To the Graduate Council:

I am submitting herewith a thesis written by James W. Andrew entitled "Resolving Seasonal Fluctuations in Flexible Pavement Subgrade Response." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Civil Engineering.

N. Mike Jackson, Major Professor

We have read this thesis
And recommend its acceptance:

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Accepted for the Council:

Associate Vice Chancellor and
Dean of The Graduate School

RESOLVING SEASONAL FLUCTUATIONS IN FLEXIBLE PAVEMENT SUBGRADE RESPONSE

A Thesis Presented for the Master of Science Degree

The University of Tennessee, Knoxville

James W. Andrew
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DEDICATION

This manuscript is dedicated to my mother and father, Jean and John Andrew, who gave me the opportunity to dream; and to my wife, Marybeth, and my children, Alex and Galen, who help fulfill my dreams.

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ABSTRACT

The ever-increasing level of traffic on roadways in this country requires improved design techniques that will provide durable and economical pavement systems. As virtually every pavement system is built from the subgrade up, the importance of characterizing the capability of the subgrade to sustain dynamic traffic loading is paramount to efficient design. Resilient modulus (M_R) is the material property that is currently used in many flexible pavement design methods to represent the recoverable portion of the strain response of the subgrade to the stress of continuous traffic loading.

The properties of subgrade soils, including M_R, can vary regionally as well as seasonally. Regional variation is the result of variation in soil type. Seasonal variation results from seasonal changes in environmental conditions; specifically moisture and temperature. These variations must be accounted for in the process of selecting a design value of M_R.

The Tennessee Department of Transportation (TDOT) has committed to the study of environmental effects on flexible pavement systems by instrumenting pavement sections in each of the four different regions of Tennessee. The instruments will monitor temperature and moisture content in the various pavement system layers. In addition, a weather station has been installed at each site to collect climatological data. Monthly Falling Weight Deflectometer (FWD) tests are performed to assess the condition of the pavement system. Seasonal variation of subgrade M_R, backcalculated from FWD test data, has been correlated to environmental changes at each of the Tennessee test sites.

Seasonal changes in moisture content of the soil subgrade were more closely related to air temperature than precipitation. Also, changes in air temperature had the most significant effect on M_R at the four Tennessee sites during this analysis period. A method for predicting seasonal fluctuations in M_R and determining a design value is proposed.

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1. INTRODUCTION

The primary goal of roadway design is to provide a smooth and durable riding surface. As all roadways basically rest directly on soil, an important aspect of the design process is the protection of the roadbed soil from excessive deformation. Deformation of the roadbed can lead to fatigue cracks, potholes, and rutting in the pavement surface (Yoder & Witczak, 1975). Cracks, holes and ruts in the surface are an indication of decreasing serviceability. Evaluating the capacity of a soil to withstand dynamic traffic loads is complicated by the variation in soil types as well as seasonally changing environmental conditions that can affect the behavior of subgrade soils.

Resilient modulus (M_R), a measure of dynamic elasticity, is the property that best characterizes the ability of the subgrade to withstand repeated loads without permanent deformation (Seed et al., 1962). Laboratory tests to determine the modulus of a roadbed soil are complicated by the need to establish the most appropriate conditions that will simulate traffic loading. Furthermore, the density and moisture content of the soil will influence the test results, and these in-situ properties are variable.

In consideration of the difficulty associated with measuring M_R, attempts have been made to correlate values of M_R with other material properties that are easier to

measure. These attempts have resulted in various methods that require experience and judgement in selecting realistic values from a wide range of parameters.
In-situ pavement condition can be interpreted using various non-destructive testing devices. One such device is the Falling Weight Deflectometer (FWD). A force designed to simulate traffic loading (a falling weight) is imposed upon the pavement surface and the surface deflection at the centerline of the force and at several radii out from the centerline are measured by the FWD device.

In order to incorporate the elasticity of the subgrade in the design of a flexible pavement, a single value must be selected that best represents the mean or weighted mean subgrade response for every season of the year. Understanding the relationship between environmental conditions and pavement response will lead to a more rational approach to characterizing the seasonal variation of pavement material properties.

Four sections of flexible pavement, one in each of the four geographical regions across the state of Tennessee, have been instrumented to monitor moisture content and temperature in the various pavement layers. A weather station has also been installed at each of the sites to record environmental conditions. Subsurface investigations were conducted at each site to document the approximate depth of the various layers and the types of soil encountered. FWD testing has been performed monthly to evaluate the condition of the pavement at each site.

At this time, data has been collected for about 16 months at two of the sites, and almost 12 months at the other two sites. The objectives of this study include investigating the seasonal change of environmental conditions, evaluating the influence these conditions have on pavement system performance, and developing a design procedure that incorporates the influence of these environmental conditions. Analysis of the data collected so far indicates that the pavement system response varies seasonally at each site in a manner that corresponds to seasonal changes of environmental factors, particularly air temperature.

Seasonal variation of M_R can be predicted using models developed from laboratory testing of subgrade soils, or a sinusoidal function developed from the results of FWD testing. Seasonal changes of air temperature follow a sinusoidal-shaped pattern in Tennessee. Since air temperature would seem to have the most significant environmental effect on M_R in this study, a sinusoidal function can be developed to predict seasonal fluctuations in subgrade response.

With the seasonal fluctuations established, factors representing the damage to the pavement system accumulated during each season can be assigned to those seasons. Establishing these factors precedes the determination of a weighted mean value of M_R that represents the damage to the pavement system incurred throughout the year. The weighted mean value can be used for the most economical design or renovation of a flexible pavement system.

2. BACKGROUND

Flexible Pavement Design

Roadways built using relatively thin layers of aggregate material held together with a bituminous binder are considered flexible pavements. The first such roadway constructed in the United States was in Newark, New Jersey in 1870. The first hot mix asphalt sheet pavement was constructed in 1876 in Washington, D.C. (Huang, 1993). Early designs for flexible pavements involved trial and error, and until sometime after 1920, pavements overlying all different types of roadbed soils used a similar pavement thickness determined mostly from experience and rule-of-thumb (Yoder & Witzcak, 1975).

Between 1920 and 1940, the types of soils used as foundations for engineered structures gained a great deal of attention. Soil classification systems were developed, however they basically described soil characteristics considered for static structural foundations. Roadbeds, especially those under flexible pavement systems, are subjected primarily to dynamic rather than static loads. The rapid increase in aircraft loads and heavy truck traffic during WW II and into the 1950's resulted in considerable pavement damage, and inspired improved techniques for designing and managing pavement systems (Barber, 1949; and Burmister, 1943, 1945, 1958).

Test road sections built in the United States between 1920 and 1960 were analyzed after extensive traffic loading. Empirical equations were developed from the performance of these test roads. The American Association of State Highway Officials (AASHO) published an interim pavement design guide in 1961 based upon the findings from the AASHO Road Test conducted near Ottawa, Illinois in the late 1950's and early 1960's.

The early form of the empirical equation developed from the results of the AASHO road test included a regional factor to compensate for climatic conditions other than those experienced at the Ottawa, Illinois test site. While the value of the regional factor had a significant effect on the design thickness, selecting the proper value to be used was based for the most part upon the judgement of the design engineer (Yoder & Witczak, 1975). The 1986 interim version of this equation did not include a regional factor (AASHTO, 1986a). Instead, the design engineer, in order to account for environmental conditions, could modify the subgrade quality input to the equation through a relative damage value assigned to the subgrade.

The most recent version of this guide is the 1993 American Association of State Highway and Transportation Officials (AASHTO) Guide for Design of Pavement Structures. The AASHTO equation incorporates the Structural Number (SN), representing the structural capacity of the combined pavement layers, with variables for standard deviation (Z_R), standard error of prediction (S_o), and subgrade modulus of resilience (M_R) into flexible pavement design. The empirical AASHTO equation predicts the number of equivalent 18-kip single axle loads (W_{18}) that a roadway can withstand before the pavement serviceability becomes unacceptable. Baus, et al. (1989) conducted a sensitivity analysis of the 1993 AASHTO flexible pavement design equation with respect to the input variables noted above. This analysis concluded that the AASHTO flexible pavement design equation is most sensitive to variations of M_R, the subgrade variable.

A mechanistic approach to pavement design was proposed as early as 1950 (Kerkhoven and Dormon, 1953). Analyzing the mechanical behavior of the pavement materials led to establishment of failure criteria for the materials in each layer of the system. These criteria are used to predict pavement life cycle in terms of functionality or serviceability of the pavement, as opposed to structural failure. One major advantage of a mechanistic approach is the ability to incorporate new types of materials and procedures into the design.

A mechanistic-empirical approach combines the predicted performance using material properties with field verification of the actual pavement performance, and then the empirical data is correlated with the mechanistic data to further refine the initial design assumptions. The 1993 AASHTO Guide recognizes the advantages of a mechanistic-empirical approach, and incorporation of M_R into the AASHTO flexible design equation reflects a mechanistic trend.

Characterizing the Subgrade

The quality of a soil as roadbed material has been quantified as soil support value (SSV), California Bearing Ratio (CBR), resistance (R) value, and most recently as resilient modulus (M_R). SSV is an index number between 1 and 10, arbitrarily selected by the pavement design engineer to relate a particular soil to the results from the AASHO Road Test. The AASHO soil was assigned an SSV of 3, and high quality crushed stone was assigned a value of 10. The CBR test also identifies high quality crushed stone at the top of the numerical scale. For a CBR, the force required to penetrate a piston into the tested soil at a standard rate is reported as a ratio of the force required to penetrate high quality crushed stone to the same depth. The R-value is a measure of the frictional resistance of unbound materials to monotonic loading in a triaxial test apparatus, and is reported as the ratio of maximum shear stress to principal stress difference. M_R is the ratio of cyclical axial deviator stress to recoverable axial strain. In the M_R test, soil samples are tested in the laboratory in a triaxial apparatus that can apply horizontal confining pressure, repeated axial stress, and measure the recoverable axial deformation. AASHTO Test Method T274-82 (AASHTO, 1986b) describes this laboratory test procedure.

