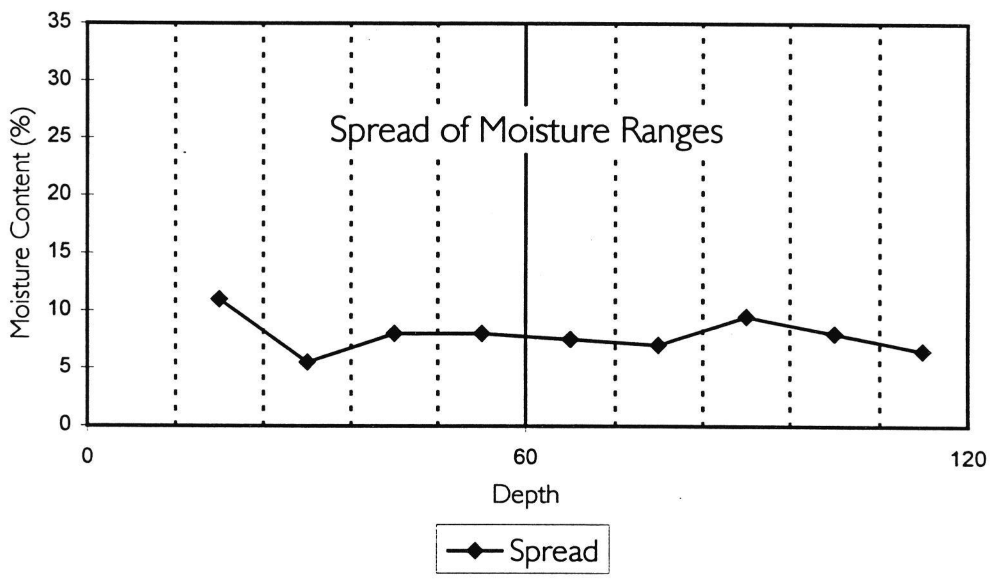
APPENDIX C



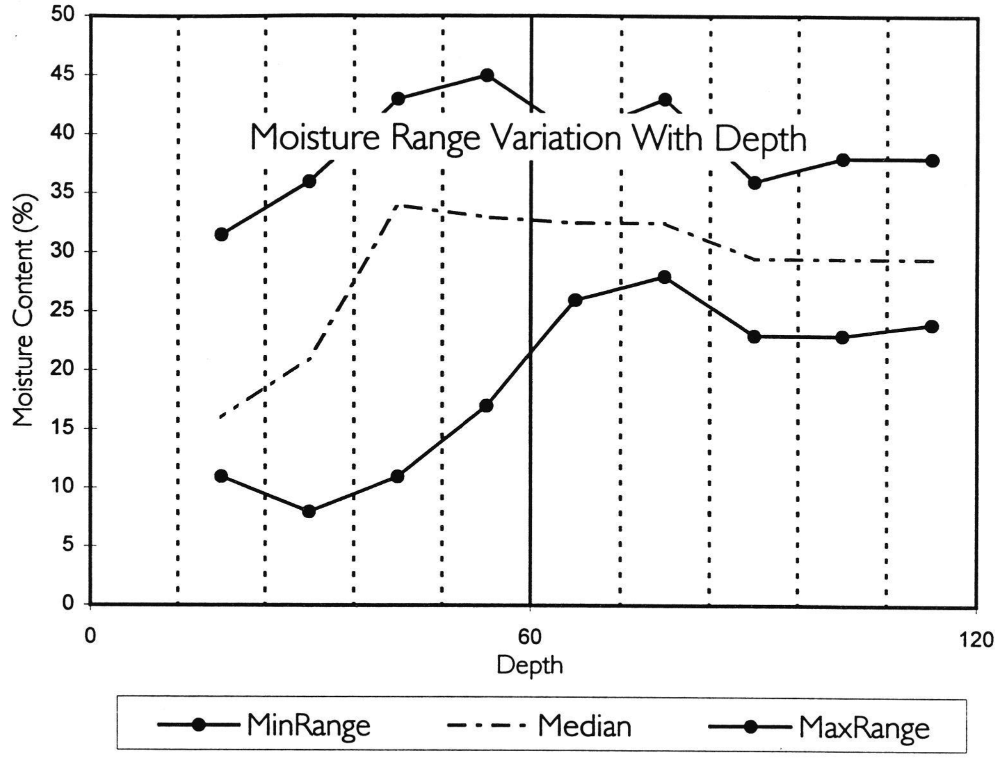


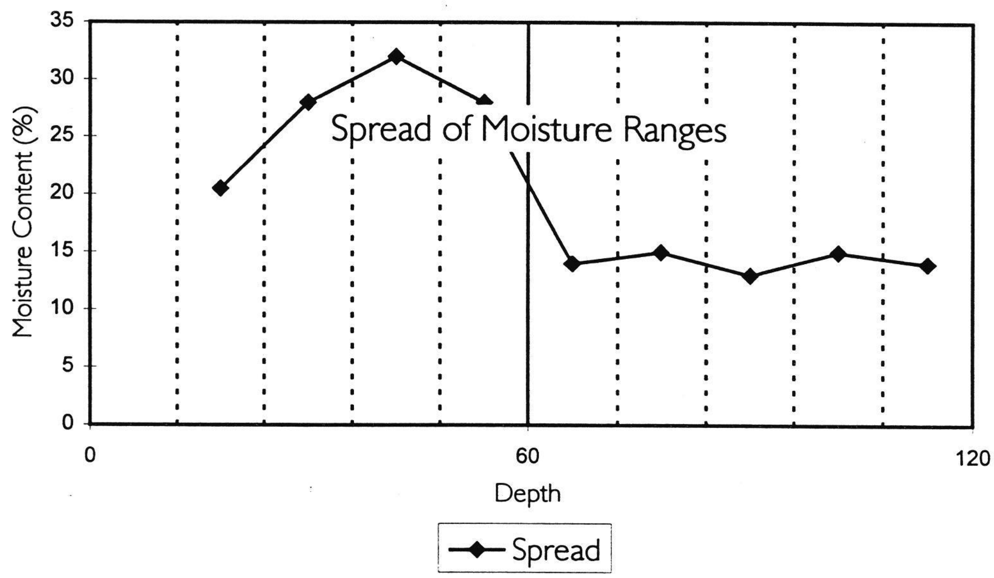
Appendix C - SITE 1. **Variation of Equilibrium Values, Median and Spread with Depth.**



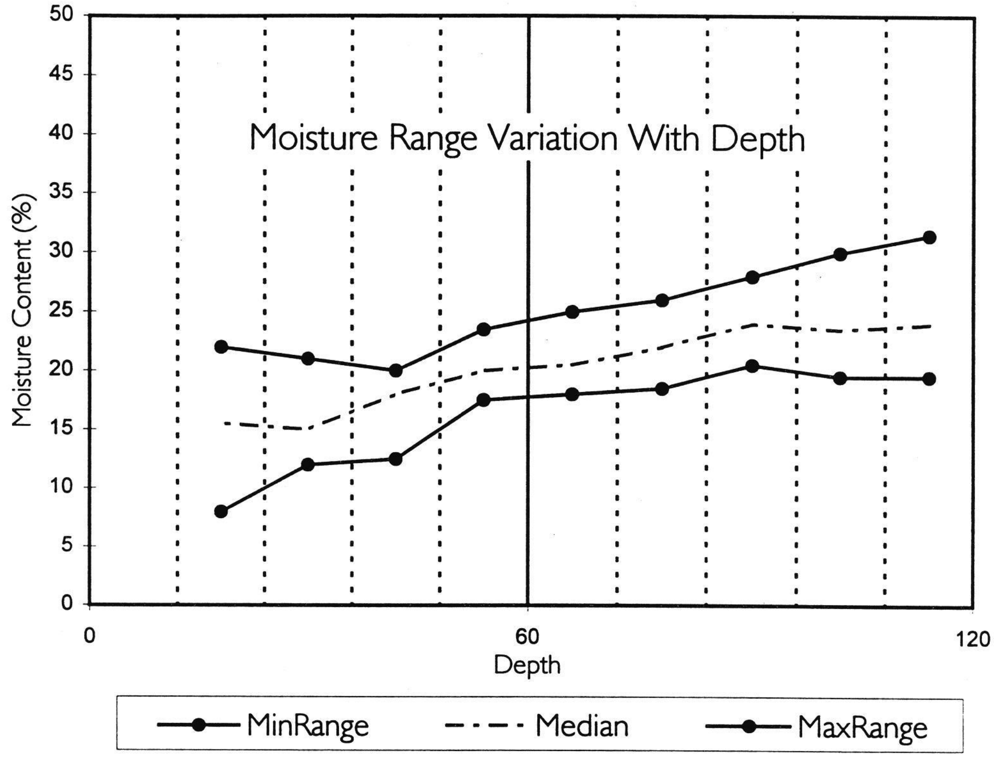


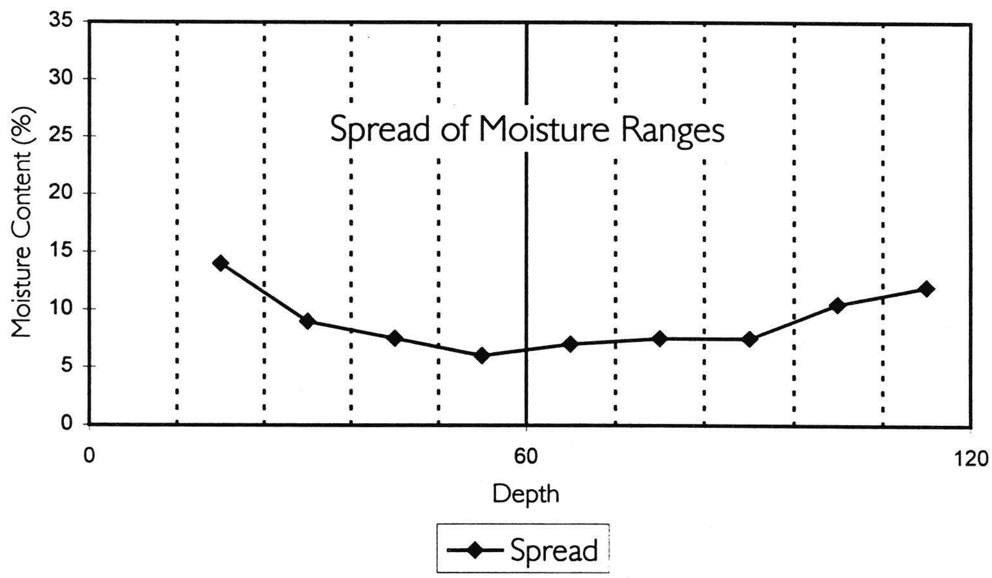
Appendix C - SITE 2. **Variation of Equilibrium Values, Median and Spread with Depth.**



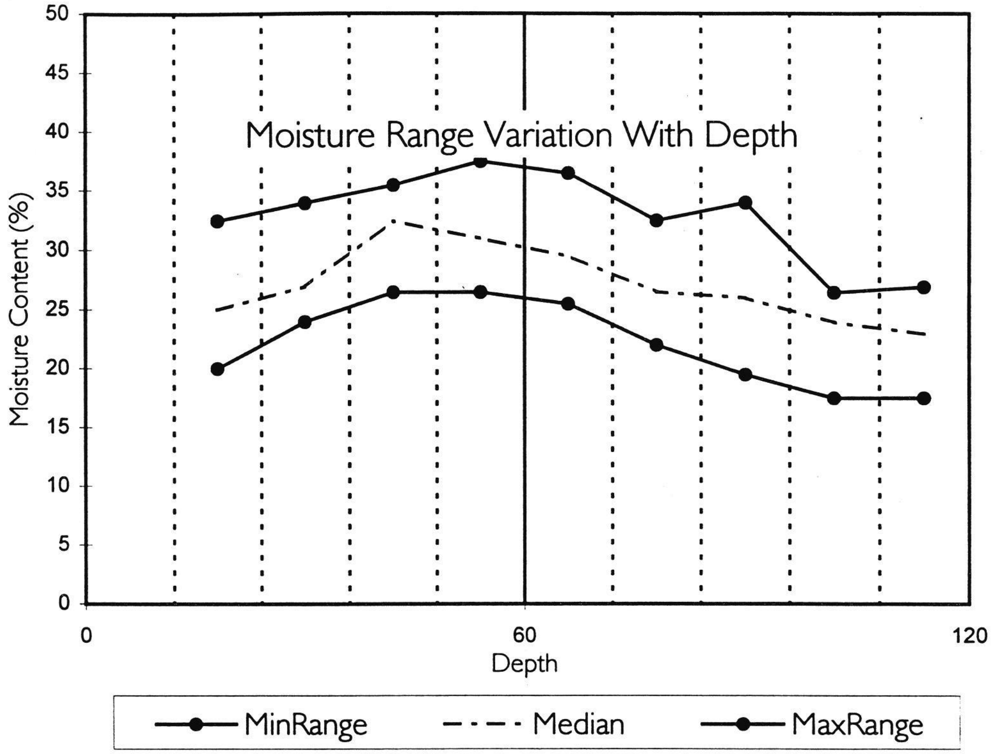


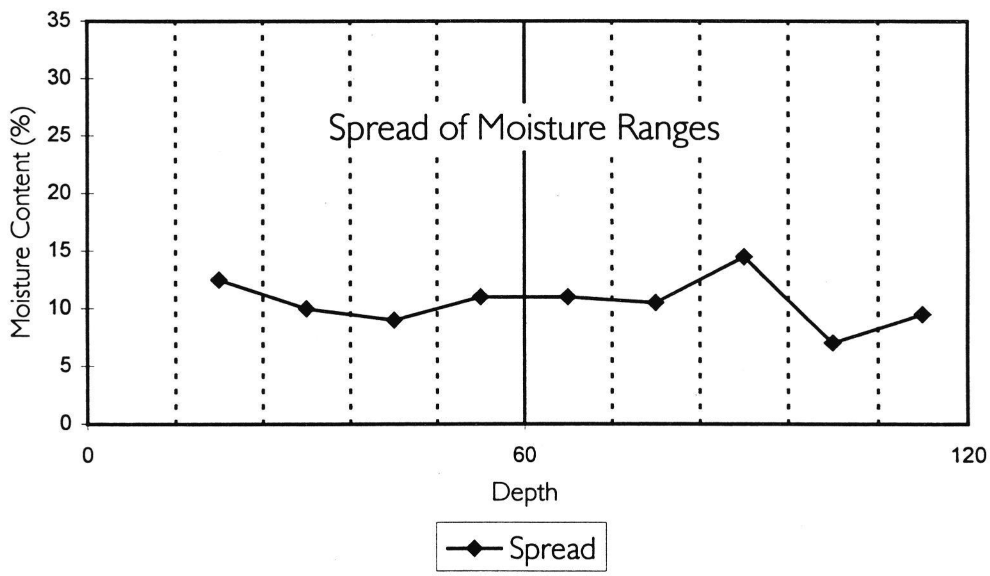
Appendix C - SITE 3. **Variation of Equilibrium Values, Median and Spread with Depth.**



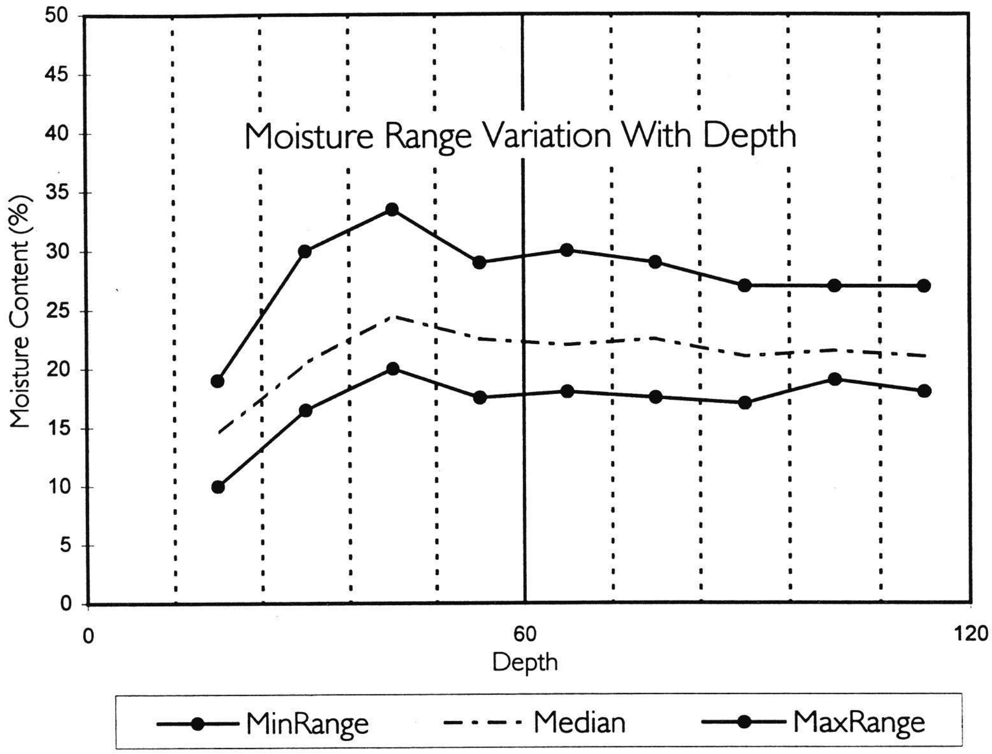


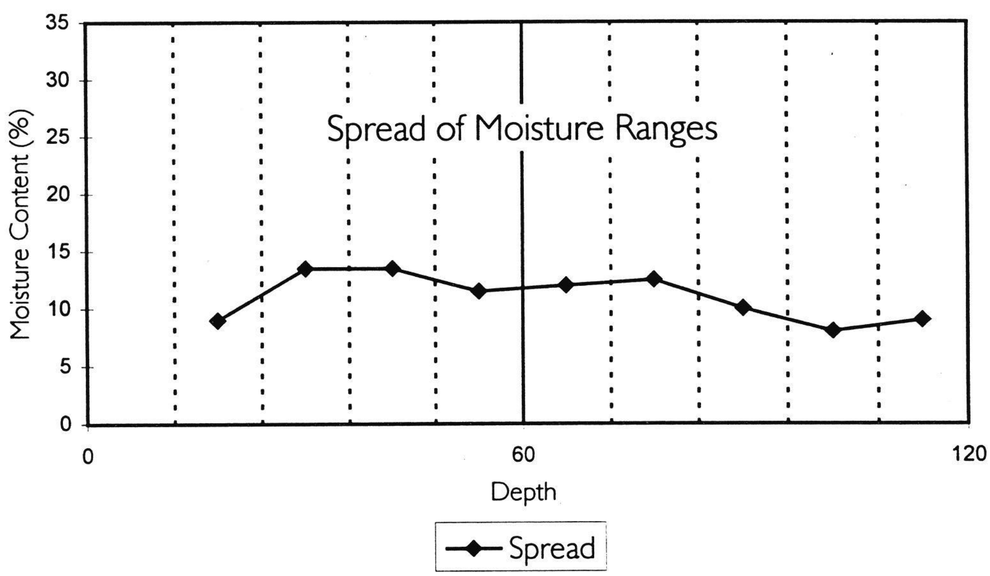
Appendix C - SITE 4. **Variation of Equilibrium Values, Median and Spread with Depth.**



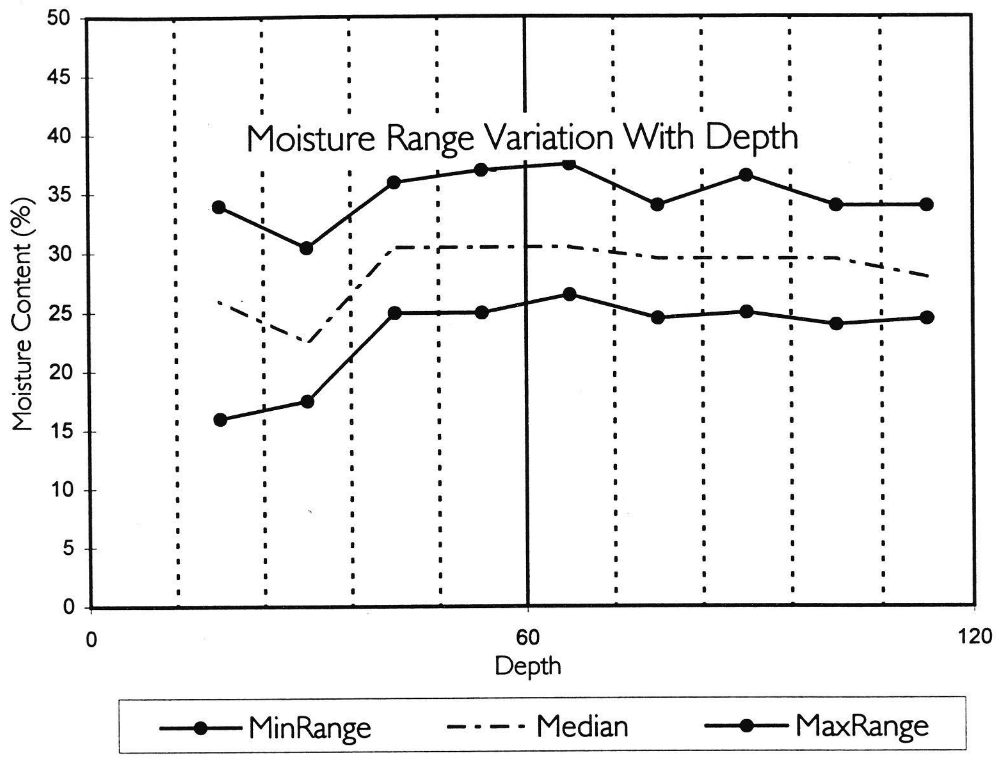


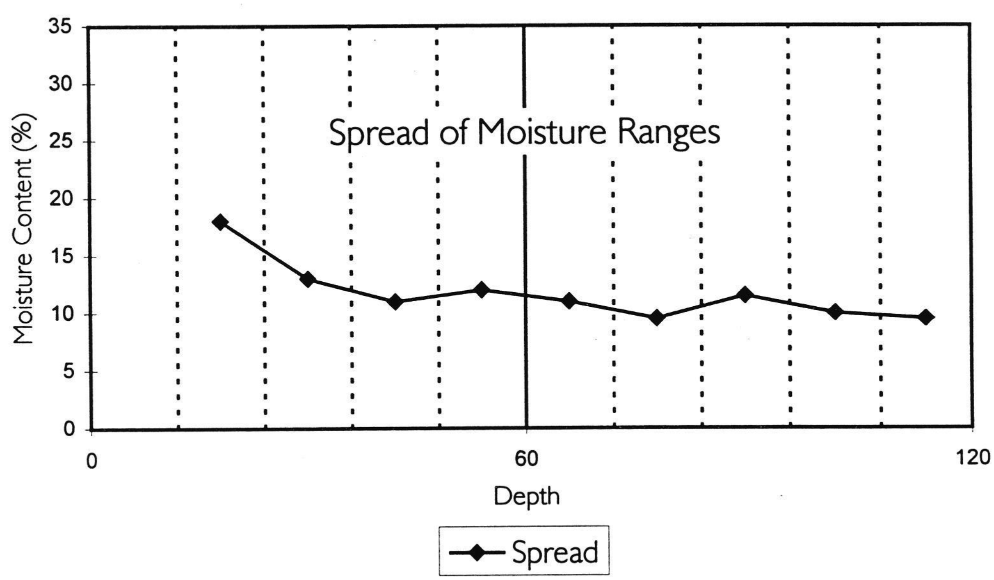
Appendix C - SITE 5. **Variation of Equilibrium Values, Median and Spread with Depth.**



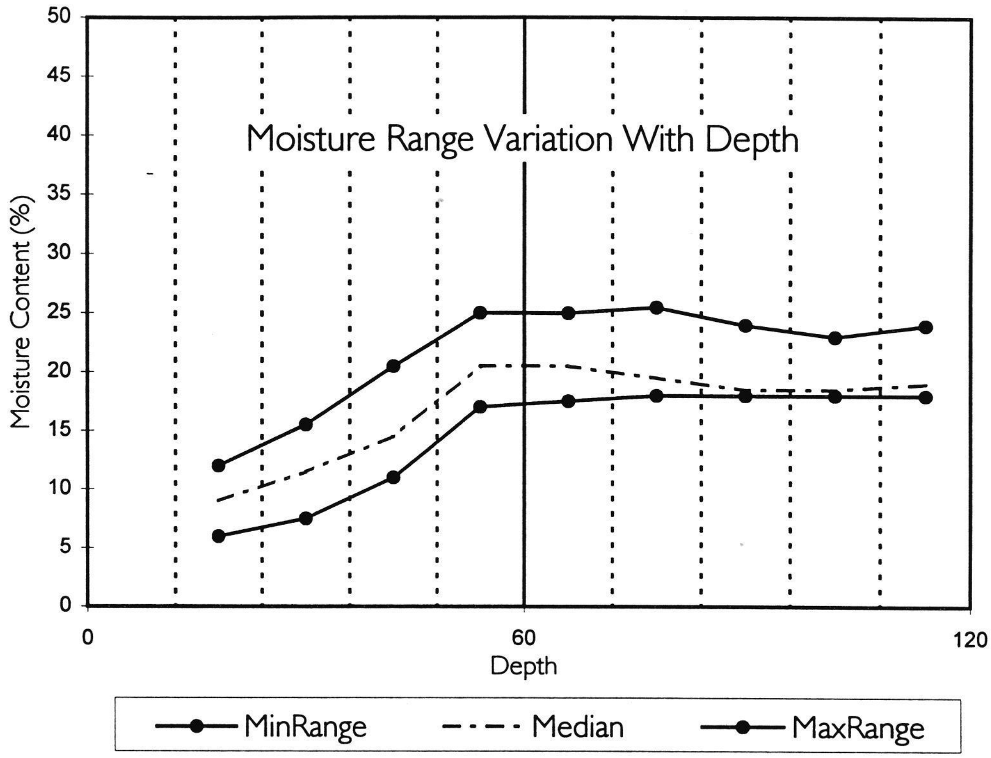


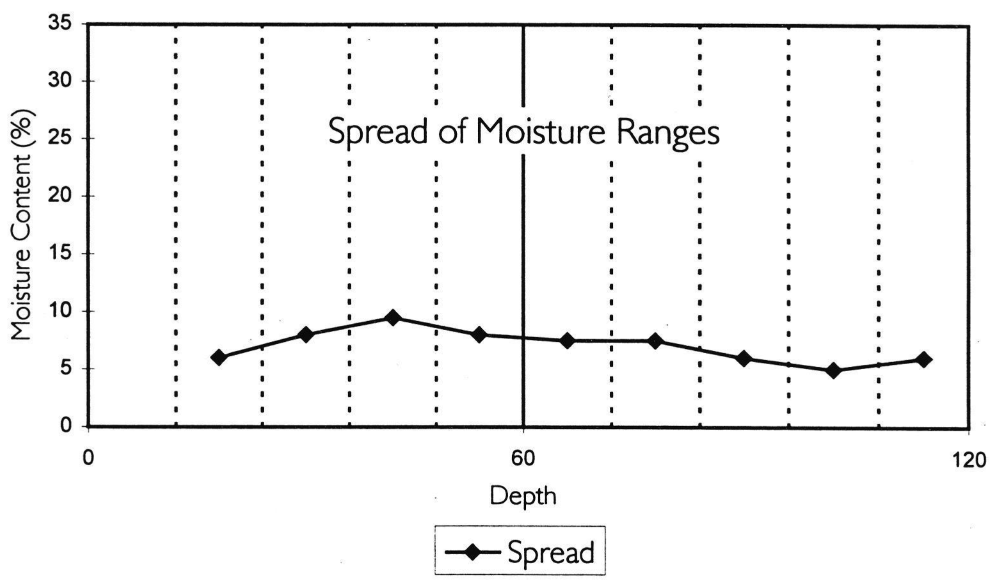
Appendix C - SITE 6. **Variation of Equilibrium Values, Median and Spread with Depth.**



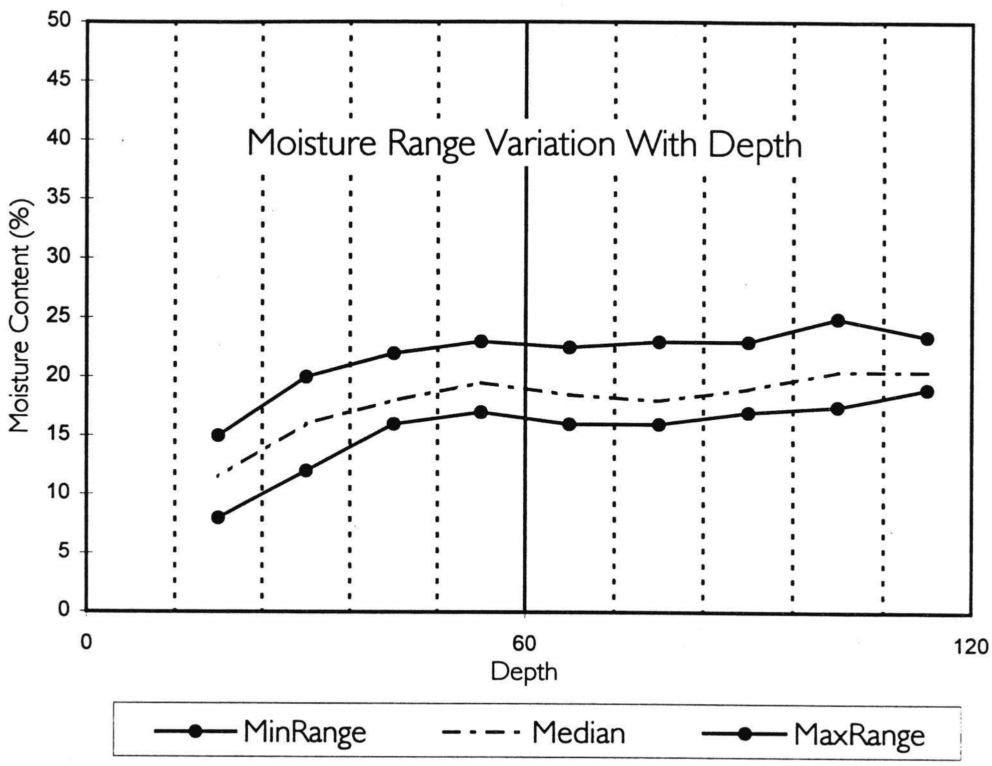


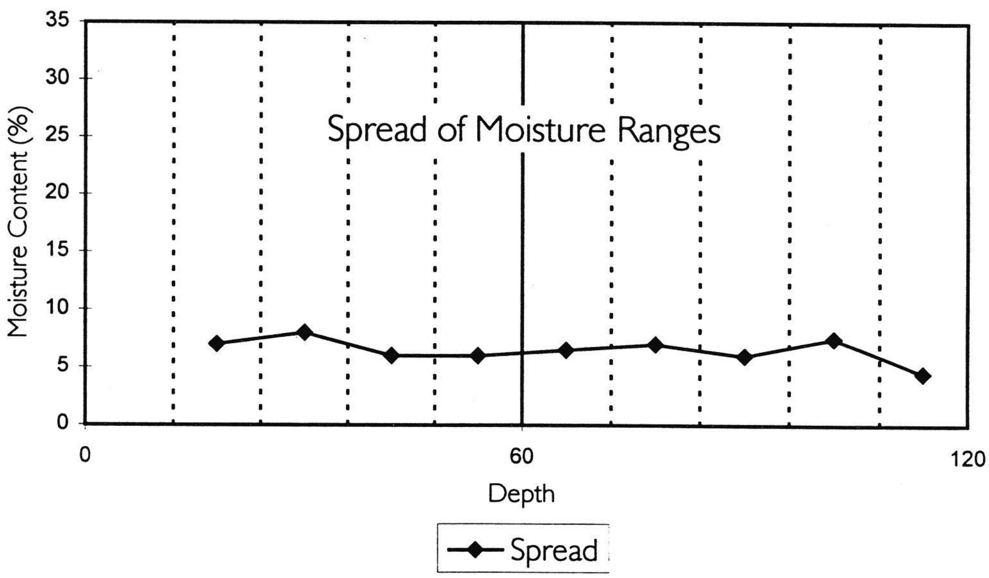
Appendix C - SITE 7. **Variation of Equilibrium Values, Median and Spread with Depth.**



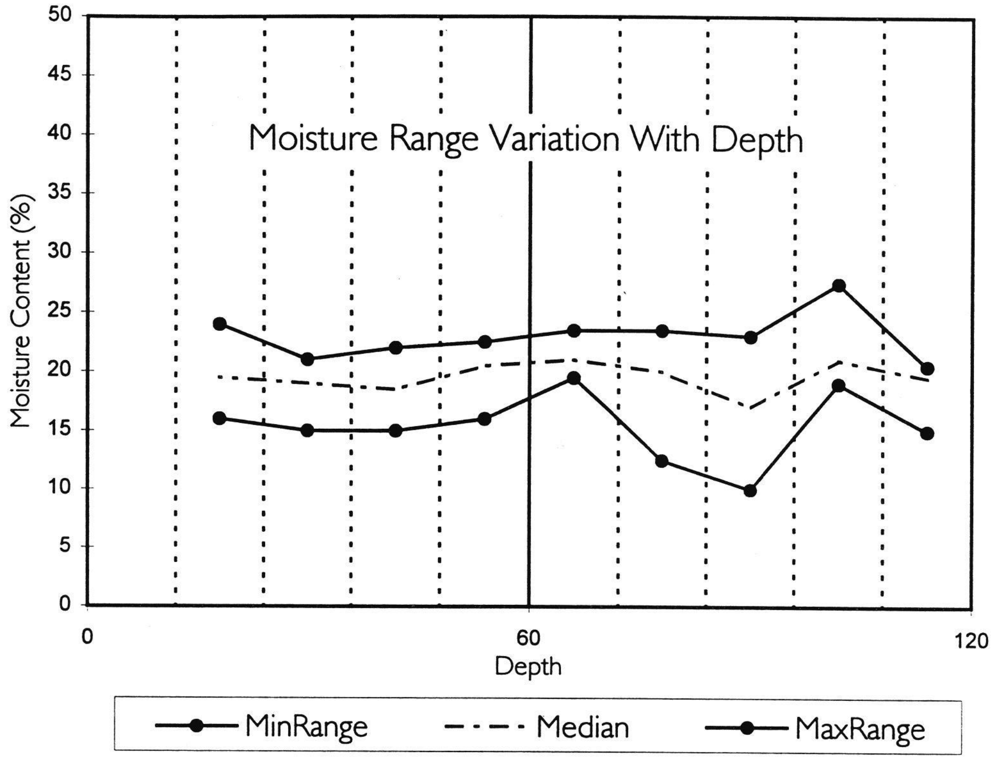


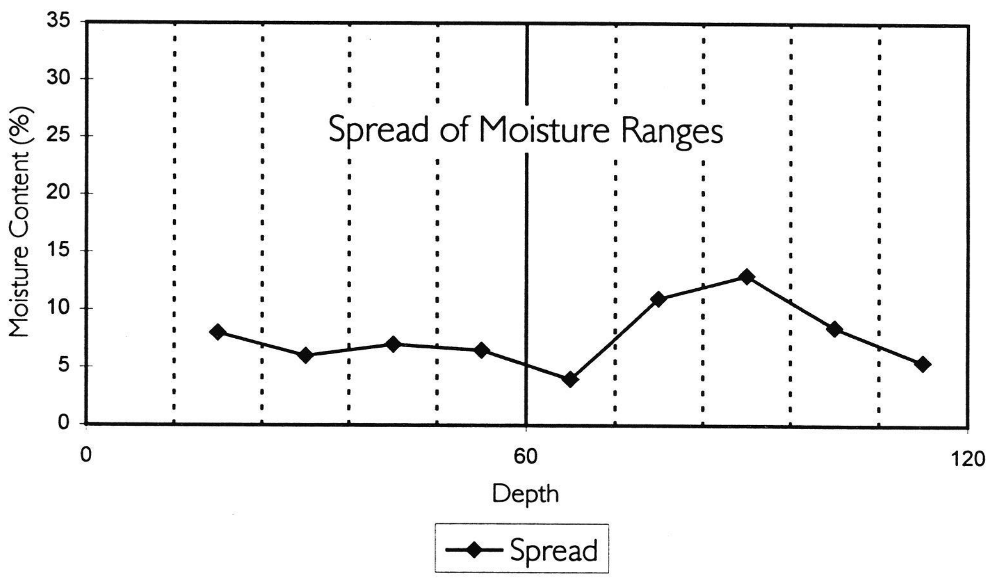
Appendix C - SITE 8. **Variation of Equilibrium Values, Median and Spread with Depth.**