Several conditions can influence the results of tests to determine M_R. These include magnitude of confining pressure and deviator stress, rate and duration of deviator stress, moisture content and density of the soil sample tested. The moisture content and density of the specimen are usually selected to represent in-situ conditions, however in-situ soil moisture content may vary with time (Russam, 1965; and

Vaswani, 1975). The variation of M_R resulting from changes in moisture content is well documented in the literature (Seed, et al., 1962; Yoder and Witczak, 1975; and Thompson and Robnett, 1976). For pavement design purposes, one value of M_R must be selected that best represents the seasonally variable condition of the subgrade.

Although M_R may be the best measure of subgrade elasticity, the test procedure is complicated and time-consuming to perform. In consideration of the difficulty associated with M_R tests, attempts have been made to correlate M_R with CBR and SSV data. Unfortunately, CBR and SSV values do not reflect the stress dependent nature of subgrade soils. The resilient modulus of fine grained soils generally decreases with increasing deviator stress, while the modulus of coarse grained soils tends to increase as the sum of the principal stress increases (Yoder and Witczak, 1975). Correlating M_R with index properties is an alternative method of estimating subgrade modulus in lieu of complicated laboratory test procedures.

Hudson et al. (1994) correlated index properties and AASHTO soil classifications of Tennessee soils with triaxial resilient modulus test results. Based on this work, M_R at optimum can be estimated using the laboratory-measured properties of plasticity, liquidity, clay content, optimum moisture content, and saturation. Drumm et al. (1997) went on to show that if soil classification and seasonal changes in degree of saturation are known, the seasonal changes in M_R can be estimated. Degree of saturation (S), the ratio of the volume of water in the soil to the total volume of void spaces in the soil, is more closely related to the elastic property of a soil than moisture content, the ratio of the mass of water in the soil to the mass of the solids in the soil. Degree of saturation is a function of the moisture content and the density of the soil. Thompson and Robnett (1976) suggested that the relationship between resilient modulus and degree of saturation is nearly linear, while the relationship between resilient modulus and moisture content is nonlinear. This was confirmed by Drumm et al. (1997) and was the basis of their adjustment procedure.

Pavement Condition Evaluation

Several factors influence the rate at which pavements deteriorate. The rate of deterioration varies from one section to the next and along the length of a given roadway. Evaluating the current condition of a pavement is an important and complicated process. Pavement condition is generally evaluated in terms of either serviceability or structural capacity. Serviceability, the quality of the riding surface, is basically related to pavement roughness, however distress conditions such as rutting and cracking may also be included in this rating. Structural capacity is more a function of the materials that make up the layers of the pavement system. Evaluating pavement condition for structural capacity usually results in the determination of a value that represents the quality of the pavement materials. As this study is concerned with variability in the quality of the pavement subgrade, the focus herein will be on evaluations of structural capacity.

Non-destructive testing (NDT) of in-situ pavement condition has the obvious advantage of leaving the system intact after the test procedure. NDT procedures basically consist of some form of input to the pavement system, such as a force or a wave, and a measurement of the response. One of the most widely used NDT procedures employed to evaluate pavement condition is the Falling Weight Deflectometer (FWD).

The FWD achieves a transient force impulse with an adjustable weight that is dropped from a variable height onto a flexible circular plate on the pavement surface. The FWD is generally recognized as the best simulation of a dynamic traffic load (Ullidtz, 1987). A row of sensors measures the vertical deflection of the pavement surface at the center of the drop and at several radii away from the centerline of the dropped weight. Pavement condition can be interpreted from the measured deflections by calculating a modulus value for each of the pavement layers. This process is referred to as backcalculation.

One approach to backcalculation is to compare theoretical deflections predicted from a pavement model with the actual deflections, and then adjust the parameters of the model until the theoretical deflections match the measured deflections within a specified margin of error. Modeling the pavement system to predict response involves a number of simplifying assumptions about material properties in each layer. Layers are generally assumed to be homogeneous and confined to the linear elastic range of stress response. The unbound granular layer demonstrates stress-sensitive anisotropic behavior (Tutumluer & Thompson, 1997). Fine-grained subgrade soils are known to be non-homogeneous and sensitive to variations in moisture as well as stress (Seed et al. 1962).

Asphaltic concrete pavements increase in stiffness immediately following construction. This increase in stiffness is typically attributed to hardening or aging of the asphalt, (Bell et al., 1994), densification of the pavement due to traffic loading, (Ownby, 1998), and densification of the unbound granular layers in a pavement system (Barksdale, 1991). The combination of these early life events will result in a net increase in pavement modulus during the initial years. This behavior tends to further complicate the evaluation of the subgrade response during field surveys as the early time stiffening initially conceals the overall deterioration of the pavement. The process of backcalculating pavement material modulii from measured deflection basins requires the guidance of an expert analyst who can recognize anomalies, and is subject to systematic as well as random errors (Lytton, 1989).

The Tennessee Department of Transportation analyzes FWD data with the commercially available computer program DARWin (*Design, Analysis, and Rehabilitation for Windows*) (AASHTOWARE, 1997). DARWin employs the equations presented in Chapter 5, Sub-section 5.4.5, of the 1993 AASHTO Guide for Design of Pavement Structures to determine M_R and the Effective Pavement Modulus (E_p). This approach estimates M_R based on the assumption that deflections measured at a sufficient distance from the FWD loading can be attributed exclusively to subgrade deformation. As the distance from the center of the drop increases, the magnitude of the surface deflection decreases, and error of measurement increases (Bentsen et al., 1989). Therefore, to minimize the distance required from the centerline to the point where only the subgrade influences the deflection, the radius of the stress bulb at the top of the subgrade is estimated, and the deflection of the next nearest sensor is used to calculate the response of the subgrade. It is important to note here that stress imparted to the subgrade from the FWD device decreases with distance from the center of loading. The 1993 AASHTO Guide notes the significance of decreasing stress levels when estimating the modulus of stress-sensitive materials.

The 1993 AASHTO Guide also suggests that subgrade response to FWD testing is not influenced by pavement temperature. However, as the temperature of the flexible pavement rises, the pavement modulus decreases, and more stress is transmitted through the pavement to the subgrade. Increasing stress will result in decreasing resilient modulus for stress softening materials such as cohesive subgrade soils. Long, et al. (1997) determined the influence of temperature variation on FWD backcalculated subgrade modulus to be more significant than moisture content at two of four pavement sections analyzed in a study in Kansas.

The values of subgrade modulus determined from FWD deflections have been shown to exceed results determined from laboratory tests on similar soils by a factor on the order of 3 (AASHTO, 1993). The significant difference between pavement layer modulii values estimated from field data and the modulus values calculated from the material properties measured in the laboratory may be related to differences in confining stress and the variability of subgrade materials in the field (Von Quintus and Killingsworth, 1998). Although the Tennessee Department of Transportation applies a correction factor of 0.33 to subgrade modulus values estimated from FWD tests, no correction factor has been applied to the FWD data analyzed in this study. Therefore the M_R values reported herein may be on the order of 3 times greater than values obtained through laboratory testing and estimates of M_R based on laboratory results.

Previous Studies

Concern for the influence of environmental factors on the performance of pavement materials has inspired several investigations of this problem. Sophisticated instruments have been employed to monitor in-situ subgrade temperature and moisture content, as well as stress response of the pavement system. Climatic conditions, especially precipitation and air temperature, are available for most regions from the weather service, or can be measured specifically at the site under study.

Russam (1970), with the British Road Research Laboratory, studied the variation of moisture content in the subgrade under impermeable concrete slabs and in the exposed soil adjacent to the experimental slabs. Russam (1970) also investigated moisture conditions under airfields in arid climates, and under roadways in tropical climates. This investigation concluded that soil moisture conditions remain relatively stable when the ground is covered with a semi-impermeable surface. Seasonal effects have less influence on soil under the roadway than on the uncovered soil. Russam (1970) suggested that soil moisture under an impermeable surface is most influenced by the depth to the water table. He further concluded that soil suction can affect the water content 20 feet above the water table in clay soils, 10 feet in sandy clay or silt, and 3 feet in sand. When the water table is deeper than this "effective" depth for the soil type, the pavement subgrade soil will eventually reach an equilibrium moisture content that is not influenced by seasonal change.

In Virginia, Vaswani (1975), with the Virginia Highway and Transportation Research Council, investigated subgrade moisture content and temperature under pavements that ranged from new to 12 years old. The Virginia study found that the moisture content of the subgrade increased rapidly through the construction period, continued to increase, although less rapidly, for several years after the completion of the roadway, and after a period of about 10 years, the moisture content of the subgrade changed very little. Vaswani also established fluctuations in subgrade moisture content related to subgrade temperature. After the post-construction increase of moisture content, small changes in subgrade moisture were attributed to the temperature gradient corresponding to depth of subgrade soil. The temperature of the subgrade was higher at shallow depths in the spring and summer, and higher at deeper depths in the fall and winter.

Bandyopadhyay and Frantzen (1983) employed a computer program to establish a direct correlation between precipitation and change of subgrade modulus at two sites in Kansas. The U. S. Weather Bureau provided precipitation history, and the subgrade modulus was estimated from deflections measured from NDT procedures performed weekly using a Dynaflect cyclic force generator. Deflections measured at the outermost sensor, located 48 inches from the center of the load, are considered an indirect measure of subgrade modulus for this NDT device. This investigation demonstrated that the change of subgrade response resulting from precipitation events might lag the event by as much as three weeks.

Newcomb et al. (1989) studied pavement performance evaluations conducted in the states of Washington and Nevada. Long-term monitoring of FWD tests performed at 16 sites in Washington and 27 sites in Nevada will be used to contribute to the development of mechanistic design procedures by each of these states. An analysis of pavement material modulus values in Washington demonstrated that the granular base course exhibited much greater seasonal variation than the subgrade. In Nevada the variations of subgrade modulus were found to be greater along the length of the test sections than they were seasonally.