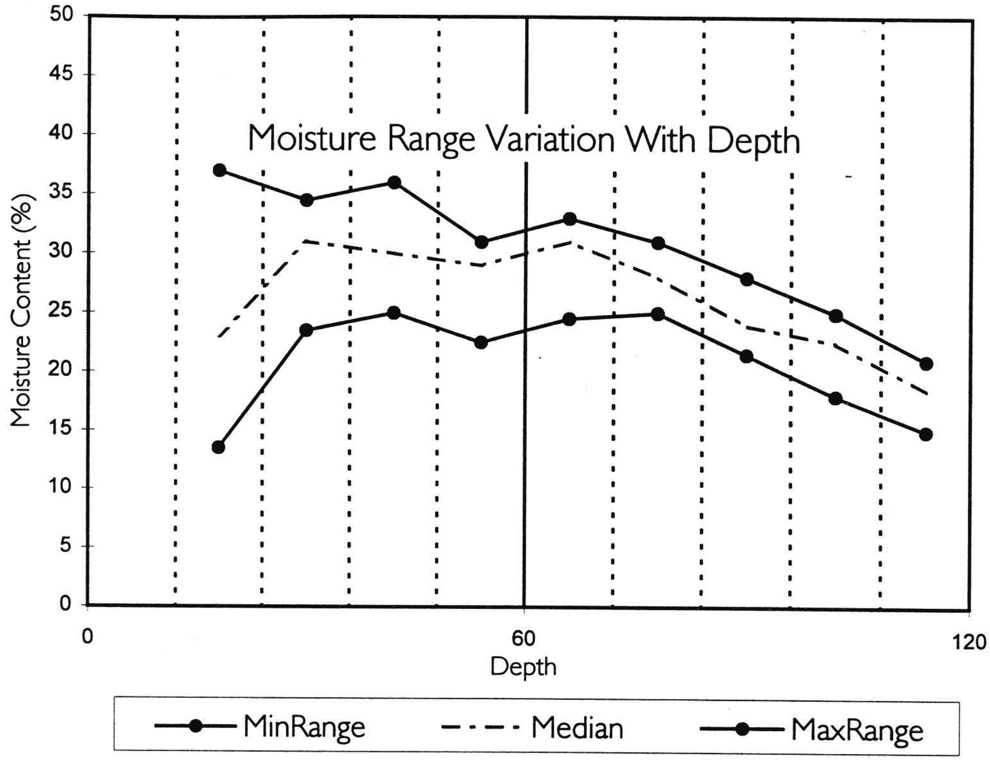


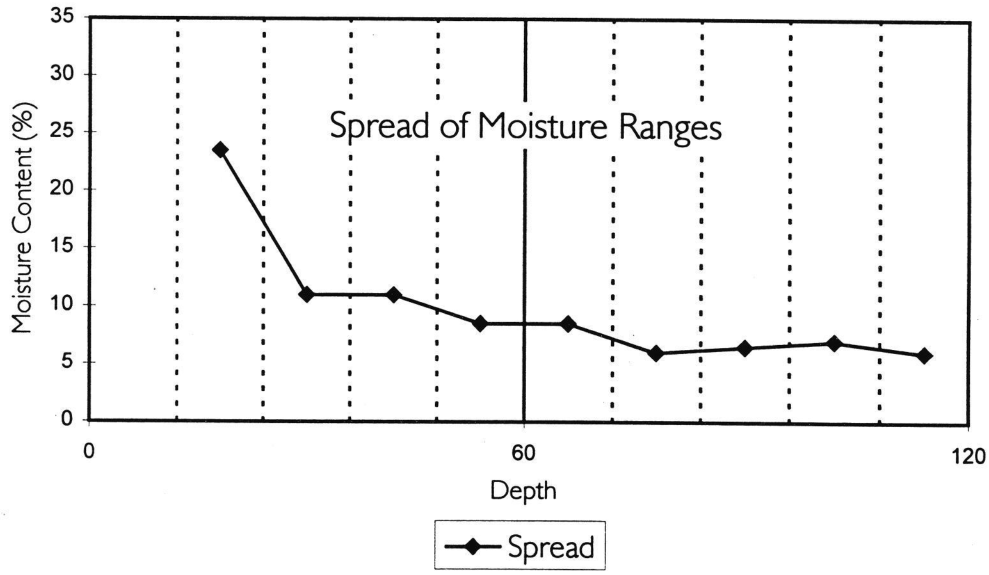
Appendix C - SITE 9. Variation of Equilibrium Values, Median and Spread with Depth.



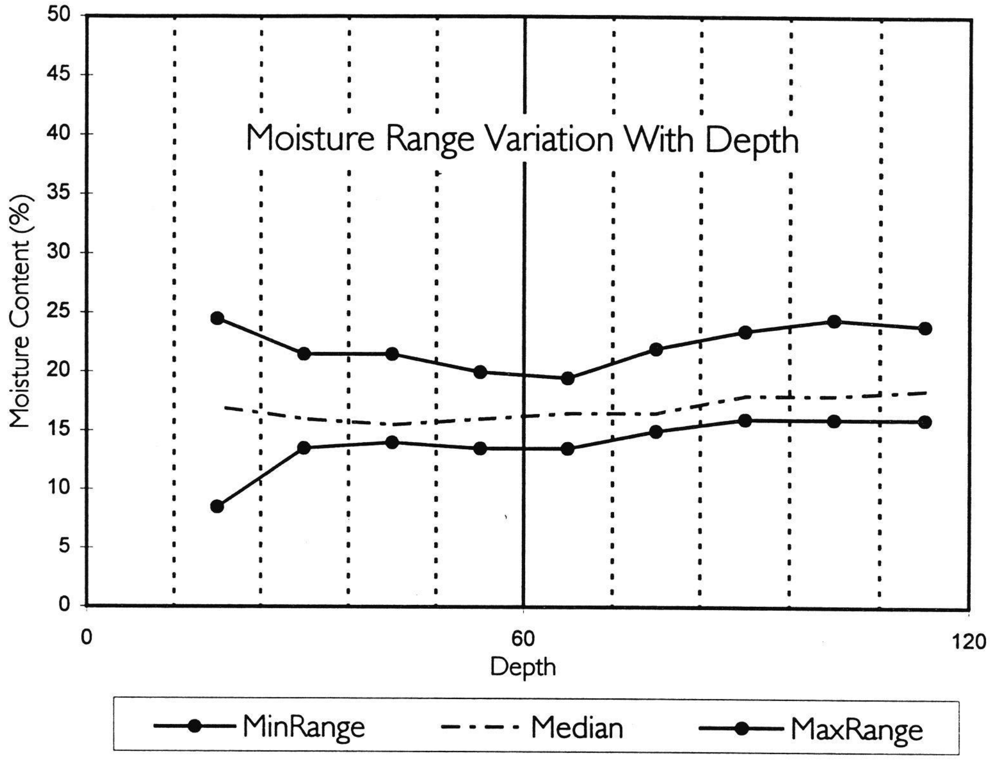


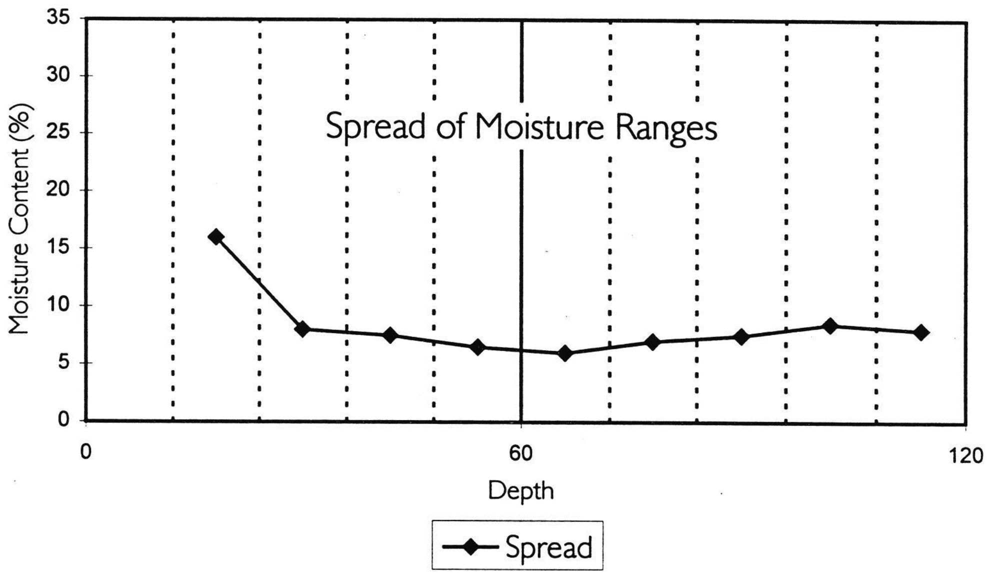
Appendix C - SITE 10. **Variation of Equilibrium Values, Median and Spread with Depth.**



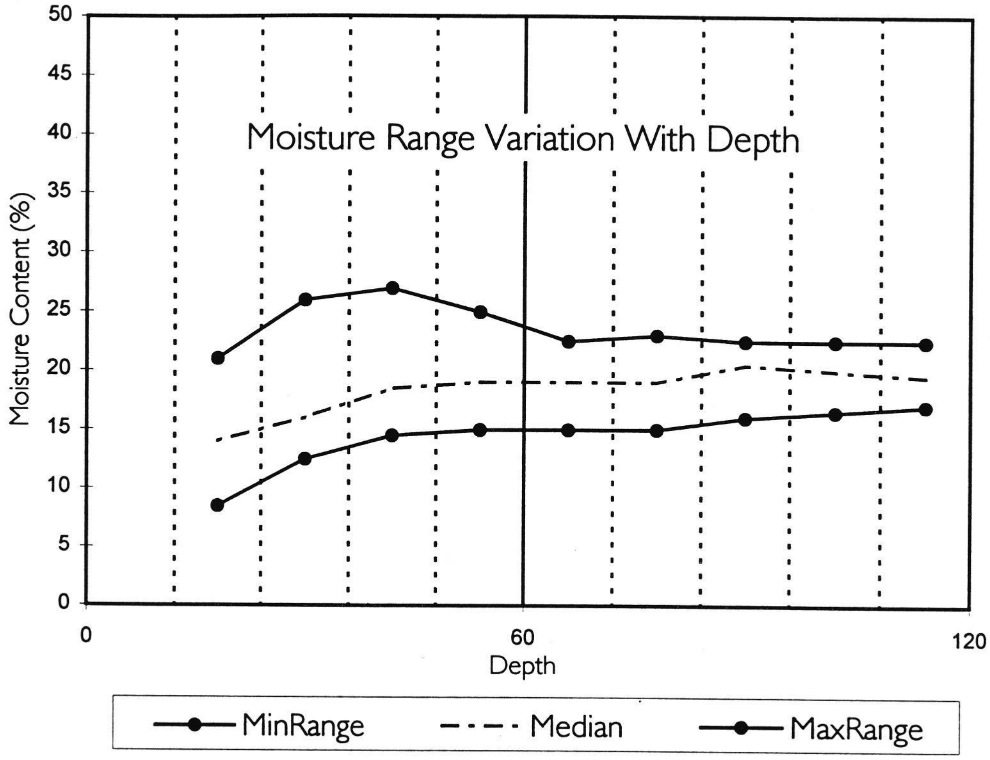


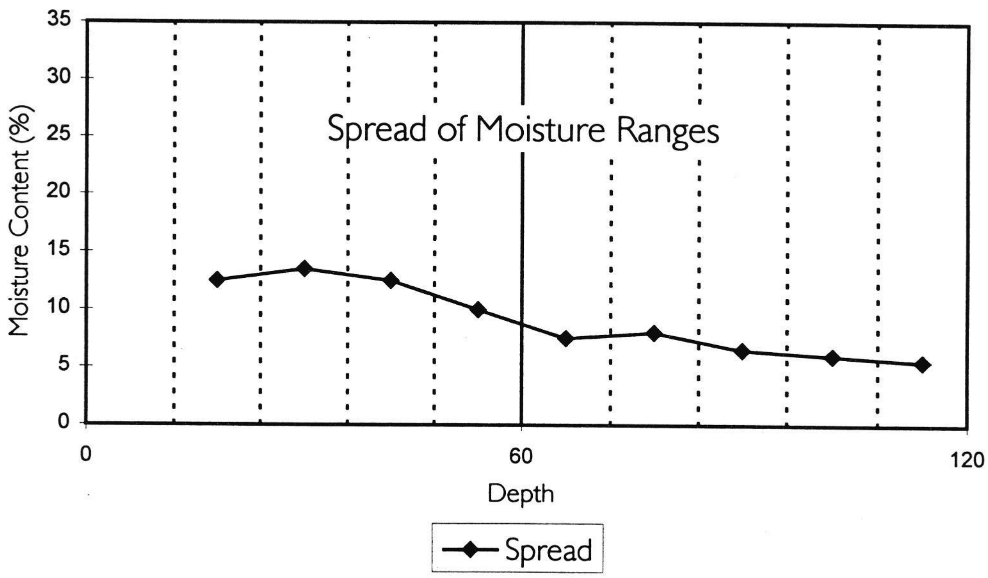
Appendix C - SITE 11. **Variation of Equilibrium Values, Median and Spread with Depth.**



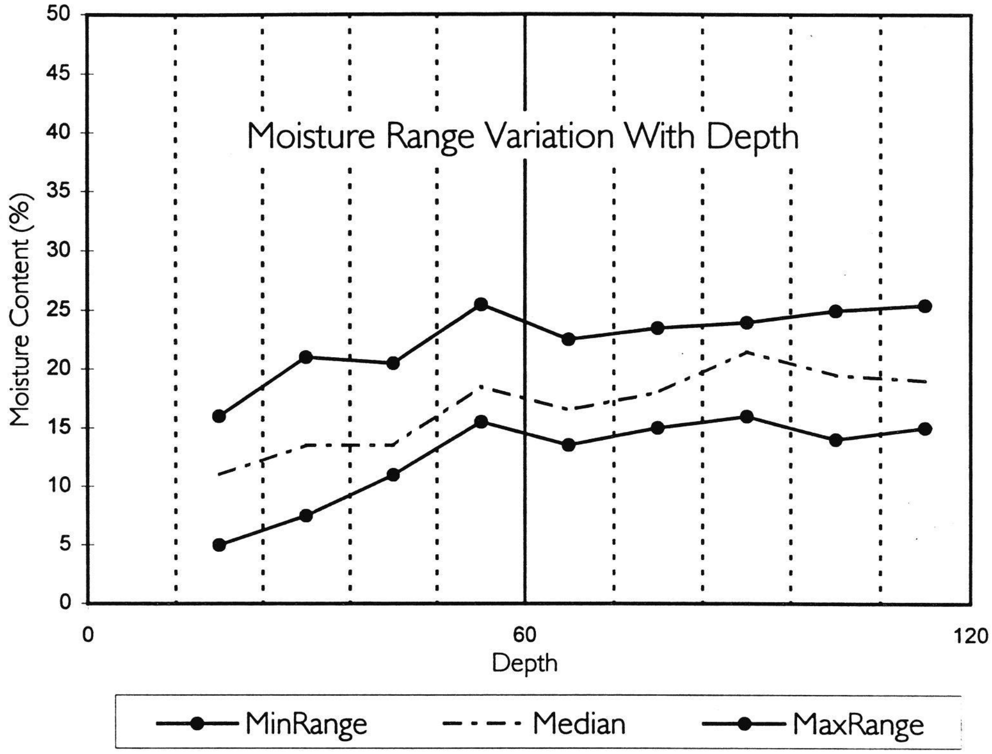


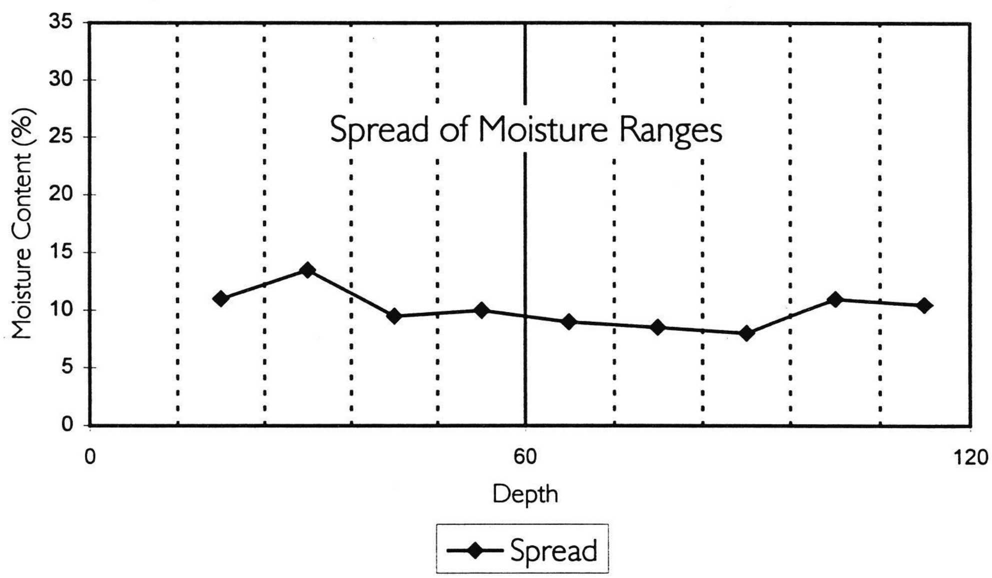
Appendix C - SITE 12. **Variation of Equilibrium Values, Median and Spread with Depth.**





Appendix C - SITE 13. **Variation of Equilibrium Values, Median and Spread with Depth.**





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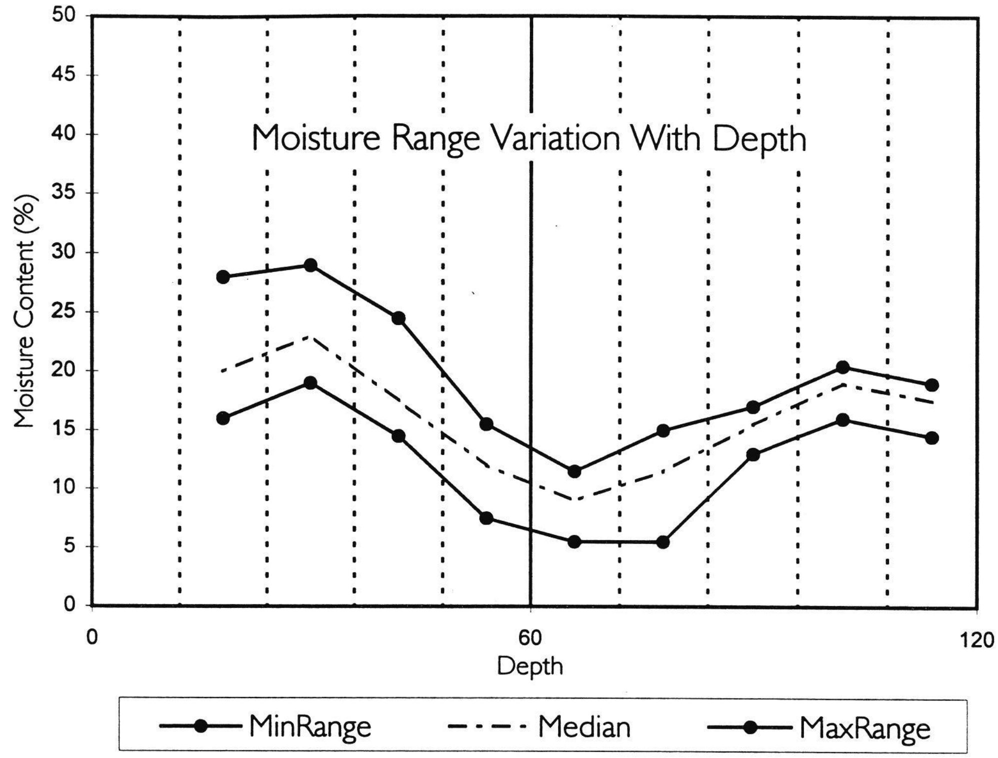
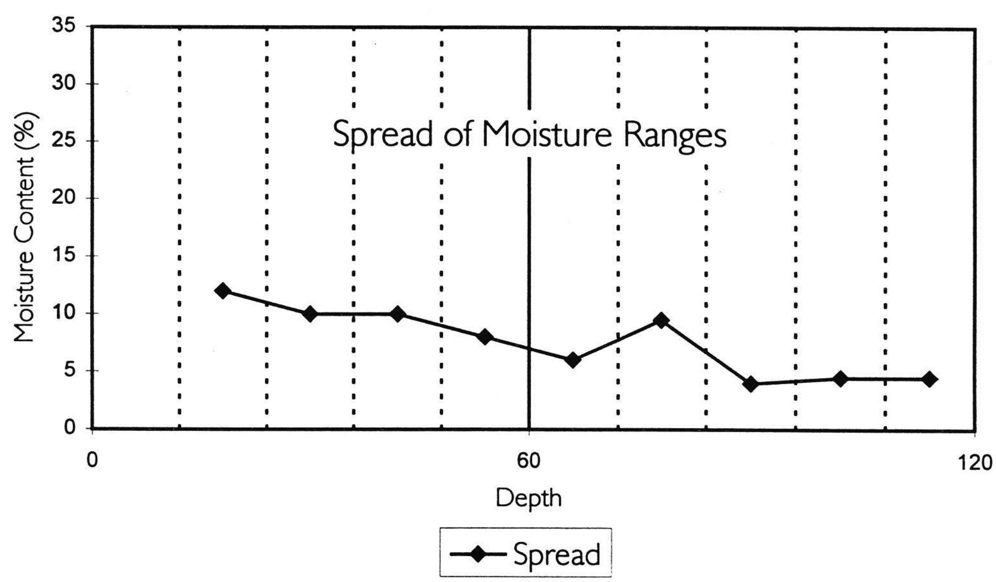
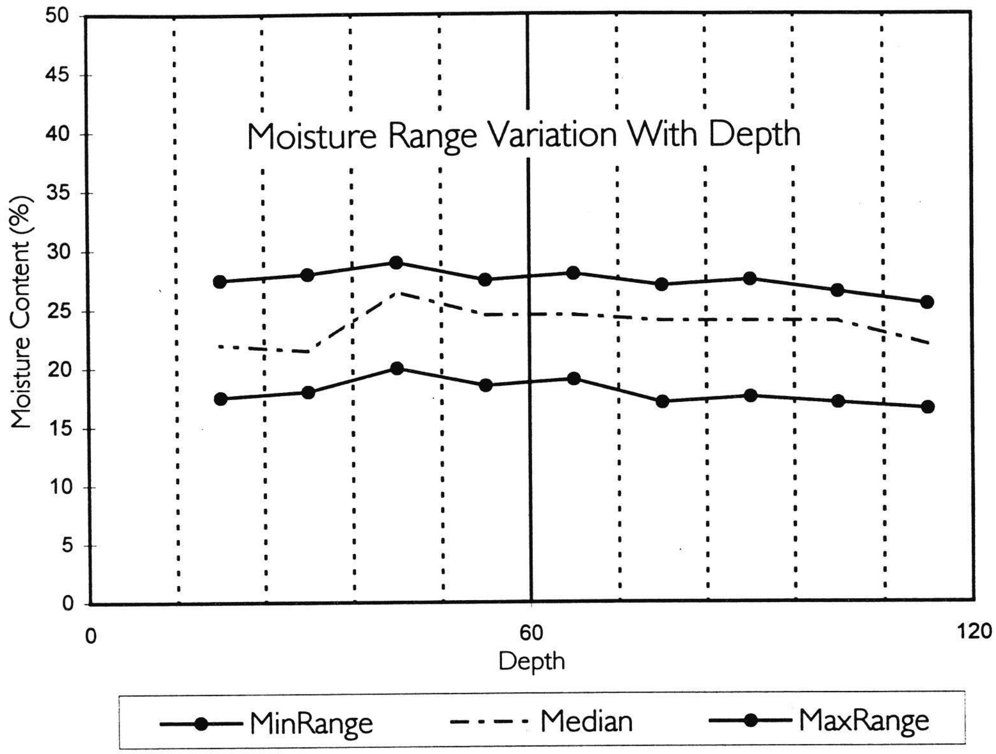
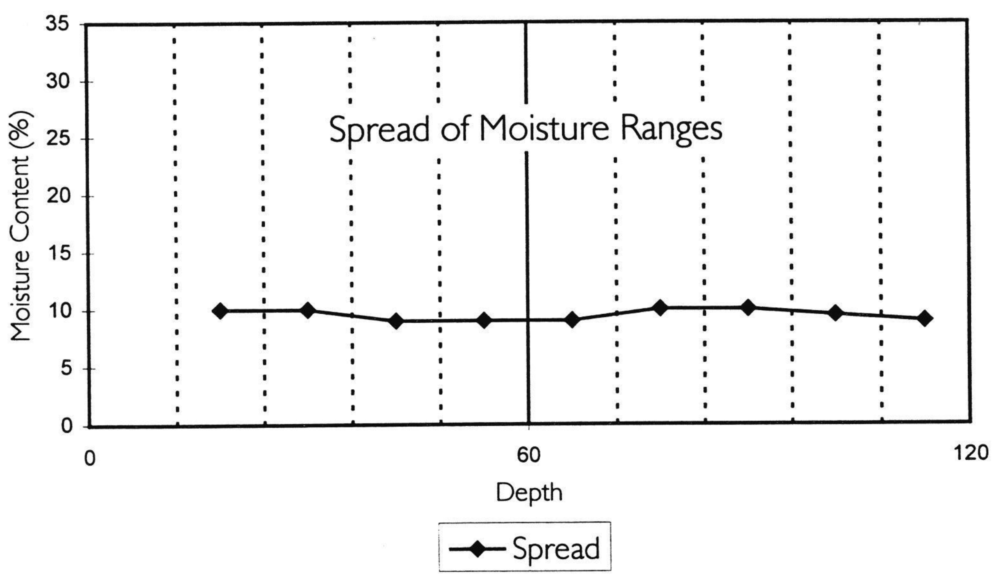


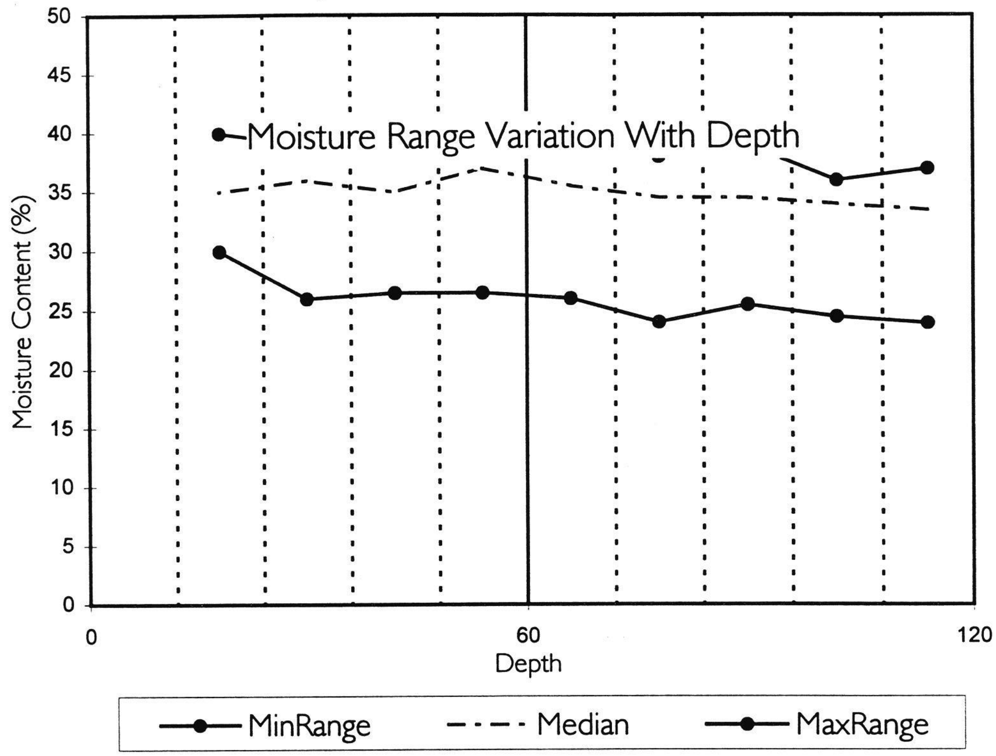


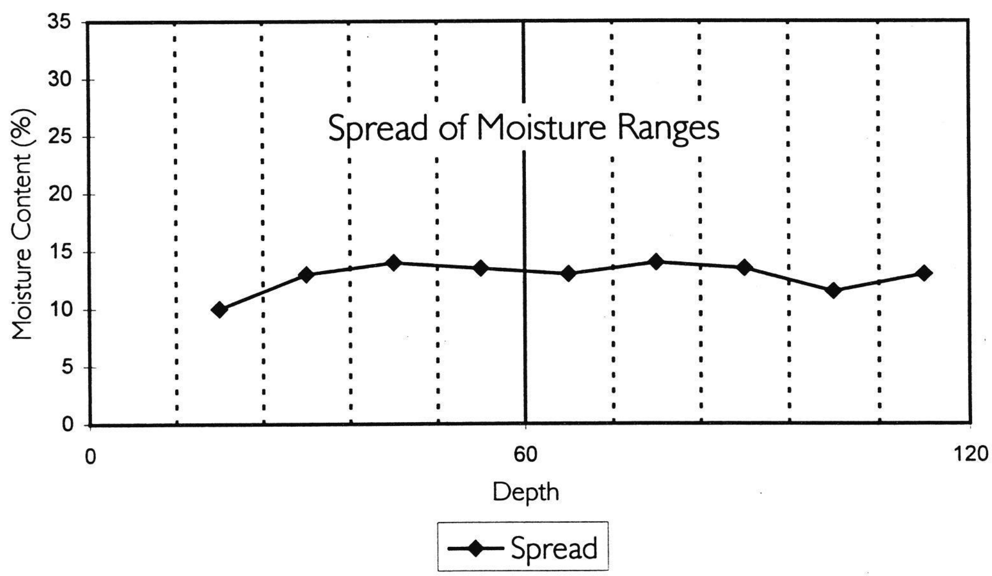
Appendix C - SITE 15. **Variation of Equilibrium Values, Median and Spread with Depth.**



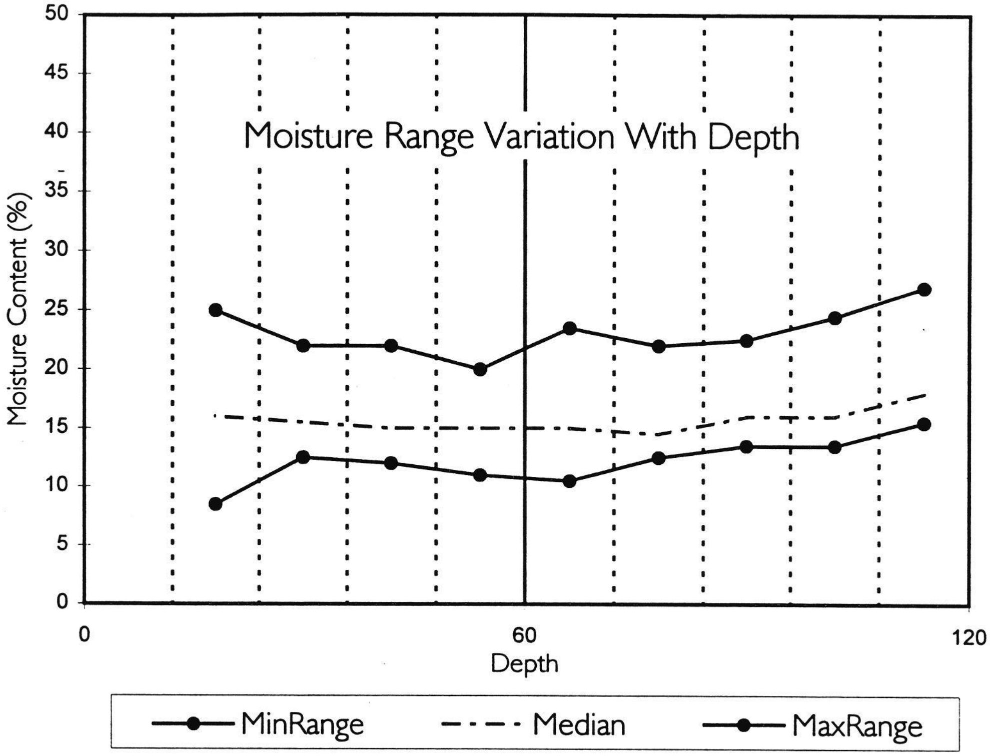


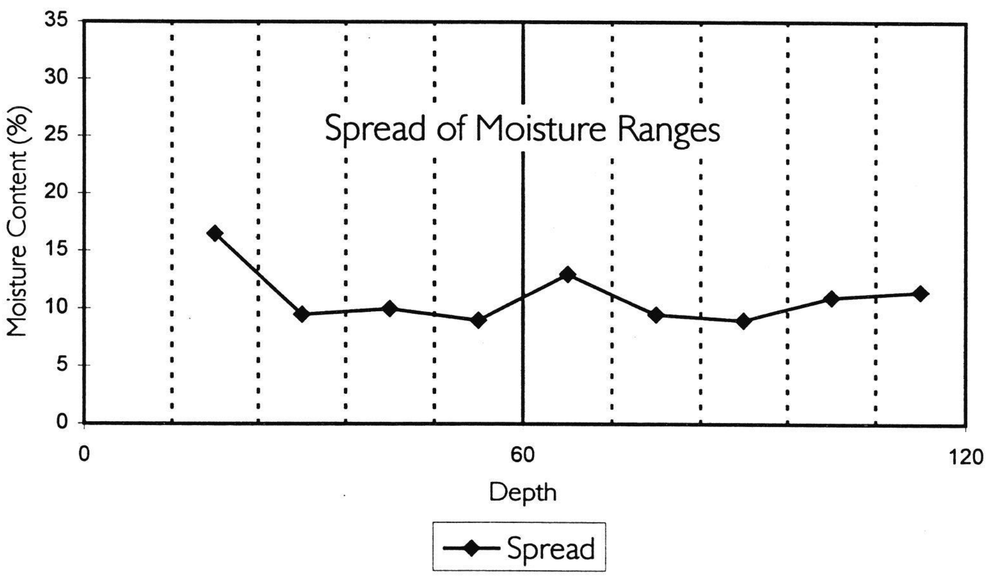
Appendix C - SITE 16. **Variation of Equilibrium Values, Median and Spread with Depth.**





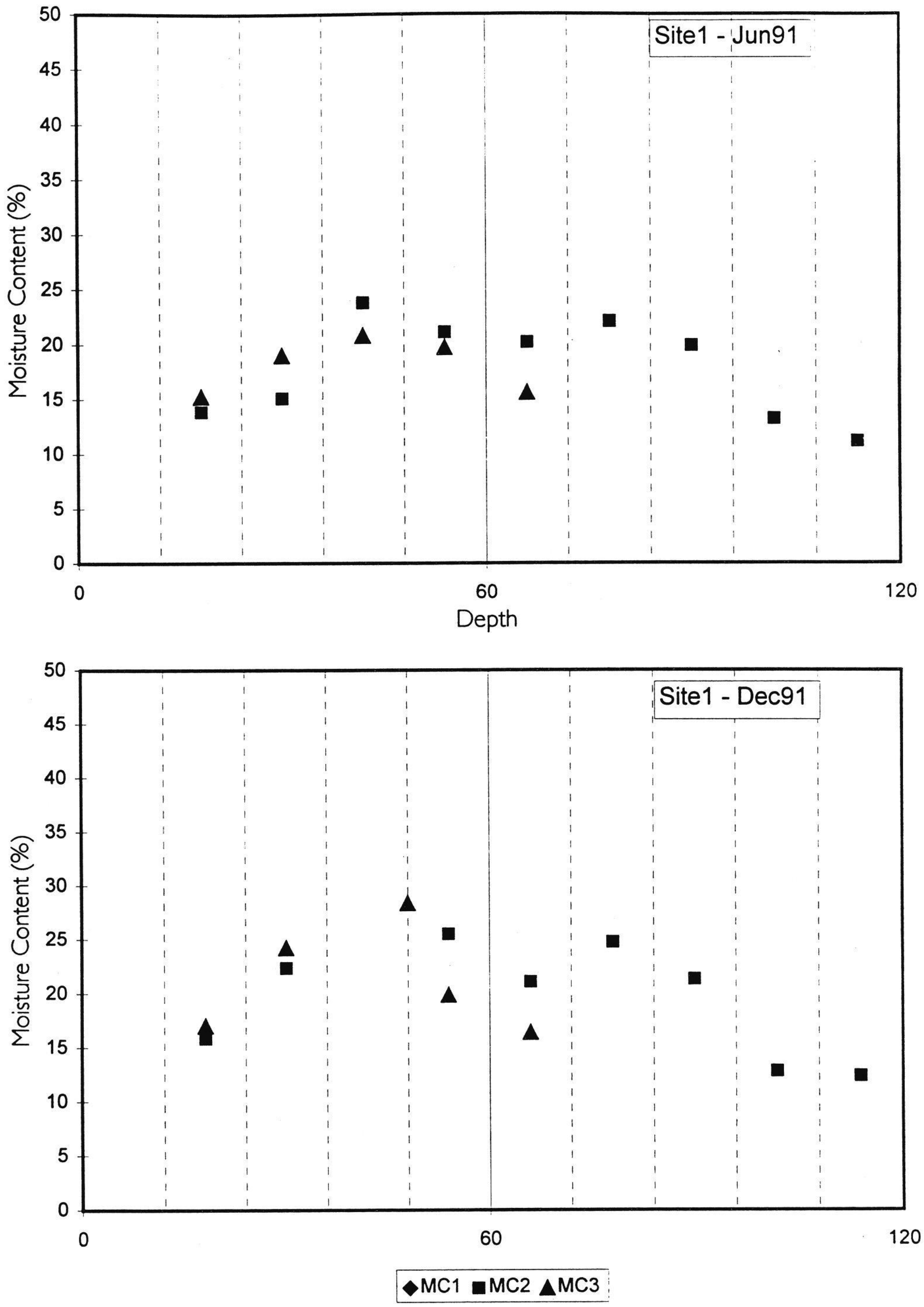
Appendix C - SITE 17. **Variation of Equilibrium Values, Median and Spread with Depth.**