Bentsen et al. (1989) investigated the accuracy, reliability and repeatability of seven different NDT devices. For most of the devices, including the FWD, the accuracy was around 10%, with a range from about 2% up to 20%. The coefficient of variation for short-term repeatability was between 0.3% and 2.6%. The short-term repeatability consisted of 25 tests performed in as short a period as possible by each NDT device. Reliability was measured as the long-term repeatability, with several tests performed using each device over a period of three days. The range in coefficient of variation for the long-term repeatability was 2% to 9%.

Lindly and White (1989) collected data from FWD testing of 15 flexible pavement sites in Indiana during 1986. The testing was performed during the spring thaw season and the summer season. This research was focused on determining an effective roadbed soil resilient modulus, as outlined in the 1986 AASHTO Interim Guide. A comparison of the mean values from the two different seasons indicated that the spring thaw subgrade modulus values were much closer to the summer modulus values than expected. While the AASHTO Guide suggests that spring thaw subgrade modulus values can be estimated at 20% to 50% of the summer values, this research indicated the modulus values for this spring thaw season were closer to 79% to 87% of the summer values.

A more recent study conducted in Kansas by Long, et al. (1997) of seasonal factors affecting flexible pavement response revealed a strong correlation between subgrade response and pavement surface temperature. FWD tests were performed during this study on four different flexible pavement sections on a monthly basis for a period of one year. Ten stations at 15-meter intervals in the outer wheel path were tested at each section. Subgrade moisture content was measured at the time of each FWD test using time domain reflectometry (TDR) probes. Two different backcalculation techniques were used to derive the subgrade modulus values; the linear elastic program MODULUS and the AASHTO (1993) algorithm. As previously noted, the AASHTO algorithm is incorporated into the DARWin program. The equations employed by both programs are very similar, differing only in the value for Poisson's ratio. The equation for MODULUS allows user input of a Poisson's ratio, however input of a Poisson's ratio of 0.5 in this equation results in the same equation used by DARWin.

When the subgrade modulus values from the Kansas study were plotted versus the subgrade moisture content, the trend represented a sinusoidal function, indicating to the investigators the influence of temperature on subgrade response. This hypothesis was supported by close correlation between subgrade modulus values and temperature, with correlation coefficients between 0.75 and 0.90.

The significance of the previous studies discussed herein can be summarized as follows:

- Moisture content of subgrade soils under nearly impervious pavements has much less seasonal variation than the surrounding uncovered soil.
- Water table depth is significant in terms of vertical movement of moisture through the mechanism of soil suction.
- Subgrade soil moisture content may increase for several years, rapidly during the initial period and then gradually until equilibrium with surrounding soil is reached.
- Precipitation effects on subgrade response may not be realized for several weeks after the occurrence of a given precipitation event.
- Subgrade modulus values can vary significantly both spatially and systemically.
- Seasonal temperature variation can have a significant effect on subgrade response.

3. TENNESSEE FLEXIBLE PAVEMENT STUDY

Test Site Selection

The Tennessee Department of Transportation (TDOT) (Drumm et al., 1998) selected four sites for a study of environmental effects on flexible pavements, one in each of the four regions that represent the range of geographic and climatic conditions found in Tennessee. Figure 1 provides the general locations of the respective test sites. The Blount County test site, located in TDOT Region I, is on I-140 south of Knoxville, near the city of Alcoa. Region I includes the Valley and Ridge region of Tennessee. The first instruments were installed at this site in September of 1996. The monitoring system began collecting data in November of 1996, and was fully operational in mid-April, 1997. The Overton County site is located in Region II on State Route 42, north of Cookville. Region II is considered the Eastern Highland Rim. Instruments were first installed at the Overton County site in September of 1996. The data collection system was installed in January of 1997 and was fully operational in late April of 1997. The Region III site is in Sumner County, in the Central Basin. This site is located on State Route 139 northeast of Nashville, on the city of Gallatin by-pass. The Sumner County site was first instrumented in July of 1997 and was fully operational by late October of 1997. The McNairy County site is located in Region IV, the Southern Coastal Plain. This site is located south of Jackson, on US-45. Instrumentation at the McNairy site began in October of 1996 and was finished in September of 1997.

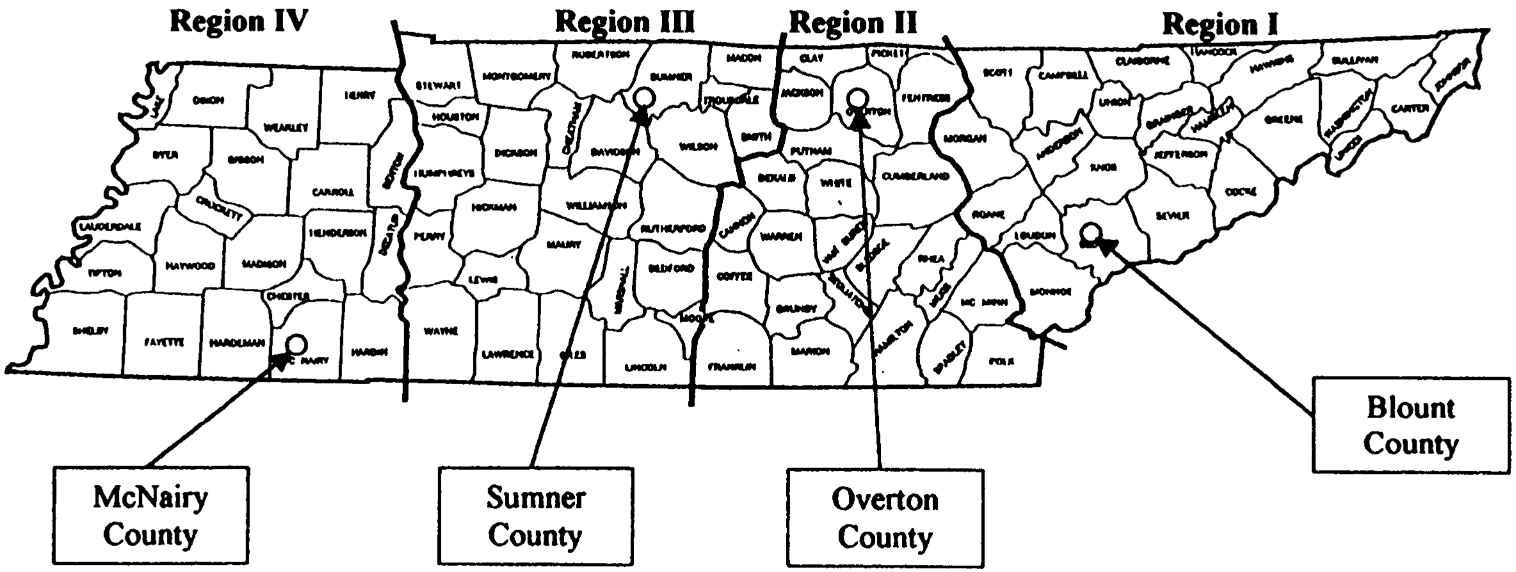

Figure 1 - Location of Tennessee Flexible Pavement Test Sites

Instrumentation

The four sites selected by TDOT in the early stages of construction offered the advantage of allowing instruments to be installed with minimal disturbance to the pavement sections. The TDR probes were installed to record the moisture content of the pavement materials at various depths in the subgrade, mineral aggregate base, and the asphalt stabilized base layers of the pavement system at each test site. Figure 2 represents typical placement of TDR probes at each test site. Thermistors were also installed at each site to collect temperature data for each layer. Details of the instrumentation process for this project are described by Drumm et al. (1998).

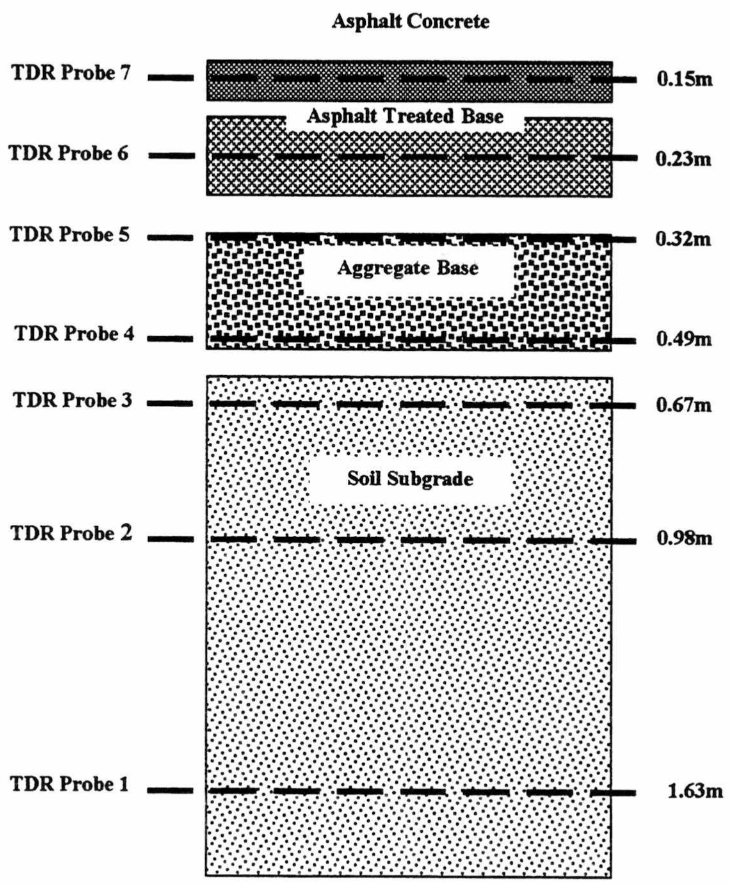

Figure 2 - Typical Instrumentation
(Not to Scale)

A weather station was installed at each site to record air temperature, wind speed, precipitation, relative humidity and solar radiation. Water table monitoring wells were installed at the Overton County and McNairy County sites. The water table monitoring wells were constructed using one of two bore holes created at each site during subsurface investigations. A monitoring well was not installed at the Blount County site because no groundwater table or evidence of saturation was encountered in the subsurface borings. Subsurface borings at the Sumner County site encountered refusal at shallow depths, and no monitoring well was installed at this site. Two pan lysimeters, with surface areas of one square meter, were installed in the aggregate base layer under the outside lane at the Overton, Sumner and McNairy County sites to measure infiltration. Two additional pan lysimeters were installed under the longitudinal joint between the lanes at the Sumner County site.