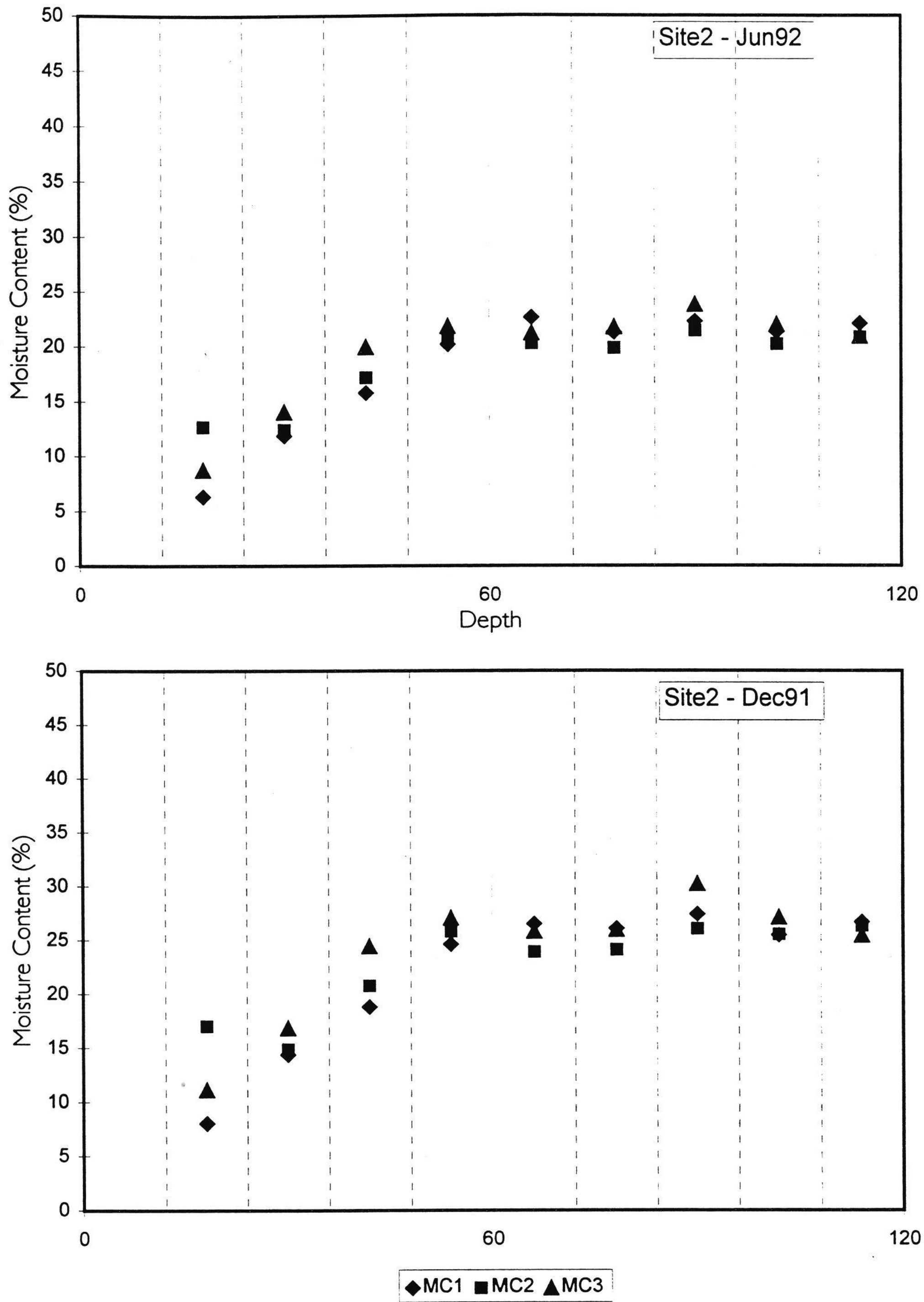


Appendix C - SITE 18. **Variation of Equilibrium Values, Median and Spread with Depth.**

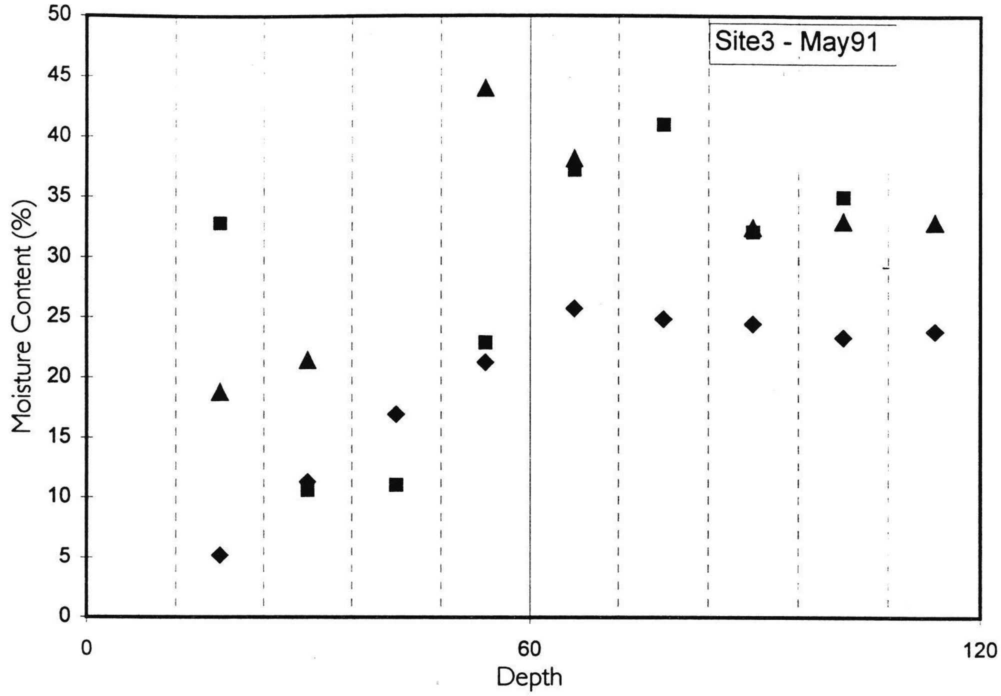
APPENDIX D

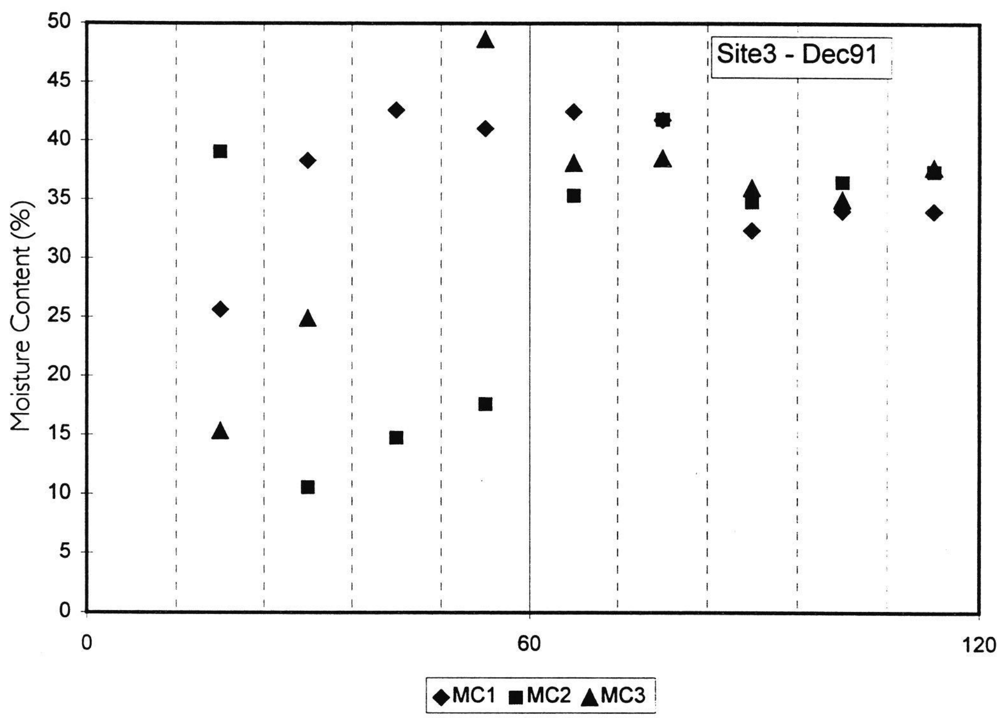


Appendix D - SITE 1. **Actual Moisture Variation with Depth During Different Times of the Year.**

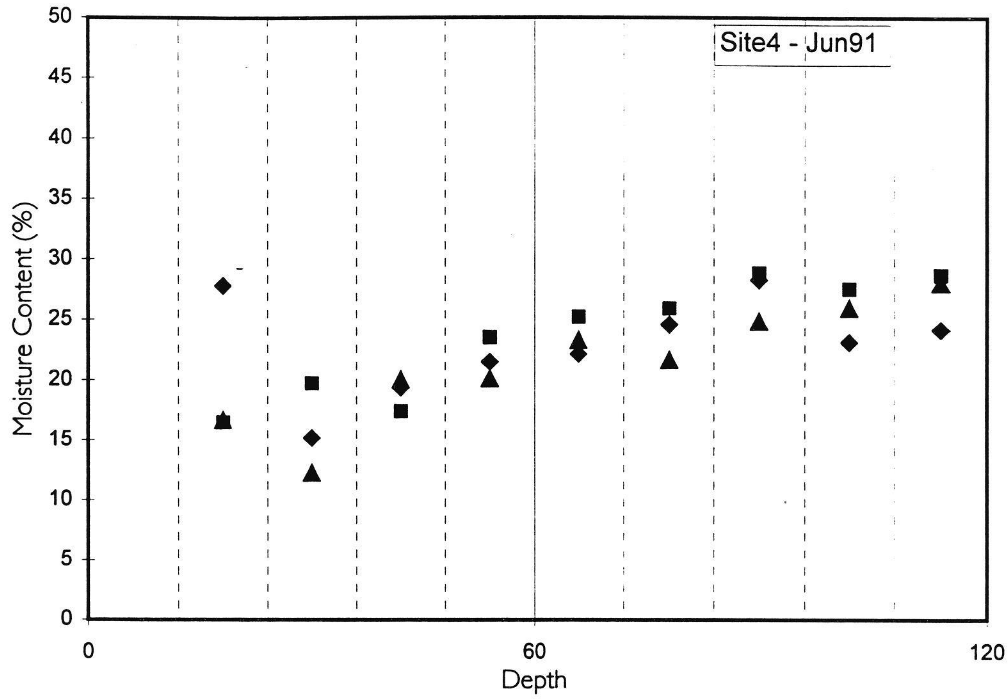


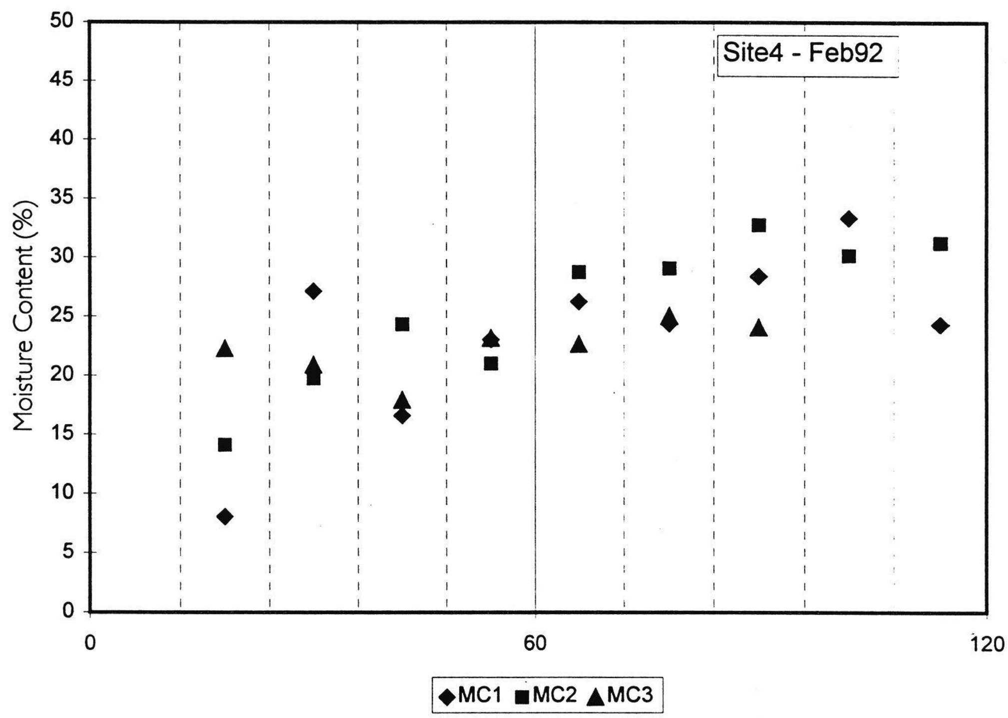
Appendix D - SITE 2. Actual Moisture Variation with Depth During Different Times of the Year.



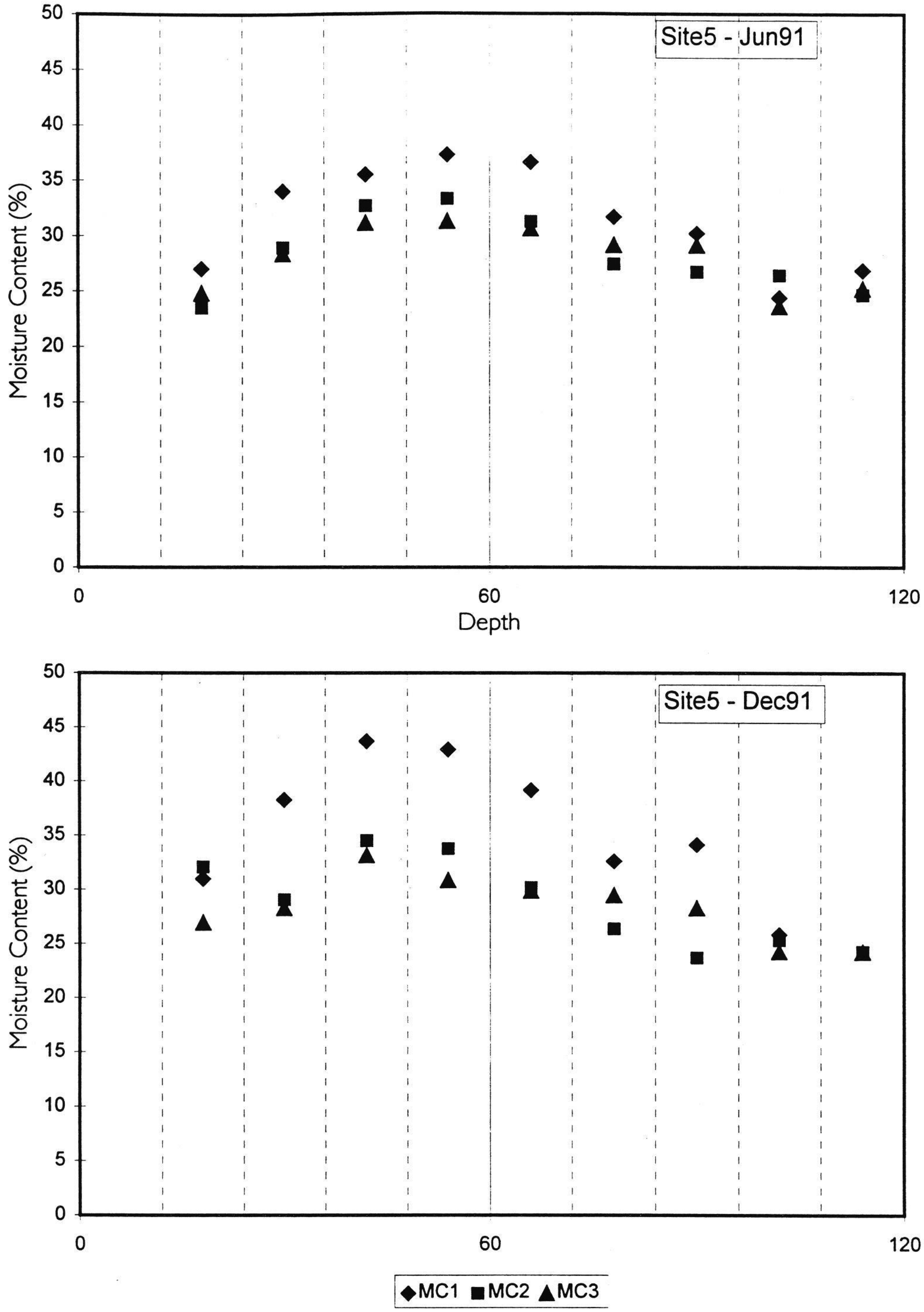


Appendix D - SITE 3. **Actual Moisture Variation with Depth During Different Times of the Year.**

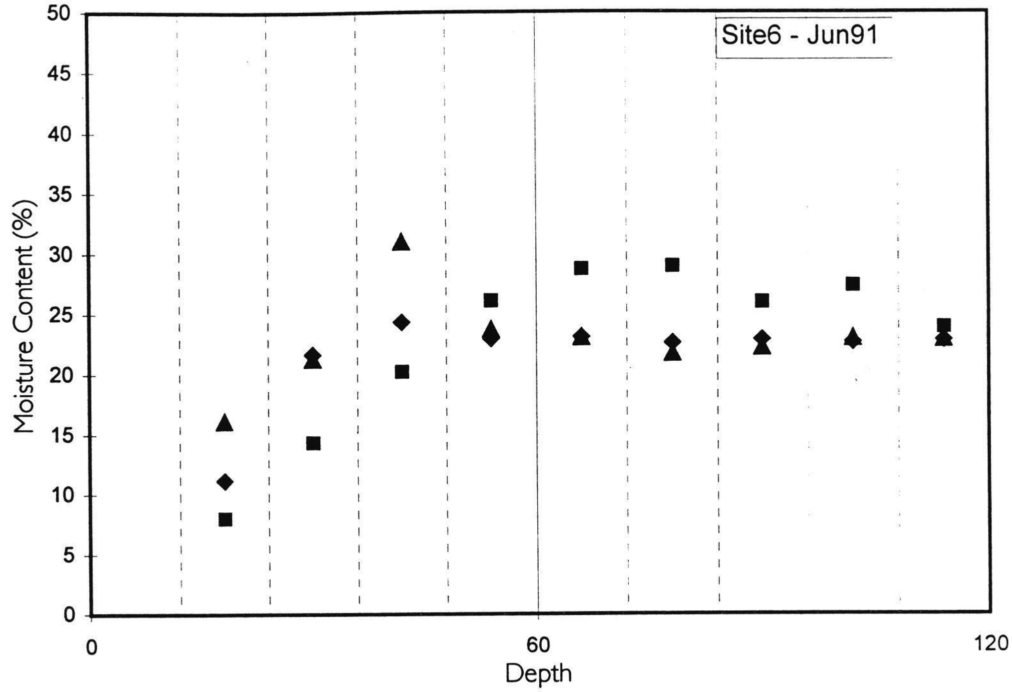


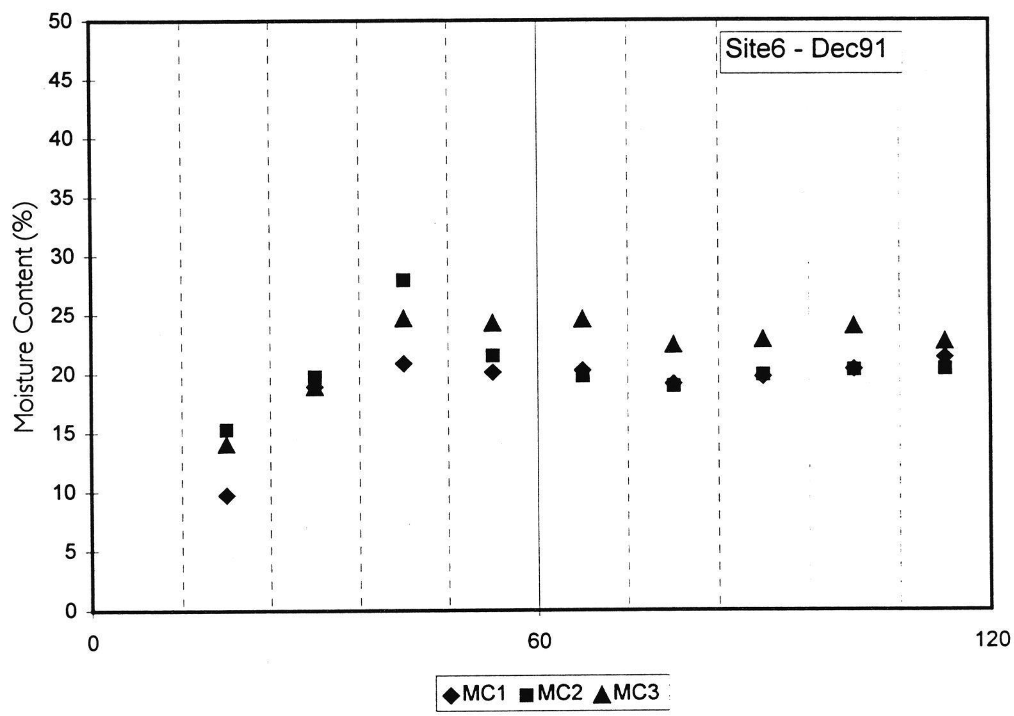


Appendix D - SITE 4. **Actual Moisture Variation with Depth During Different Times of the Year.**