Data Collection

Cables from the various TDR probes, thermistors and the weather stations were routed into a concrete vault buried off the shoulder of the roadway at each site. The vault houses the data acquisition and logging equipment. The bulk of the raw data is automatically transmitted by cellular telephone from the vault to a computer located on the campus of the University of Tennessee.

Table 1 summarizes the actual position, in-service date, and recording frequency of all instrumentation at each site.

Table 1 – Summary of Test Site Instrumentation

Instruments	Blount	Overton	Sumner	‡McNairy
Weather Station (Reported Hourly)	In-Service Date	In-Service Date	In-Service Date	In-Service Date
Rain Gage	2/97	3/97	10/97	9/97
Wind Anemometer	2/97	2/97	10/97	9/97
Temperature Gage	2/97	2/97	10/97	9/97
Relative Humidity	2/97	2/97	10/97	9/97
Solar Panel	2/97	2/97	10/97	9/97
Under Wheel Path	Date * Depth	Date * Depth	Date * Depth	Date * Depth
•108 Thermistors (Reported Hourly)	4/97 * 51 mm 4/97 * 102 mm 4/97 * 152 mm	5/97 * 51 mm 5/97 * 127 mm 5/97 * 178 mm	10/97 * 51 mm 10/97 * 102 mm 10/97 * 152 mm	10/97 * 25 mm 10/97 * 76 mm 10/97 * 127 mm
†107B Thermistors (Reported Hourly)	12/96 * 0.26 m 12/96 * 0.43 m 12/96 * 0.61 m 12/96 * 0.92 m 12/96 * 1.30 m	3/97 * 0.32 m 3/97 * 0.49 m 3/97 * 0.67 m 3/97 * 0.98 m 3/97 * 1.63 m	10/97 * 0.26 m 10/97 * 0.43 m 10/97 * 0.66 m 10/97 * 0.92 m 10/97 * 1.53 m	3/97 * 0.23 m 3/97 * 0.40 m 3/97 * 0.58 m 3/97 * 0.89 m 3/97 * 1.50 m
TDR Probes (Reported Daily)	12/96 * 0.11 m 12/96 * 0.18 m 12/96 * 0.26 m 12/96 * 0.43 m 12/96 * 0.61 m 12/96 * 0.92 m 12/96 * 1.30 m	3/97 * 0.15 m 3/97 * 0.23 m 3/97 * 0.32 m 3/97 * 0.49 m 3/97 * 0.67 m 3/97 * 0.98 m 3/97 * 1.63 m	10/97 * 0.10 m 10/97 * 0.18 m 10/97 * 0.26 m 10/97 * 0.43 m 10/97 * 0.66 m 10/97 * 0.92 m 10/97 * 1.53 m	5/97 * 0.05 m 4/97 * 0.14 m 3/97 * 0.23 m 3/97 * 0.40 m 3/97 * 0.58 m 3/97 * 0.89 m 3/97 * 1.50 m
Pan Lysimeters (Reported Hourly)	Not Installed	4/97 * 0.27 m 2 Lysimeters	10/97 * 0.21 m 2 Lysimeters	5/97 * 0.18 m 2 Lysimeters
Longitudinal Joint	Date * Depth	Date * Depth	Date * Depth	Date * Depth
TDR Probes (Reported Daily)	Not Installed	Not Installed	10/97 * 0.26 m 10/97 * 0.43 m	Not Installed
Pan Lysimeters (Reported Hourly)	Not Installed	Not Installed	10/97 * 0.21 m 2 Lysimeters	Not Installed
Monitoring Well (Measuring Frequency)	Not Installed	7/97 * 7.6 m Monthly	Not Installed	7/97 * 7.6 m 60 to 90 Days

‡McNairy County site minus binder layer and surface layer (stage construction)

•108 Thermistors have a range of -5°C to 95°C

†107B Thermistors have a range of -40°C to 56°C

Calibration of TDR Probes

TDR probes were calibrated for the soil types found at each of the test sites by compacting soil from each site at a measured volumetric moisture content into an aluminum box containing a probe (Wright, 1998). The box was placed on a digital scale inside an environmental chamber with a constant temperature and relative humidity. Water was then added to the soil in the box in small increments. In this fashion, the TDR probe response was correlated to calibrated changes of the soil volumetric moisture content. An analysis of ten different TDR calibration equations determined that the equation proposed by Herkelrath et al. (1991) offered the best fit for compacted fine-grained soils (Wright, 1998).

Pavement Structure and Subgrade

Subsurface investigations at each site consisted of boring two holes, one in the outer wheel path of the right-hand lane and one in the shoulder, with a hollow stem auger. Auger cuttings and undisturbed shelby tube samples were collected during this investigation. These soil samples were returned to the University of Tennessee for testing and classification. Pavement core samples were also collected from each site. The pavement system at the McNairy County site does not have in place the top two asphaltic concrete pavement layers. As part of a staged construction plan, these layers will be added to the pavement at some time in the future, when adjoining sections are completed. Pavement layer thickness at each of the sites is summarized in Table 2. Results from laboratory analysis of the soil samples collected from each site are summarized in Table 3.

Table 2 – Summary of Pavement Layer Thickness

Layer	Blount I-141	Overton SR-111	McNairy US-45	Sumner SR-109
AC Pavement Depth (mm)	165.1	190.5	215.9	127
Treated Aggregate Base Depth (mm)	50.8	76.2	57.15	63.5
Unbound Aggregate Base Depth (mm)	254	254	254	254
Groundwater Monitoring Well	NO	YES	YES	NO

Table 3 – Summary of Subgrade Soil Properties

Property	Blount I-141	Overton SR-111	McNairy US-45	Sumner SR-109
Cement Stabilized	NO	NO	NO	YES
Optimum Moisture Content (%)	23	20	13	20
Maximum Dry Density (Mg/m^3)	1.59	1.67	1.85	1.67
Clay Content (%)	48.3	37.8	18.4	31.6
Specific Gravity	2.68	2.68	2.72	2.62
%Pass. #200Sieve	86.7	82.2	50.4	78.5
Liquid Limit	52	44	25	48
Plastic Limit	26	19	15	28
Plasticity Index	26	25	10	20
AASHTO Class.	A-7-6	A-7-6	A-4	A-7-6
Group Index	25	20	2	17
USCS Class.	CH	CL	CL	ML

A copy of the original design parameters for each pavement system provided by TDOT can be found in Appendix B. Field boring logs constructed using results from the subsurface investigations conducted at each site are also provided in Appendix C. These boring logs exhibit the soil properties found at the various depths.

Pavement Performance Evaluation

TDOT periodically performed non-destructive FWD tests at each of the four sites with a *Dynatest Model 8000 FWD*. FWD tests were conducted in the outer wheel path of the right-hand lane at five locations for each site. The surface deflection was measured at radial distances of 0, 305, 610, 914, 1219, 1524, and 1829 mm (0, 12, 24, 36, 48, 60, and 72 in.) from the center of the applied force. The deflections from three drop loads, approximately 26, 40, and 53 kN (6, 9, and 12 kips), were recorded for each location. Subgrade M_R and effective pavement modulus (E_p) were backcalculated from the monthly deflection data using the DARWin software. Figure 3 is a schematic of a typical test site. It is important to note that all four of these sites are constructed on engineered fill.

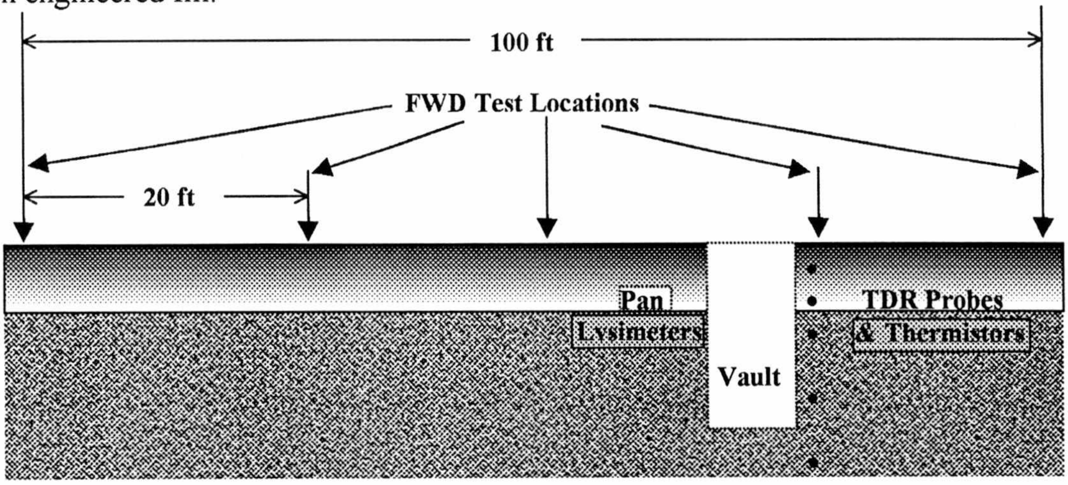

Figure 3 – Typical Test Site
(Not to Scale)

4. RESULTS FROM FLEXIBLE PAVEMENT STUDY

The period of analysis discussed herein began in April 1997 and ended in September 1998. Seasonal temperature and precipitation variation and the influence these climatic factors have on pavement system response at the four study sites are presented. Typical results are presented in this chapter, and the results from all of the test sites are provided in Appendix D.