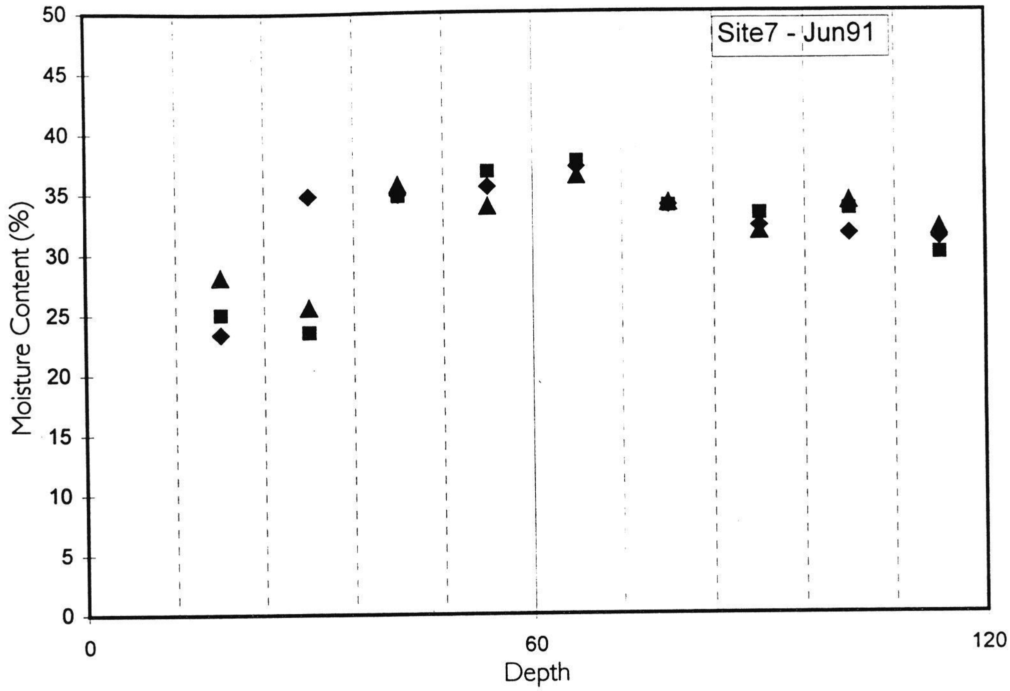


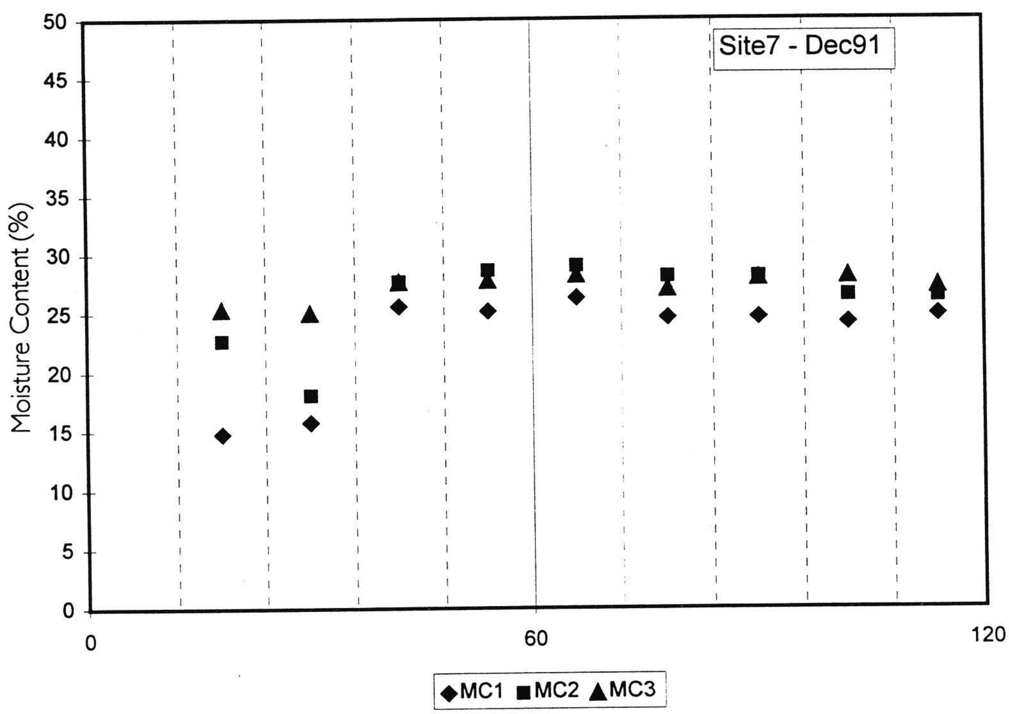
Appendix D - SITE 5. Actual Moisture Variation with Depth During Different Times of the Year.



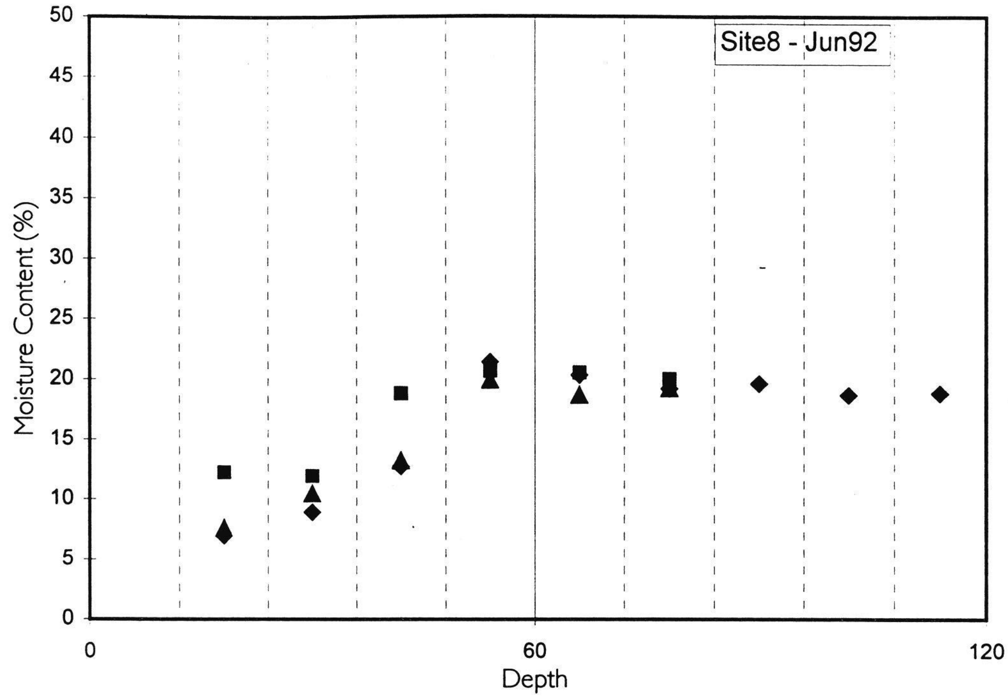


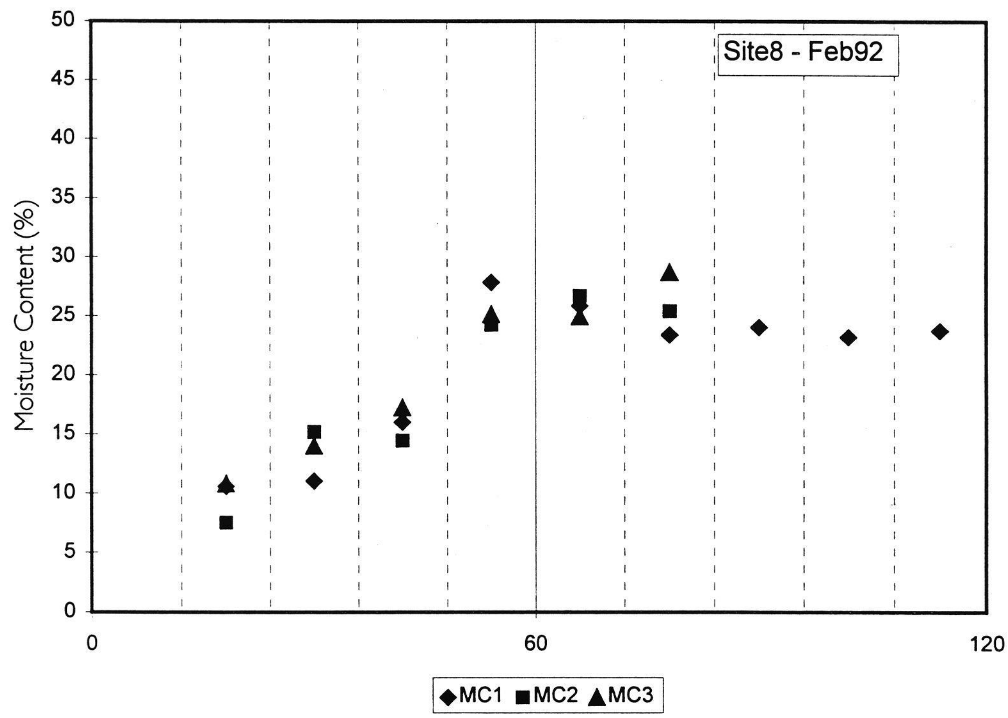
Appendix D - SITE 6. **Actual Moisture Variation with Depth During Different Times of the Year.**



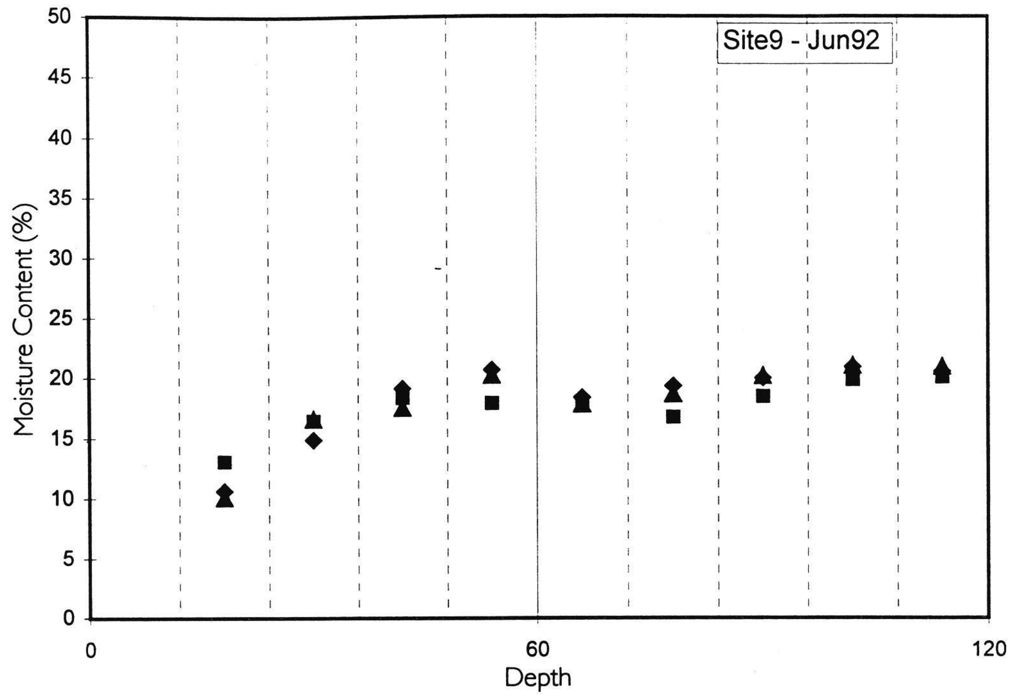


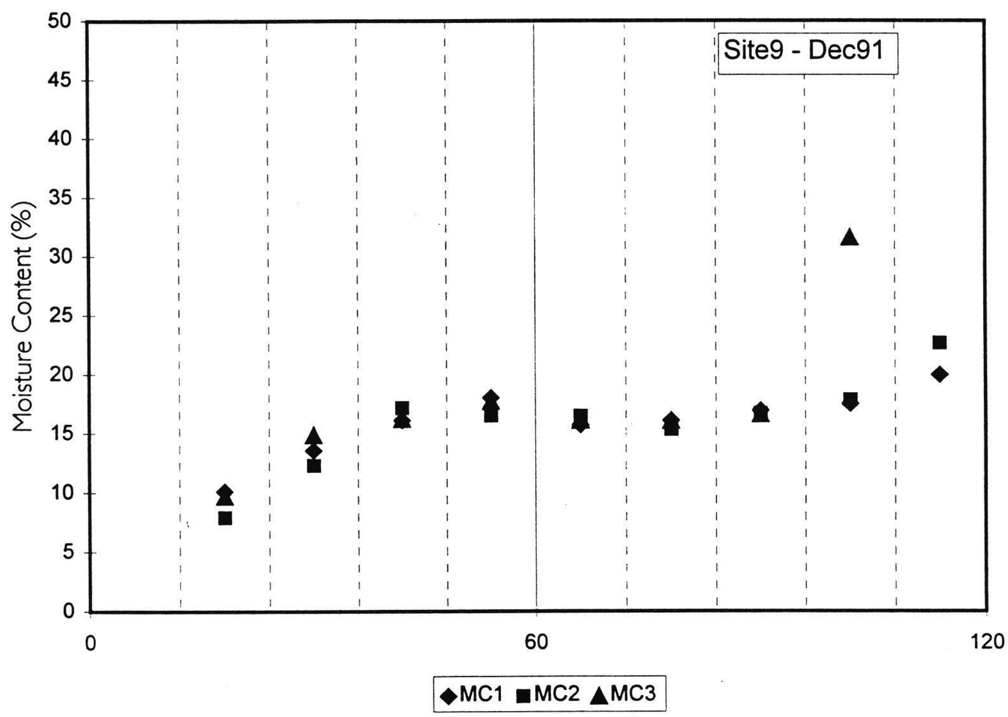
Appendix D - SITE 7. **Actual Moisture Variation with Depth During Different Times of the Year.**



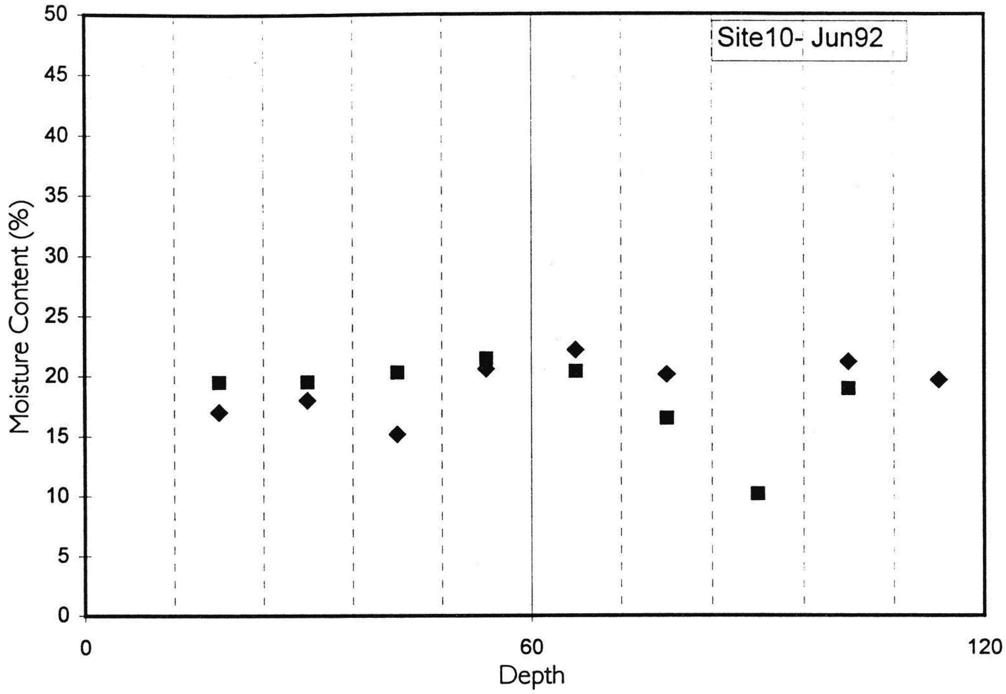


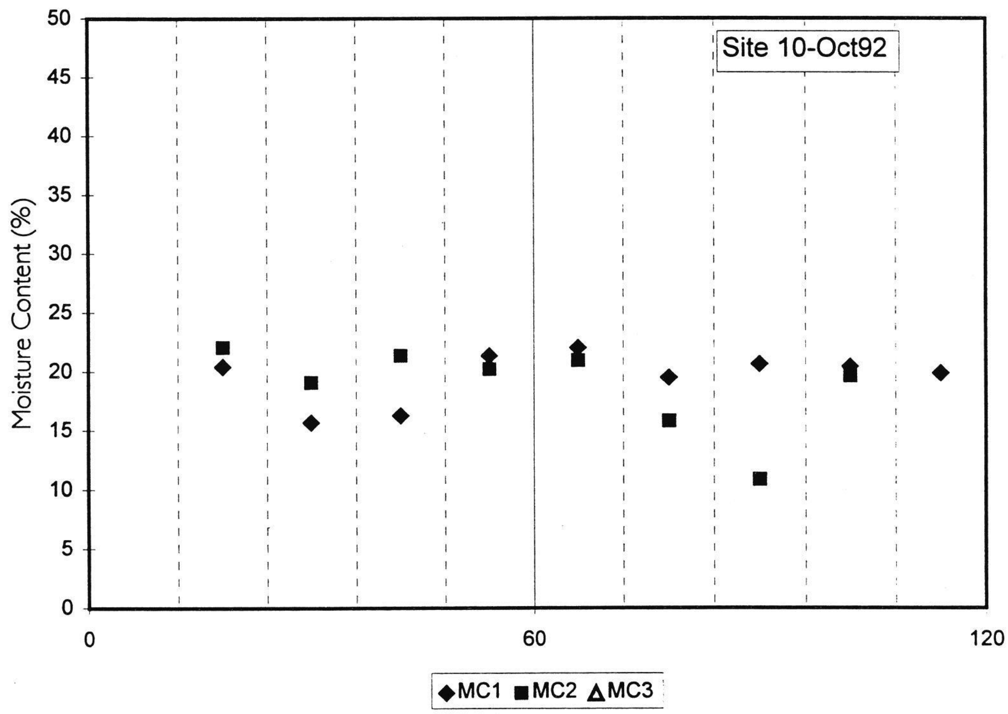
Appendix D - SITE 8. **Actual Moisture Variation with Depth During Different Times of the Year.**