Temperature

Figures 4 and 5 are plots of the monthly average air temperature for each site, with the 30-year (1961 – 1990) trends of air temperature at three cities located in the Eastern, Central, and Western portions of Tennessee (NWS, 1998). The most apparent feature of these figures is the sinusoidal-shaped pattern for seasonal temperature variation. The temperature of the flexible pavement at three different depths for the Blount County site is presented in Figure 6. The pavement temperature gradient for April 1997 is very different from the gradient for April 1998. This is attributed to the fact that the average air temperature for April 1997 was over 11°C lower than the average for April 1998, and over 12°C lower than the 30-year average for Knoxville. Figure 7 presents the changes of temperature in the subgrade at Blount County. As might be expected, temperatures are higher near the surface of the subgrade during the summer season, and higher in the deeper layers during the winter season. It can be seen from Figures 6 and 7 that pavement temperature and subgrade temperature also fluctuates seasonally with a sinusoidal pattern.

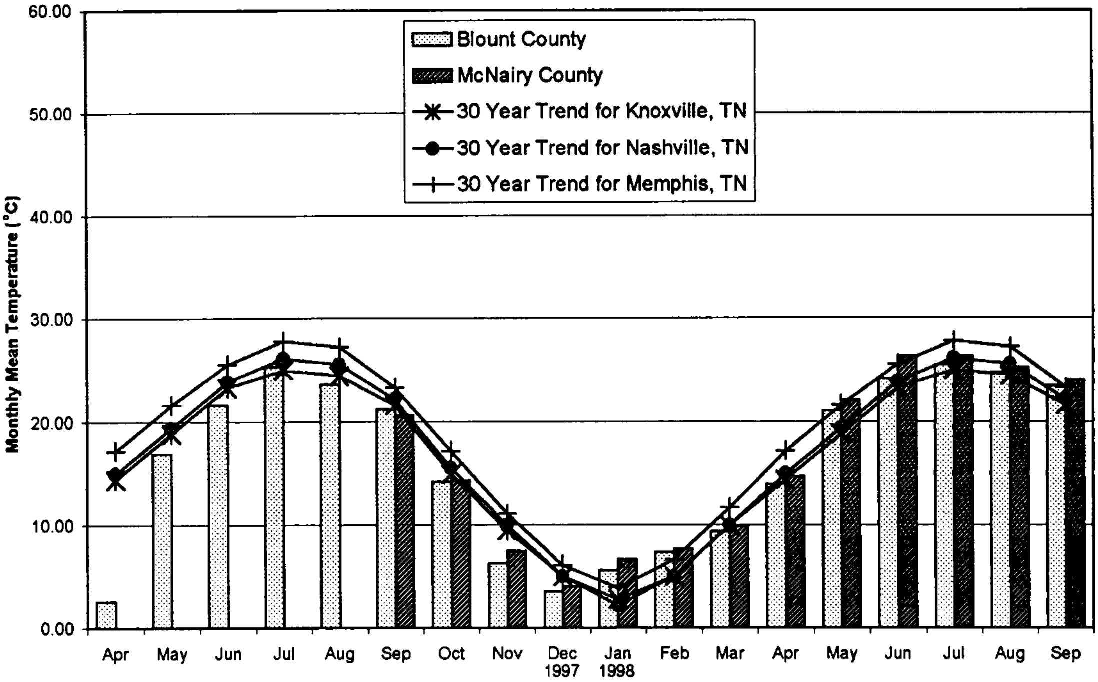

Figure 4 - Monthly Mean Ambient Air Temperature I

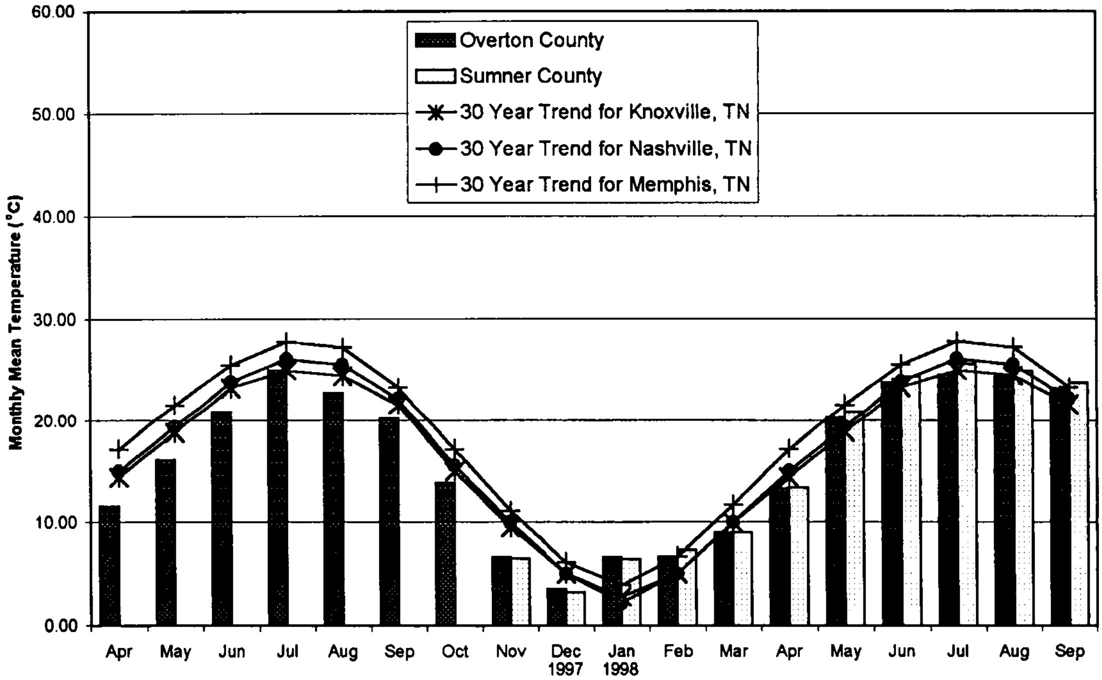

Figure 5 - Monthly Mean Ambient Air Temperature II

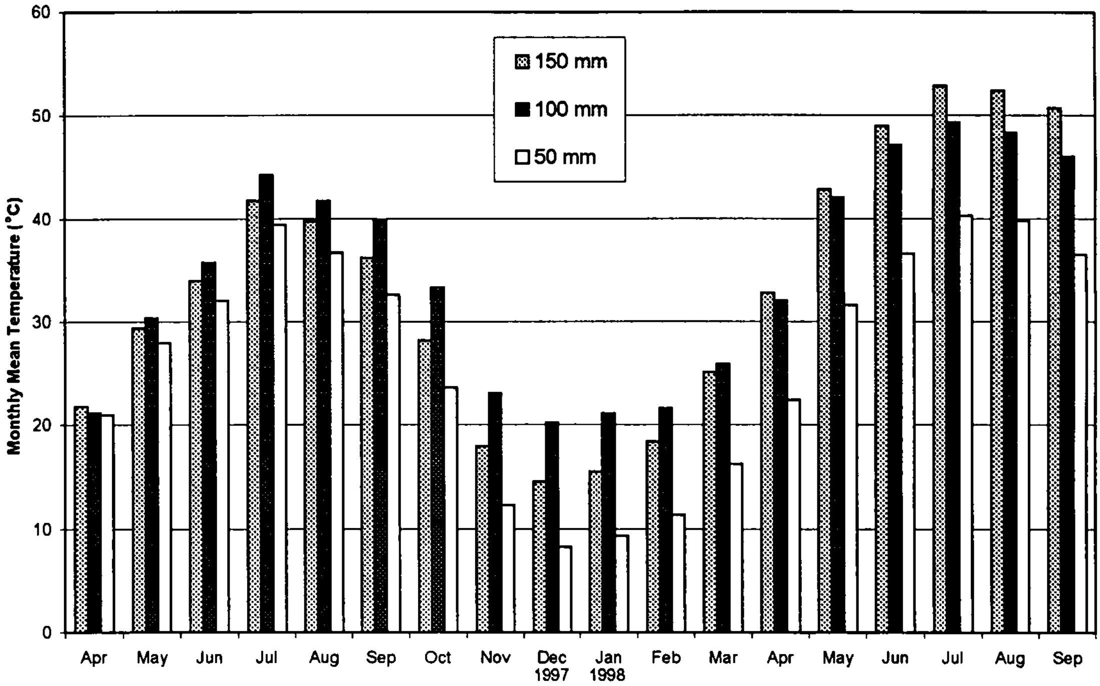

Figure 6 - Blount County Monthly Mean AC Pavement Temperature

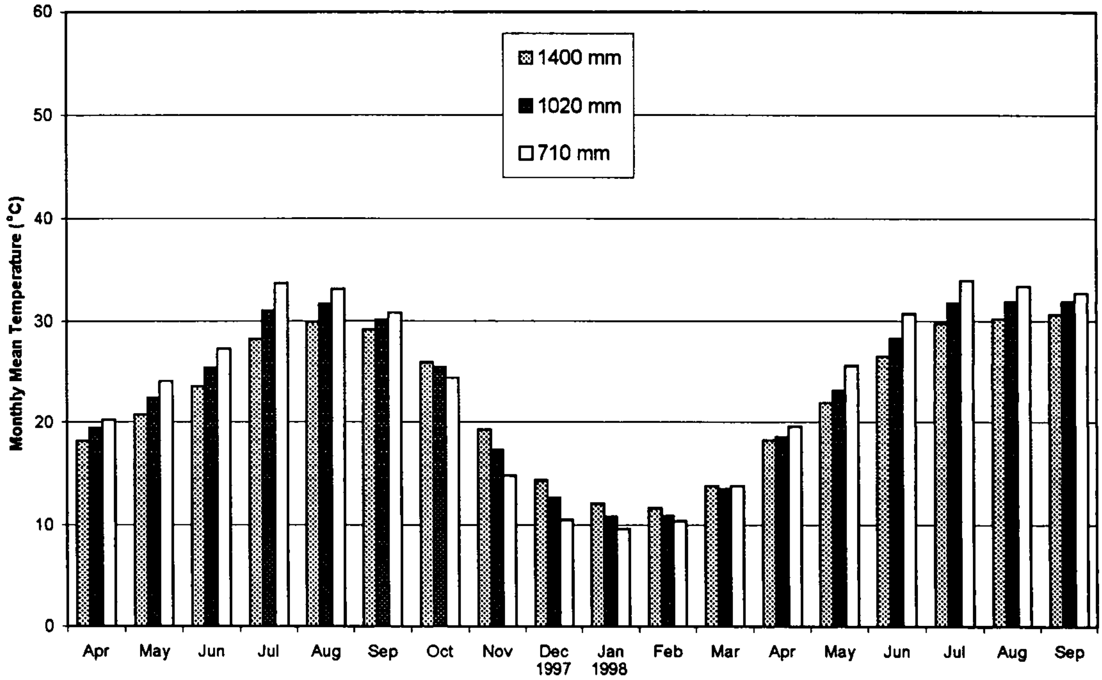

Figure 7 - Blount County Subgrade Monthly Mean Temperature

Precipitation

Monthly total precipitation measured at each of the four test sites is illustrated in Figures 8 and 9, with the 30-year precipitation trends for the three selected Tennessee cities (NWS, 1998). Total rainfall at all four sites during the month of April 1998 was significantly greater than the 30-year average for any of the three Tennessee cities. Precipitation was also well above average for the Overton County site in June 1997. Average monthly precipitation is generally least in the early fall season, and greatest in the winter and spring for the regions of Tennessee. Precipitation has considerably more variation from the 30-year trend than air temperature does.

Infiltration

Daily infiltration measured during February 1998 by the pan lysimeters at the Sumner County site is plotted along with the daily precipitation in Figure 10. This month is demonstrated as typical because the amount of precipitation recorded for February 1998 at the Sumner County site was very close to the Sumner County site annual average. The data from only one of each set of two lysimeters is presented. The data from the second lysimeter at each location indicated very little infiltration throughout the analysis period, and demonstrated no correlation to precipitation events. However, this inconsistency is typical of lysimeter data (Yoder, 1998). Figure 10 compares infiltration under the wheel path with infiltration under the longitudinal joint. It would appear that over three times as much moisture is infiltrating the pavement through the longitudinal joint as is infiltrating through the travel lane.

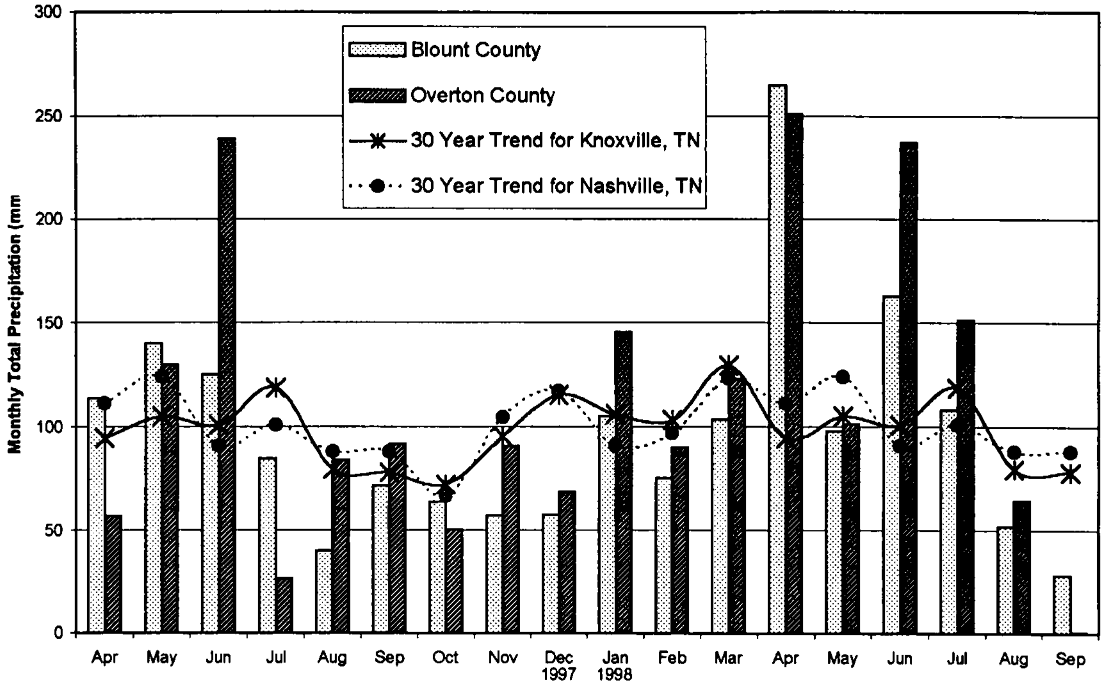

Figure 8 - Monthly Total Precipitation I

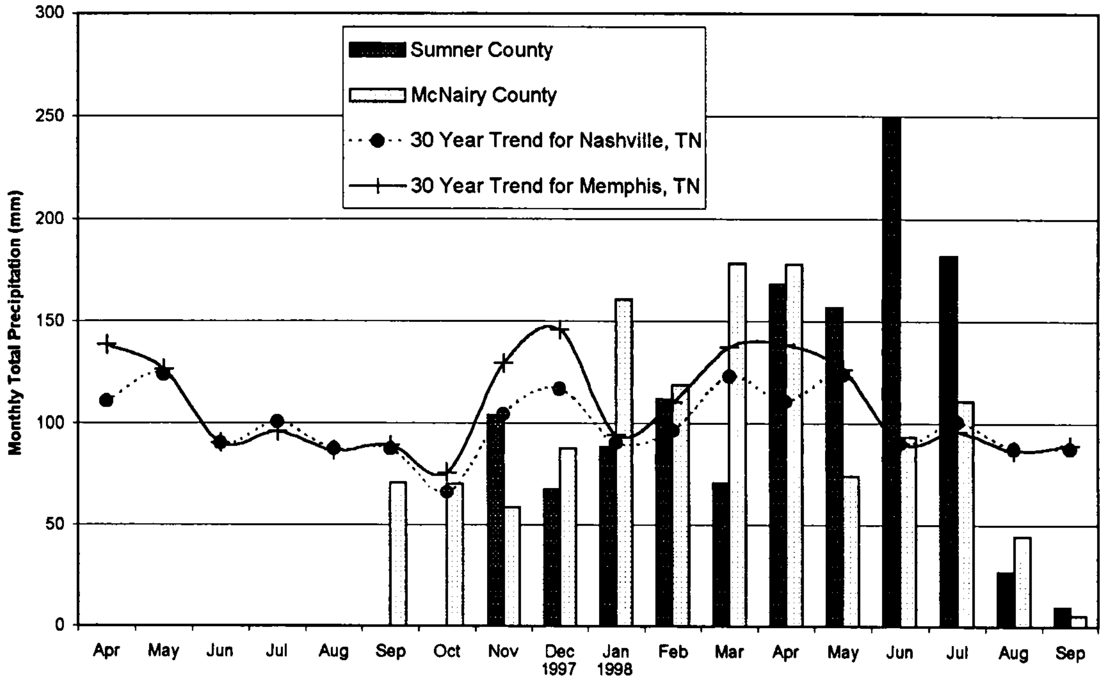

Figure 9 - Monthly Total Precipitation II

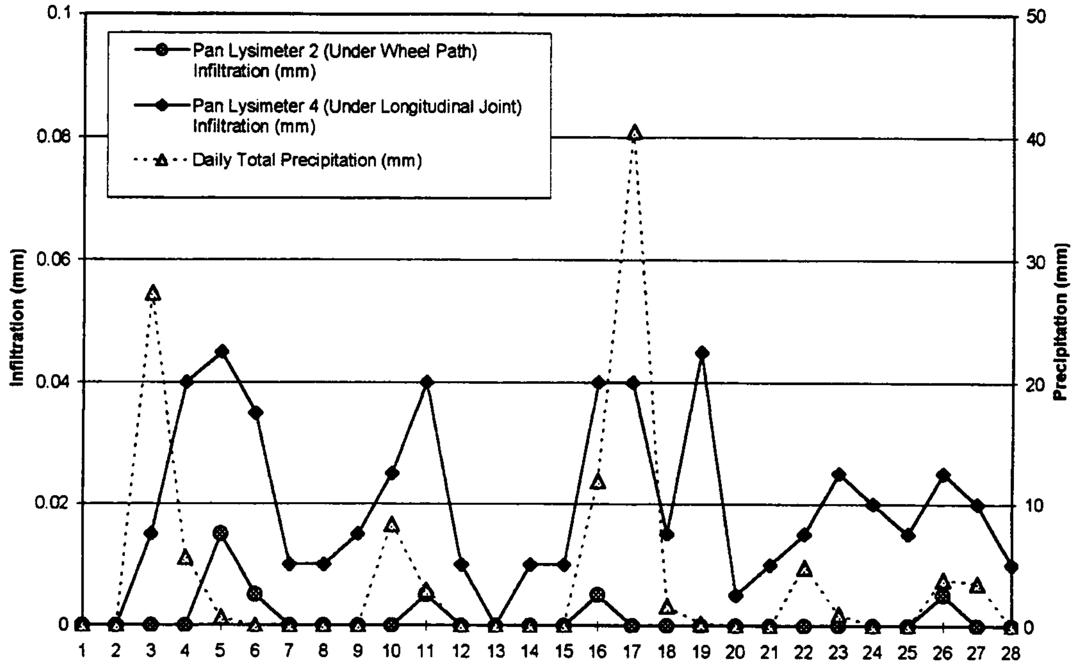

Figure 10 - Sumner County Daily Precipitation & Infiltration for February '98

As previously noted, the staged construction process at the McNairy County site included a plan to leave off the semi- impermeable surface layer for at least one year. Figures 11 and 12 compare infiltration with and without the semi-impermeable asphaltic concrete surface layer that has not been installed at the McNairy County site. The Overton County site experienced a total of 239 mm of rainfall in June 1997, the month plotted in Figure 11, and the pan lysimeters under the wheelpath collected a total of 0.18 mm of infiltration. Conversely, only 178 mm of rain fell on the McNairy County site during the month of April 1998 (plotted in Figure 12), while 0.82 mm of infiltration were collected under the wheelpath at this site. These two different months were selected for comparison because similar patterns of precipitation were experienced at the two sites during these time periods.