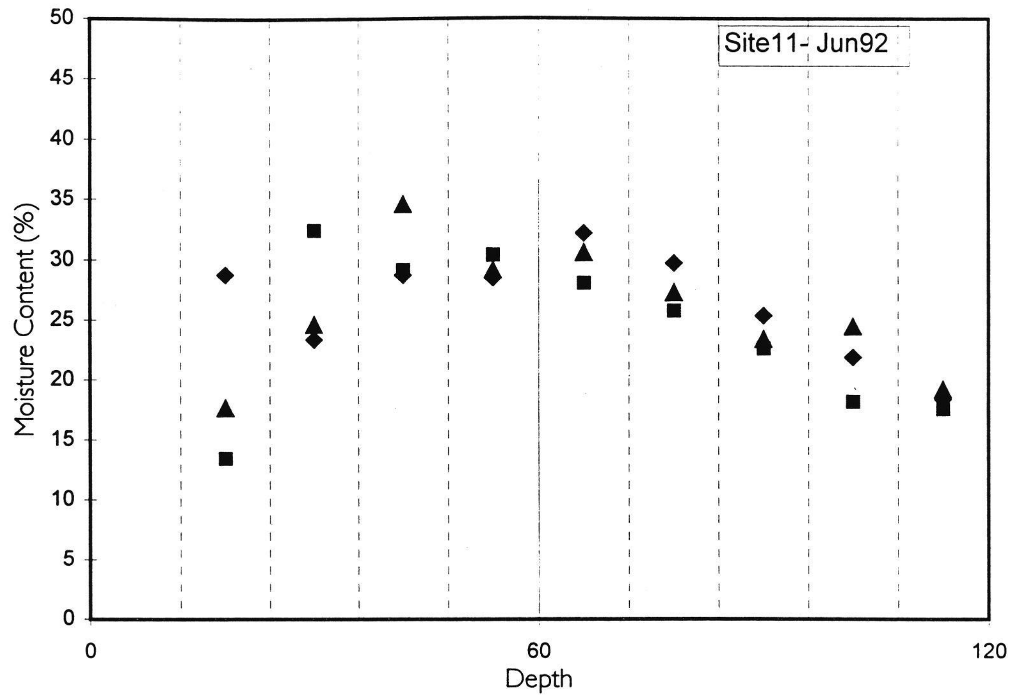


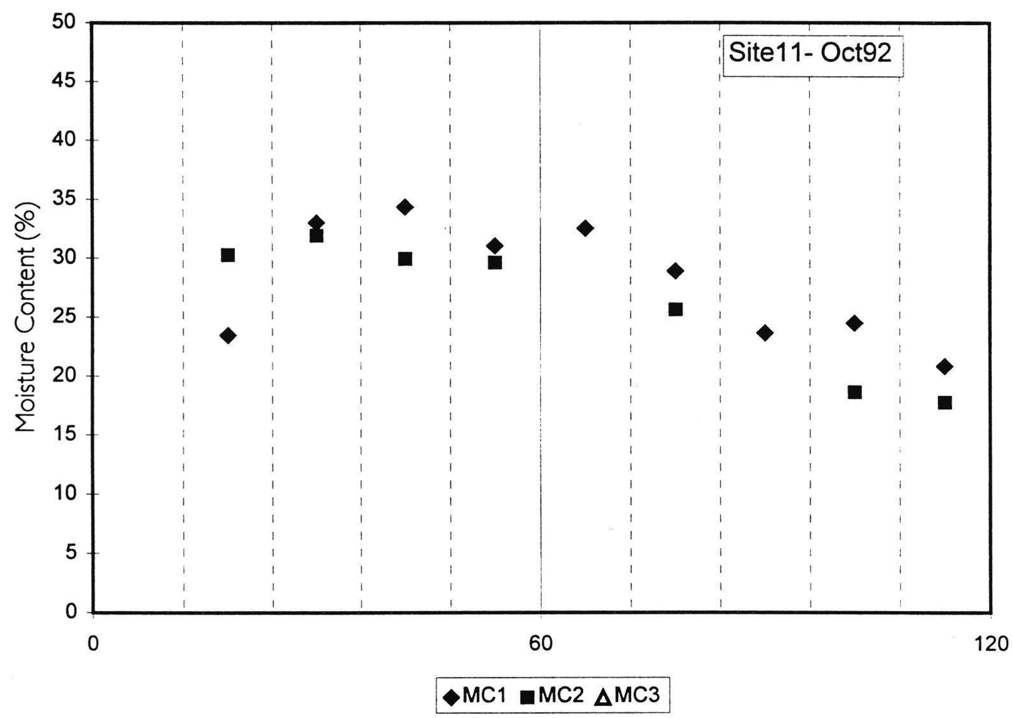
Appendix D - SITE 9. Actual Moisture Variation with Depth During Different Times of the Year.



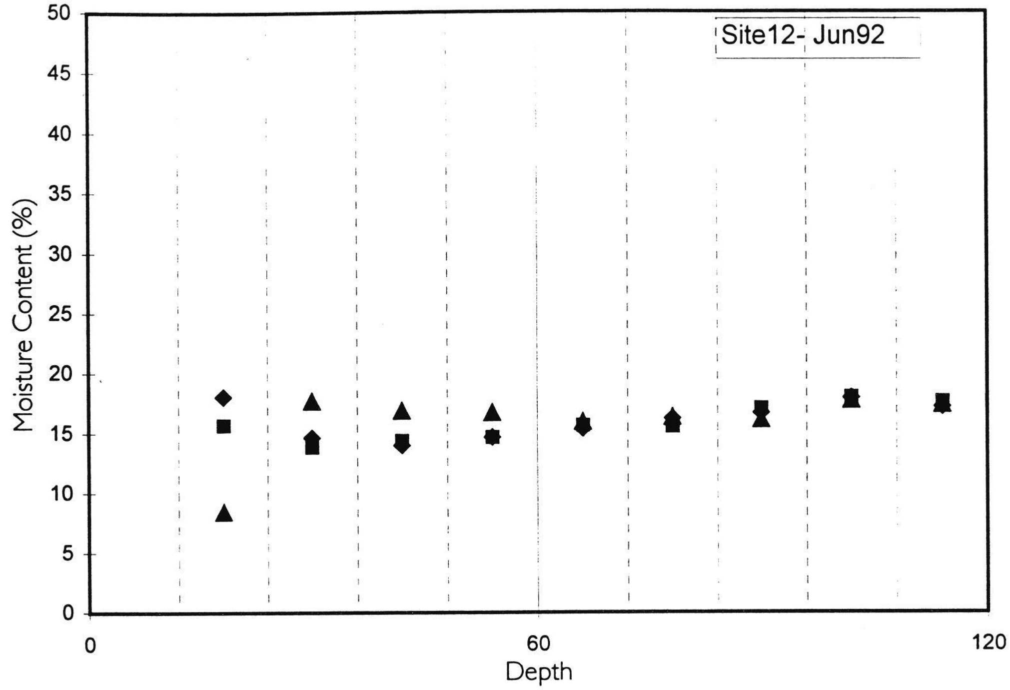


Appendix D - SITE 10. **Actual Moisture Variation with Depth During Different Times of the Year.**





Appendix D - SITE 11. **Actual Moisture Variation with Depth During Different Times of the Year.**



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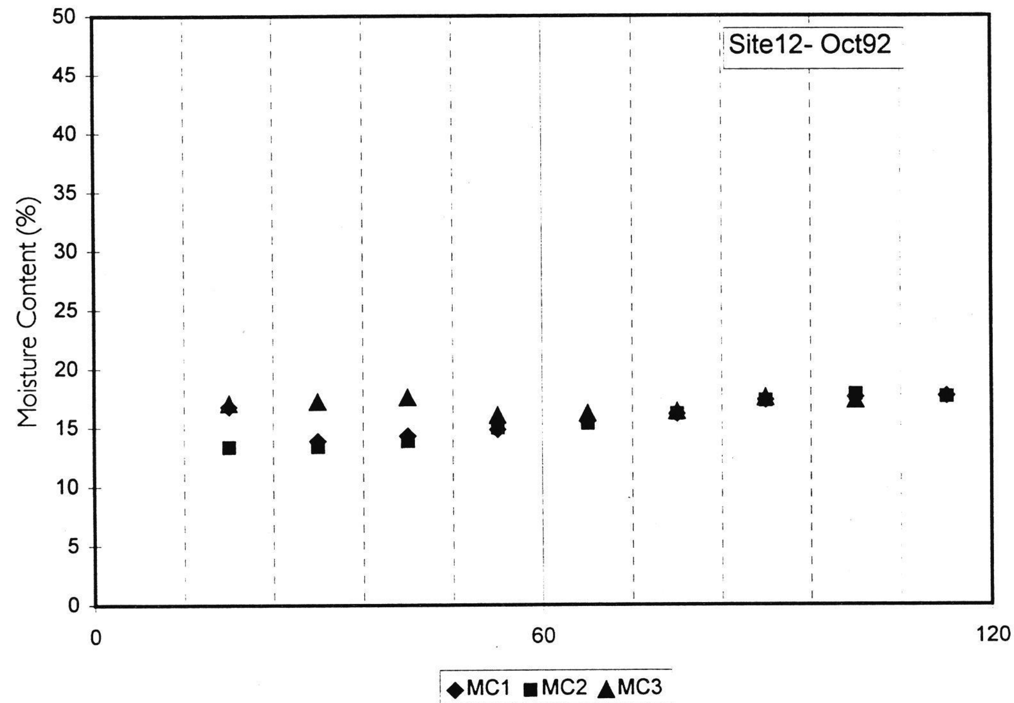
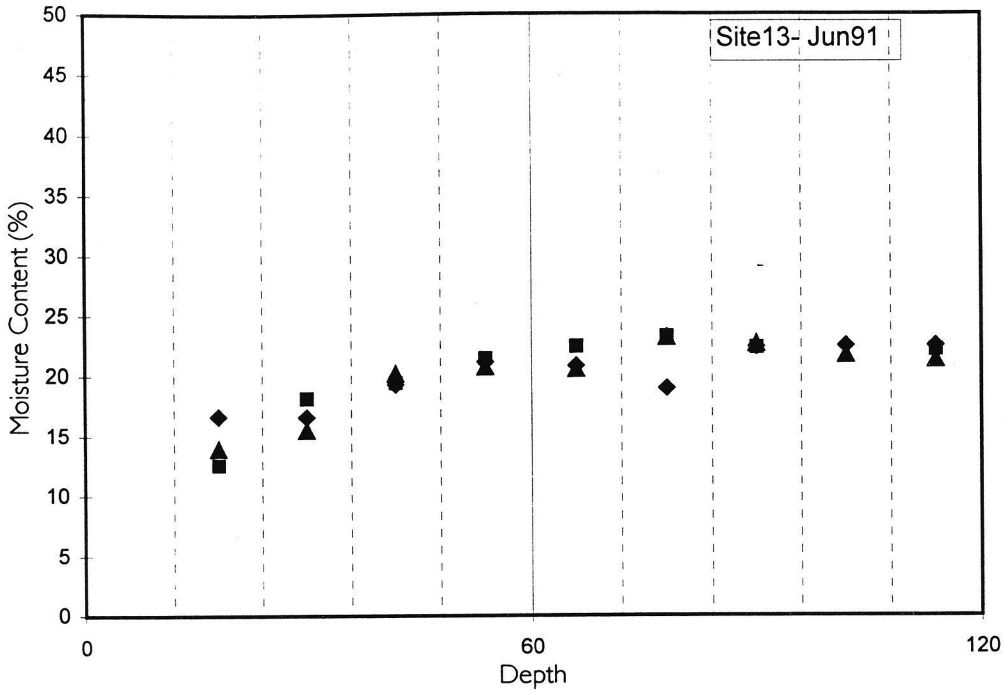
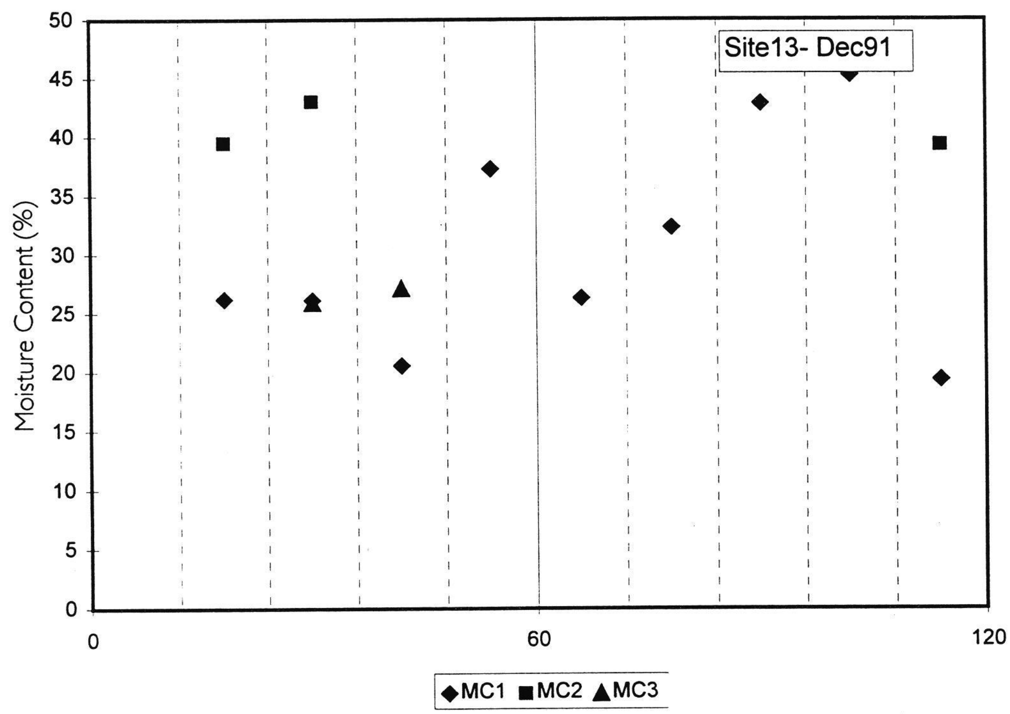
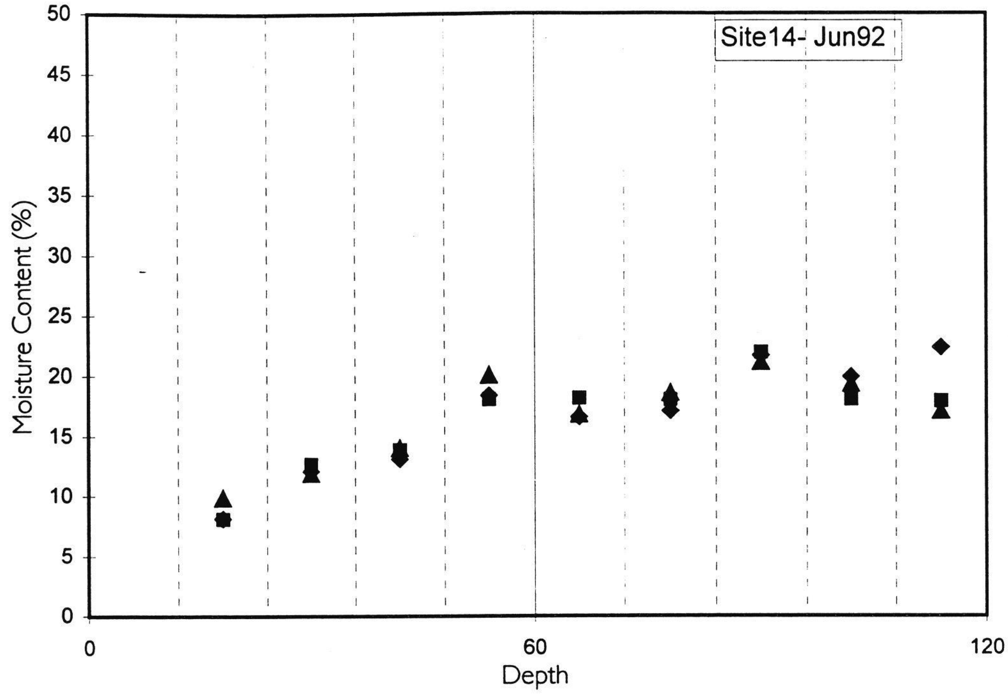


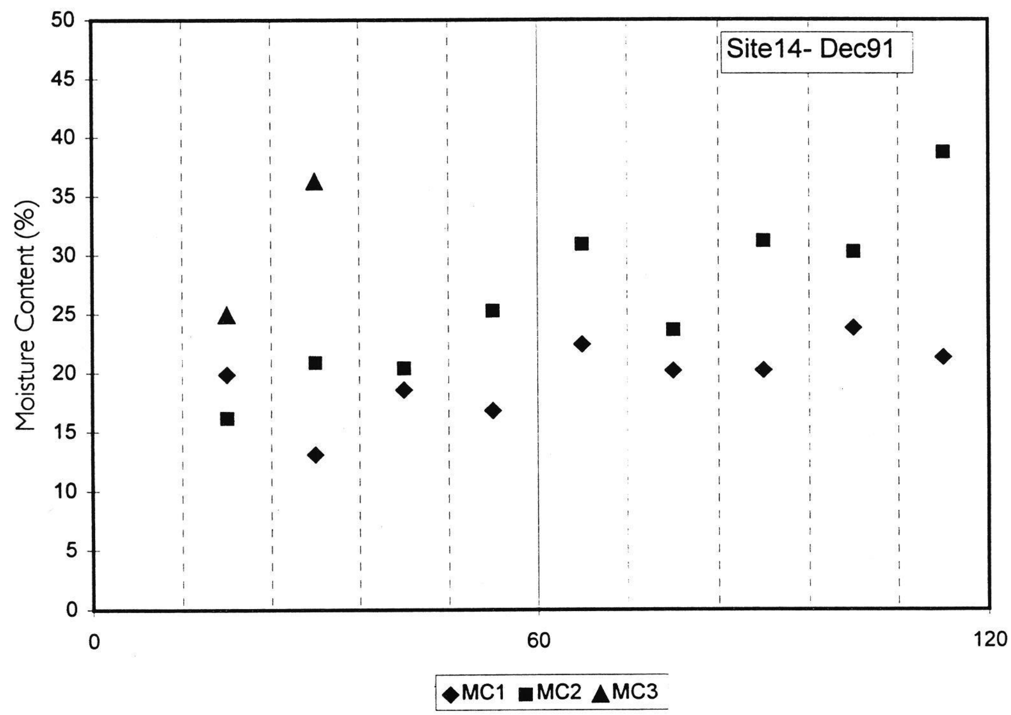
Appendix D - SITE 12. **Actual Moisture Variation with Depth During Different Times of the Year.**