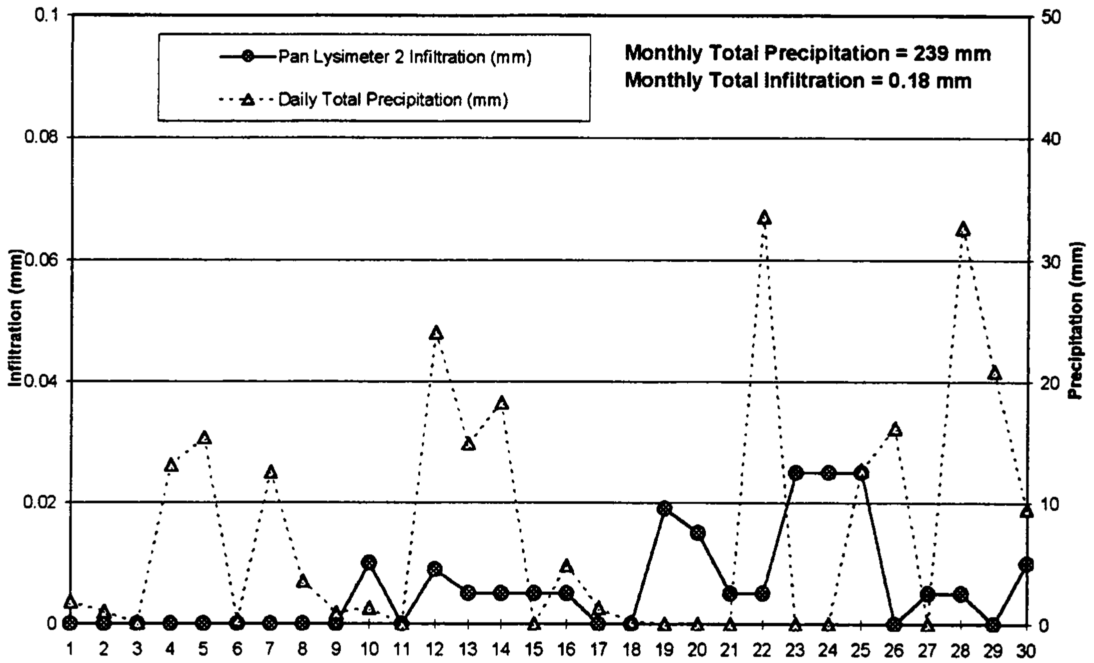

Figure 11 - Overton County Daily Precipitation & Infiltration for June '97

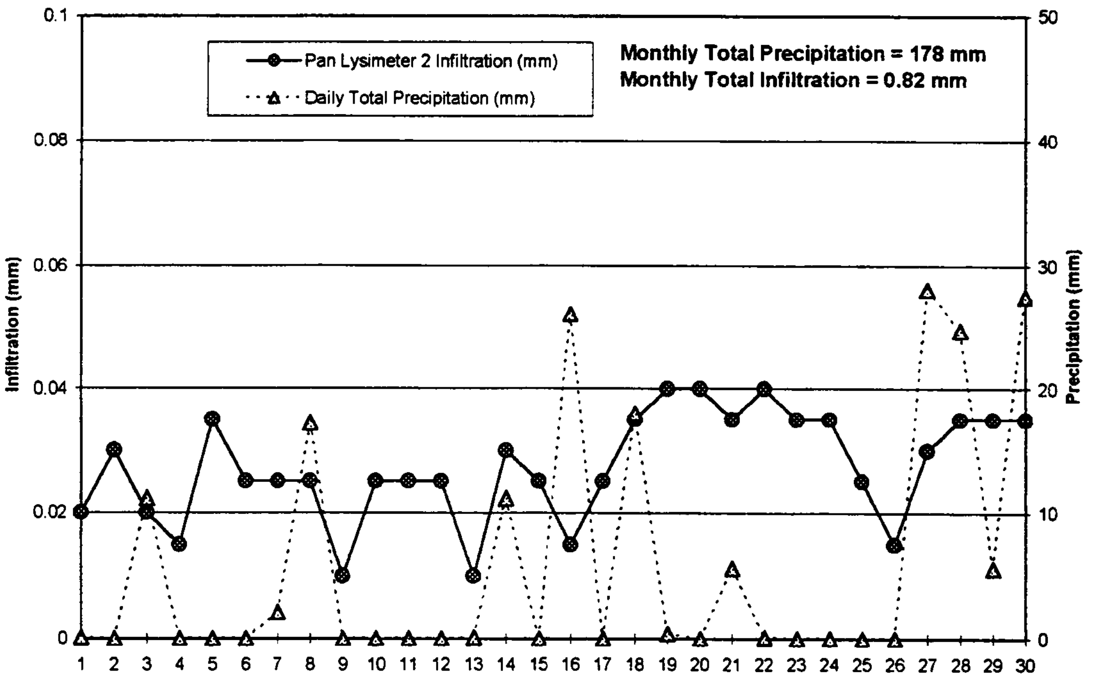

Figure 12 - McNairy County Daily Precipitation & Infiltration for April '98

Aggregate Base and Subgrade Moisture Content

Daily and monthly average volumetric moisture content of TDR probe 4, located at the bottom of the mineral aggregate base layer at the Blount County site, are presented in Figure 13. The seasonal variation of moisture content is apparent, especially in the plot of monthly averages. There are indications of systemic problems with the TDR probe near the end of May 1998, however the data from this probe appears reasonable before and after this period.

Figure 14 illustrates the variation of the Blount County subgrade volumetric moisture content as measured by TDR probe 3, located near the top of the subgrade. The daily averages appear scattered, yet the standard deviation for the probe 3 data from Blount County is only 1.8%. The monthly averages are a good indicator of an increasing trend, with a 4% increase from April 1997 to April 1998. This trend should be viewed with the understanding that this is only about one year of data and the precipitation in April 1998 was almost 43% greater than the precipitation in April 1997.

Figure 15 presents a comparison of precipitation at the Blount County site with average moisture content in the aggregate base and the subgrade. The base layer response to precipitation lags the event by one to three weeks, and the subgrade response may lag the base layer by about one month. Monthly average moisture content of the subgrade at the Blount County site appears to be closely correlated with monthly average air temperature in Figure 16.