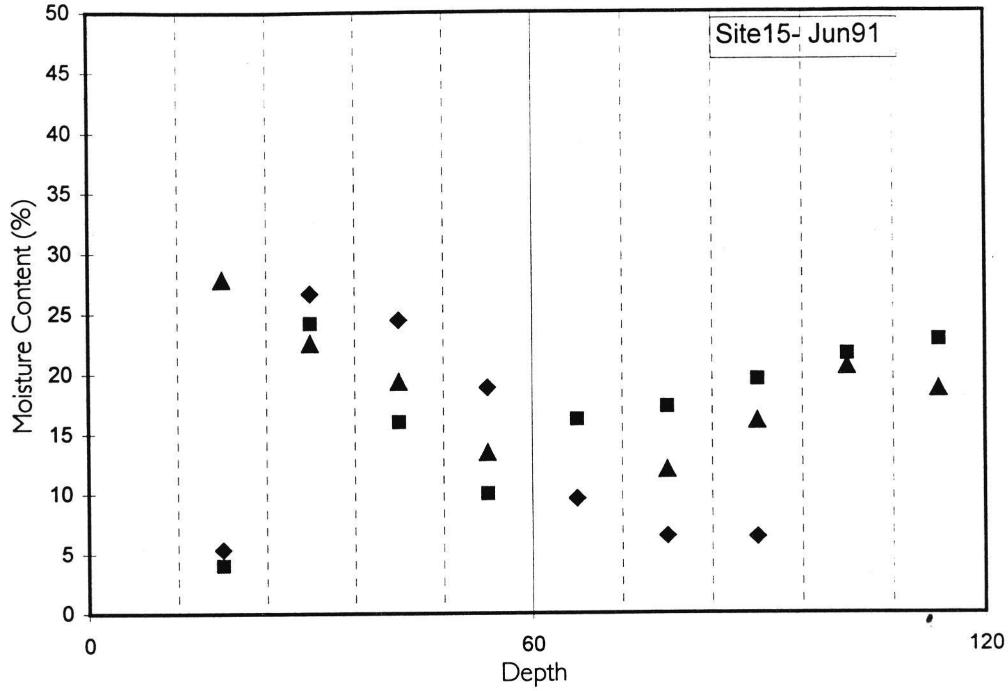


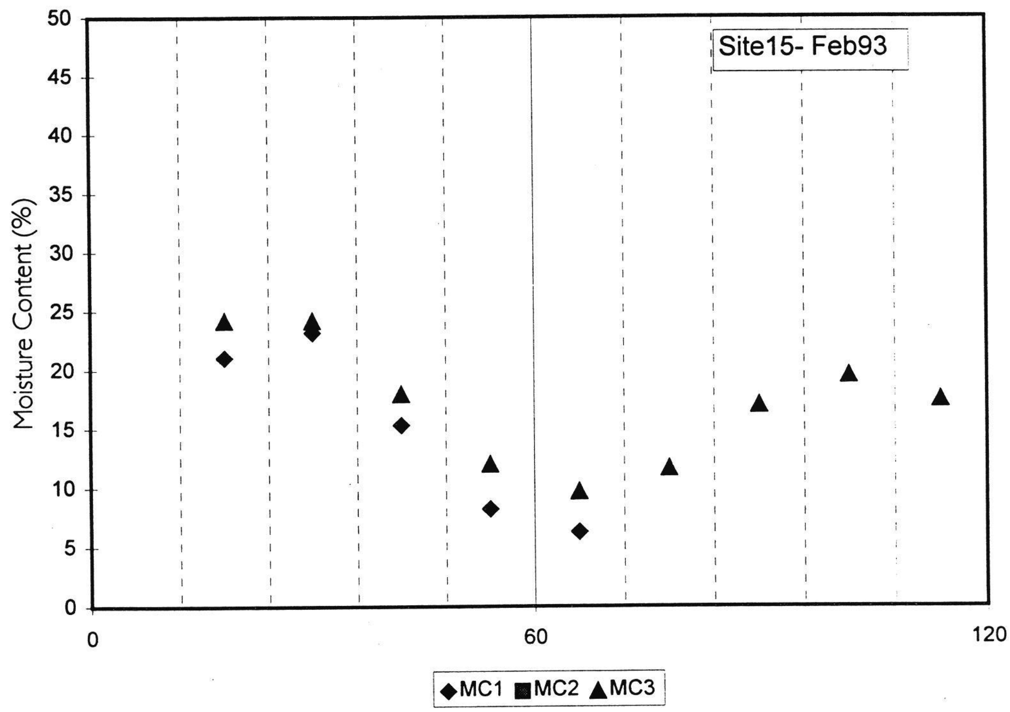
Appendix D - SITE 13. **Actual Moisture Variation with Depth During Different Times of the Year.**



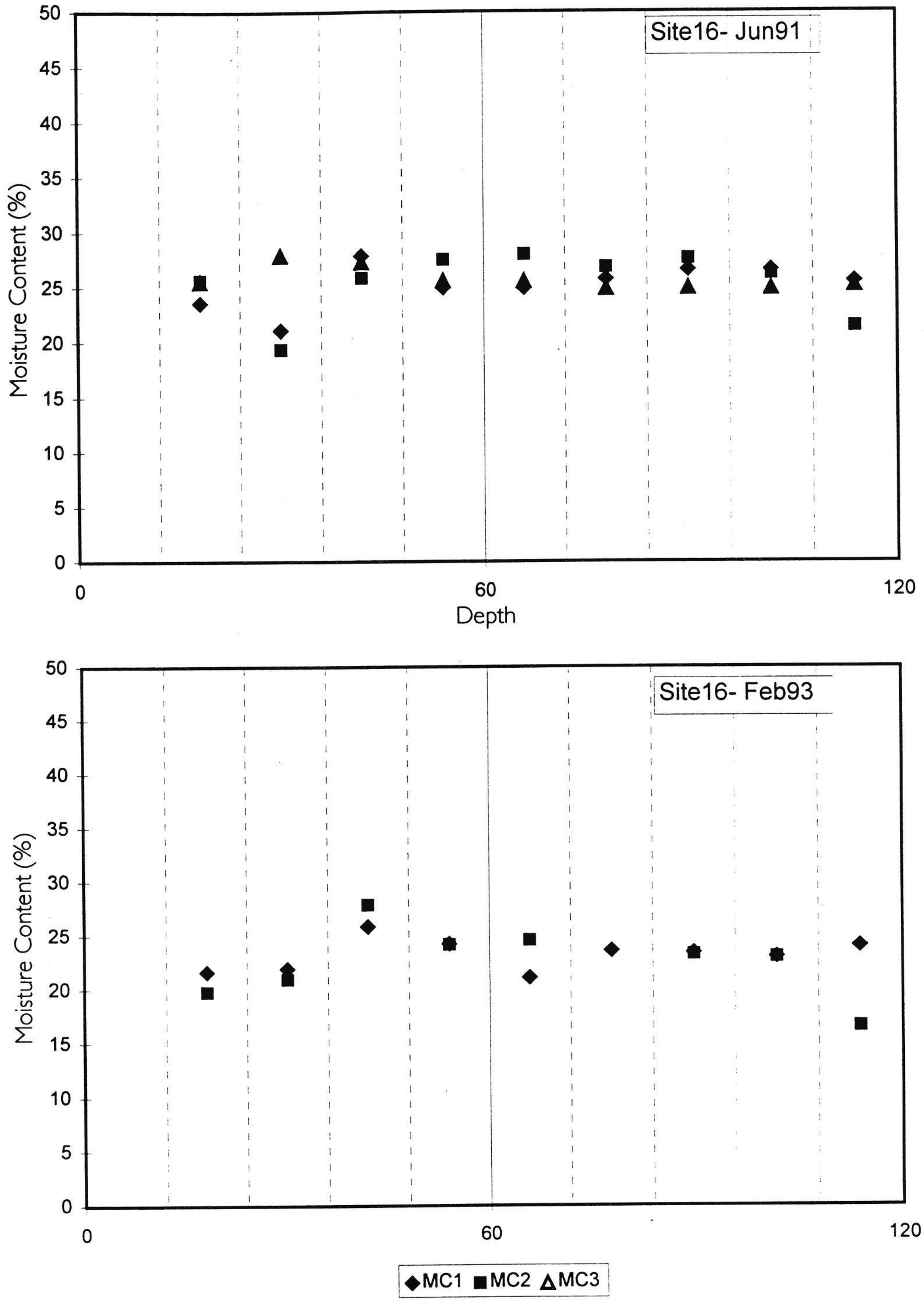


Appendix D - SITE 14. **Actual Moisture Variation with Depth During Different Times of the Year.**

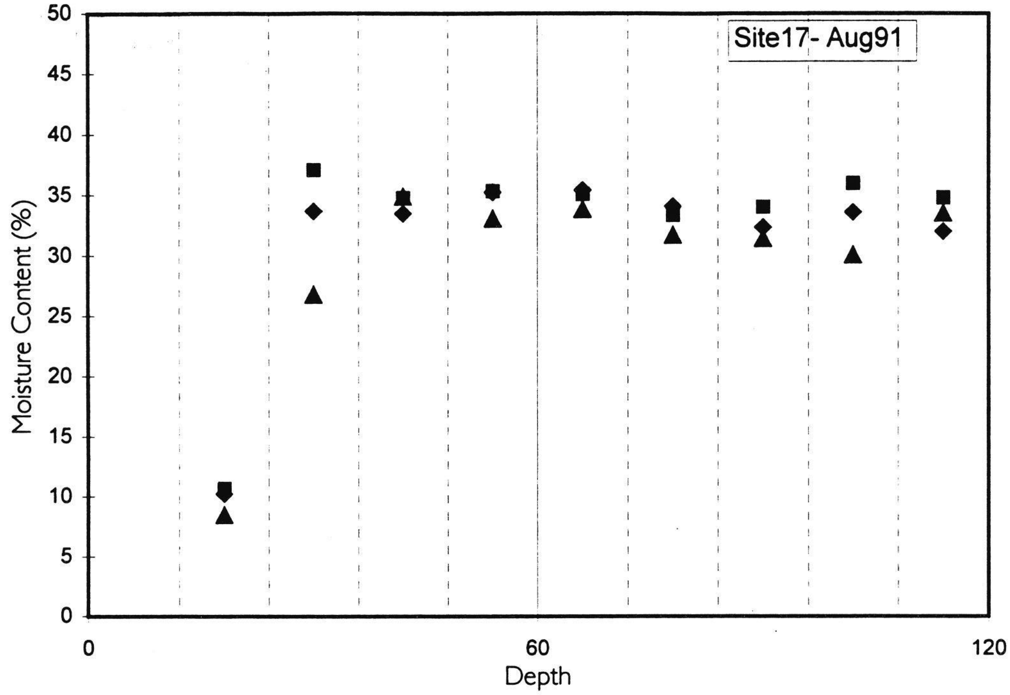




Appendix D - SITE 15. **Actual Moisture Variation with Depth During Different Times of the Year.**



Appendix D - SITE 16. **Actual Moisture Variation with Depth During Different Times of the Year.**



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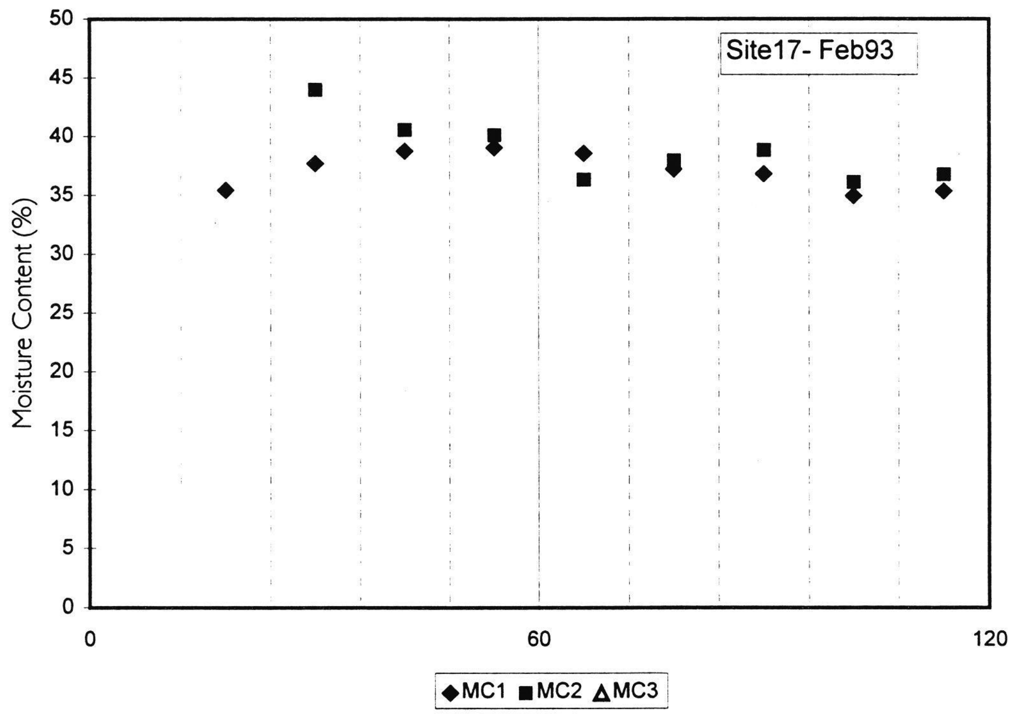
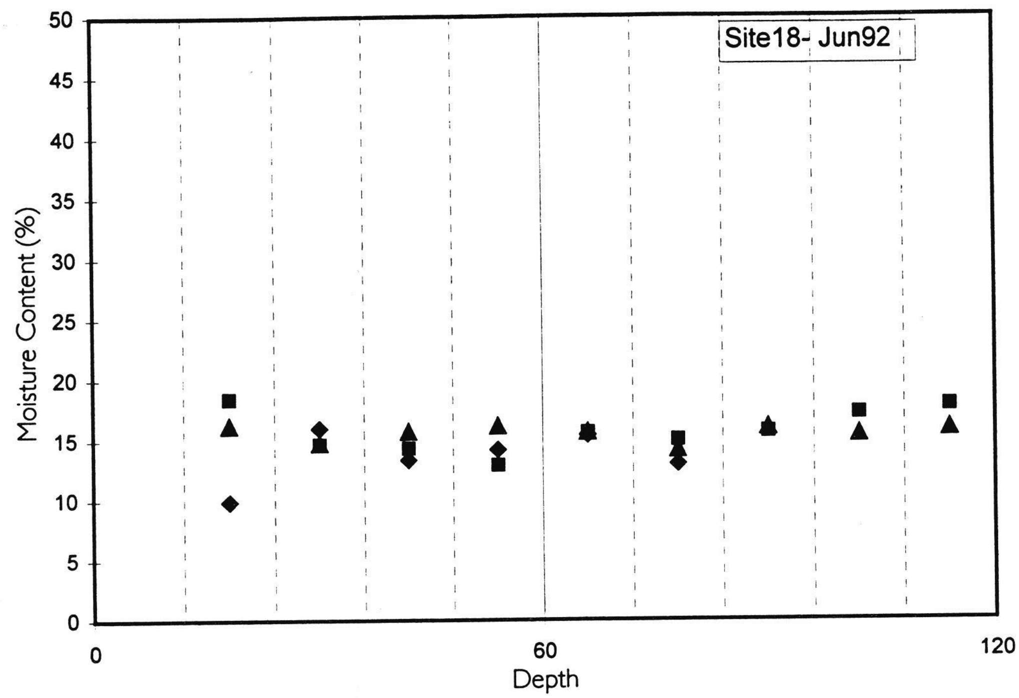
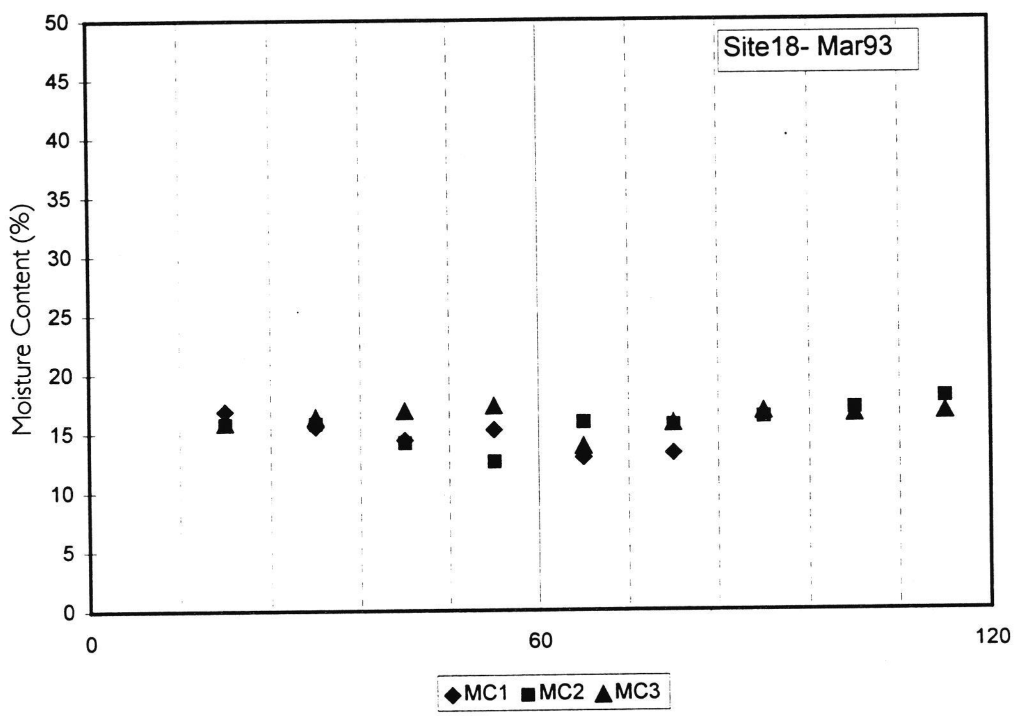


Appendix D - SITE 17. **Actual Moisture Variation with Depth During Different Times of the Year.**





Appendix D - SITE 18. **Actual Moisture Variation with Depth During Different Times of the Year.**