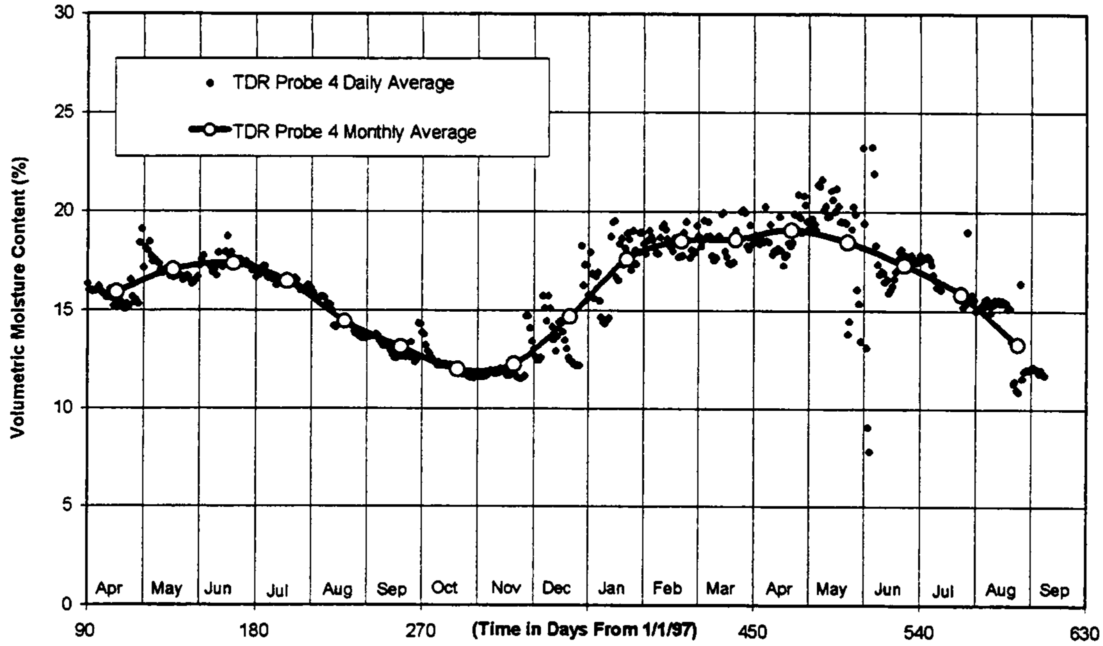

Figure 13 - Blount County Aggregate Base Volumetric Moisture Content

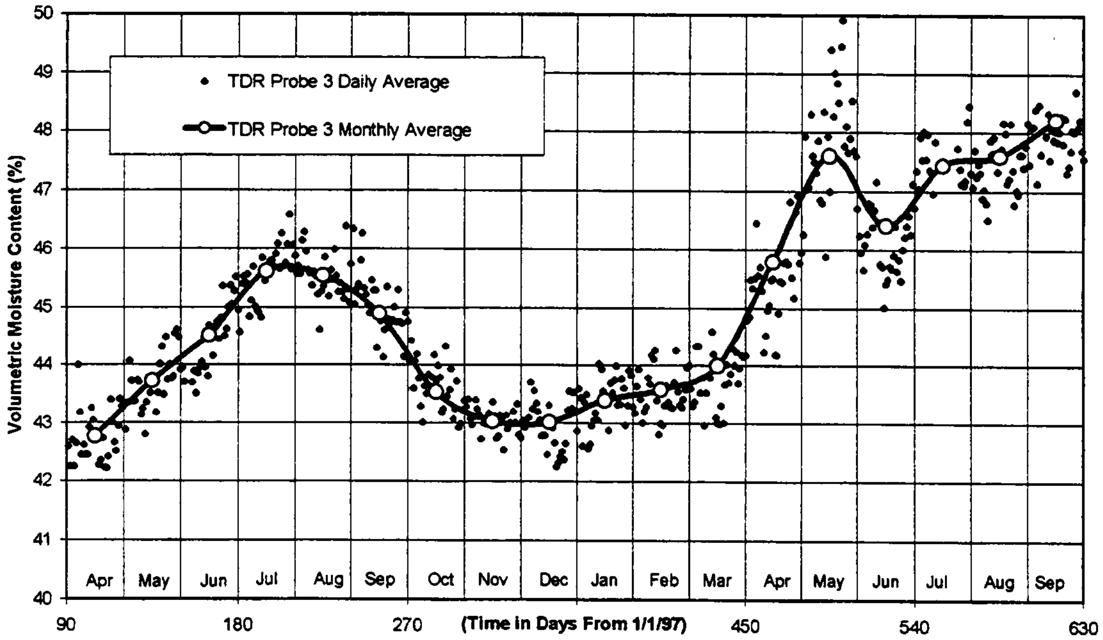

Figure 14 - Blount County Subgrade Volumetric Moisture Content

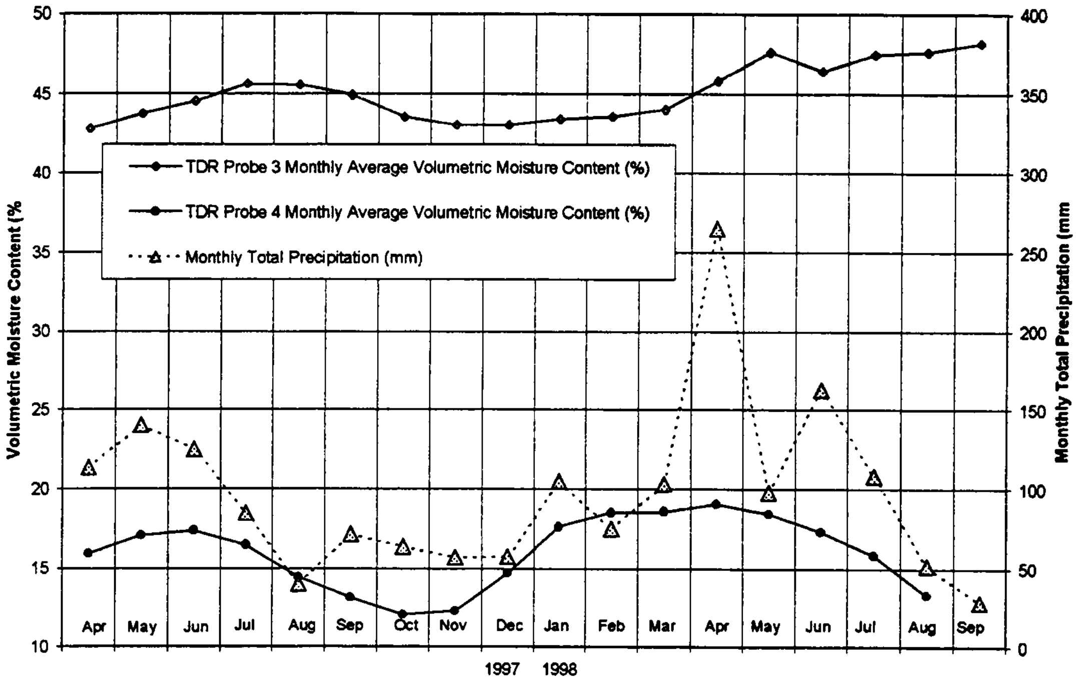

Figure 15 - Blount County: Precipitation and Moisture Content

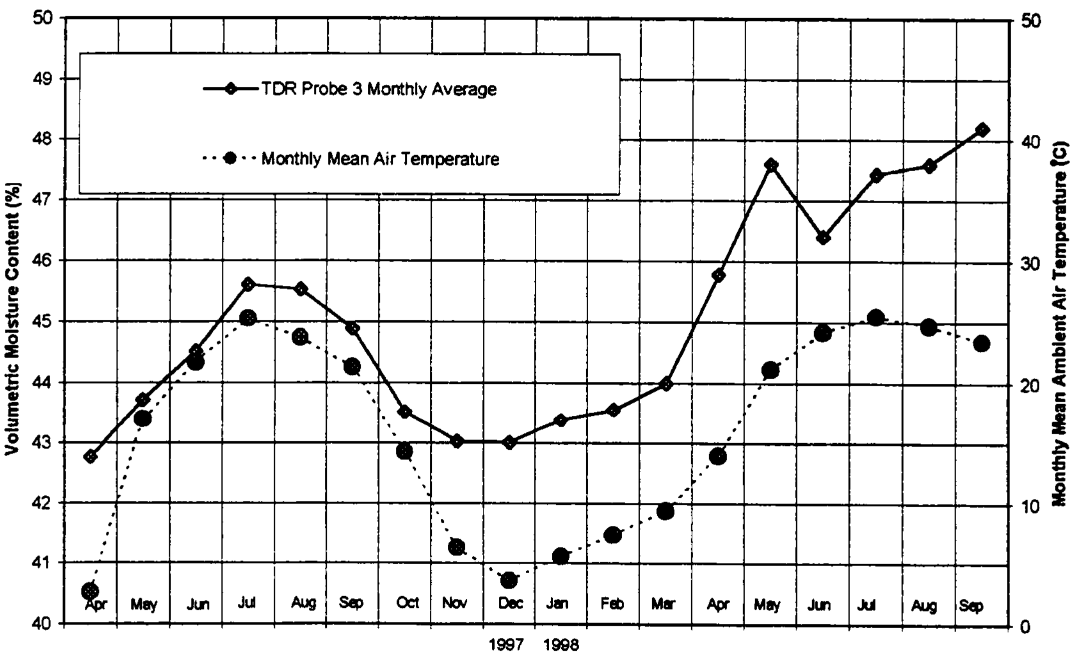

Figure 16 - Blount County: Air Temperature and Moisture Content

Similar plots of moisture content with precipitation and air temperature for all of the test sites are included in Appendix D. The trends for each site are similar to those demonstrated for Blount County. Moisture content of the subgrade and aggregate base fluctuates seasonally, and subgrade moisture content correlates closely with air temperature. It should be noted that the relative changes in subgrade volumetric moisture content are considered valid, although the reported values may be unrealistically high. This is a symptom of measuring the moisture content of compacted soils with high clay content using TDR probes (Wright, 1999).

Water Table Monitoring Wells

The change in depth to the water table level over the course of the analysis period at the Overton and McNairy County sites is presented in Appendix D. Both sites show a continuous rise of water table throughout the period of study. At this time, no correlations between precipitation and water table elevation or between subgrade moisture and water table depth are apparent.

FWD Test Results

The FWD backcalculated effective pavement modulus (E_P) values for Blount County and Overton County are plotted in Figure 17. A linear trend line has been included for each site demonstrating the overall increase in E_P at both sites. These values have been adjusted for pavement temperature by the DARWin program. Pavement temperature at a depth of 50mm was selected as input to the program. The initial densification of asphaltic concrete pavements has been recognized (Ownby, 1998).

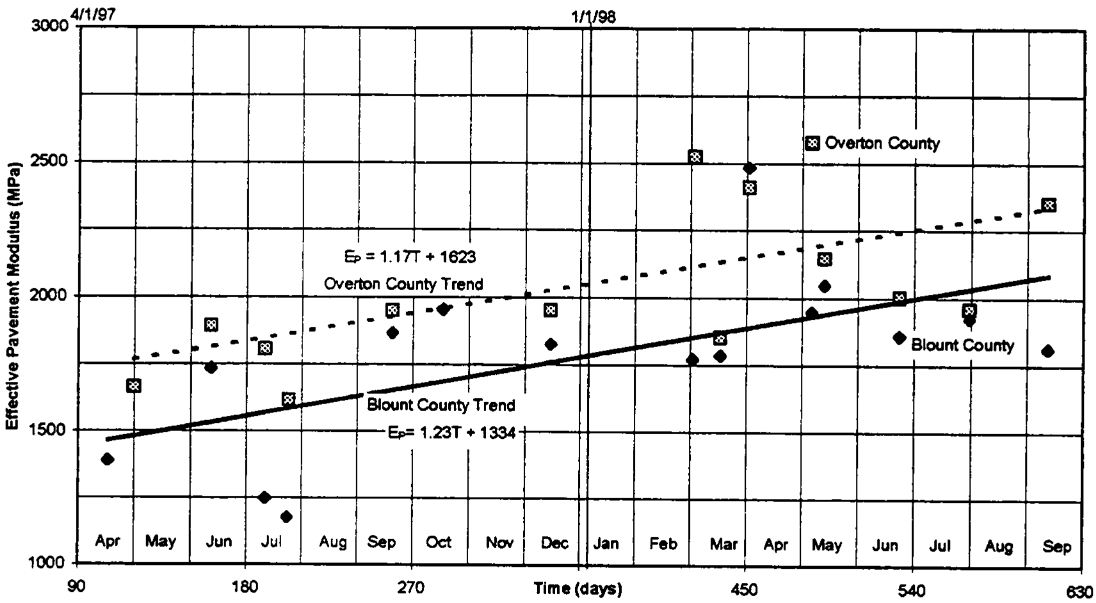

Figure 17 - Effective Pavement Modulus Trends

Figures 18 - 21 present the seasonal variation in FWD backcalculated subgrade modulus values for Blount, Overton, Sumner, and McNairy Counties respectively during the analysis period. The general trend for each site is an increase of M_R during the winter months and a decrease in the summer months. The noticeable drop in backcalculated subgrade modulus value for Overton County in July 1997 can be attributed to the significant amount of precipitation experienced at this site during the month of June 1997. Also the pavement temperature recorded at the time of the FWD test in July 1997 was the maximum value recorded for the entire period at this site. This combination of high pavement temperature and high subgrade moisture content resulted in the most critical impact on subgrade modulus at the Overton County site.

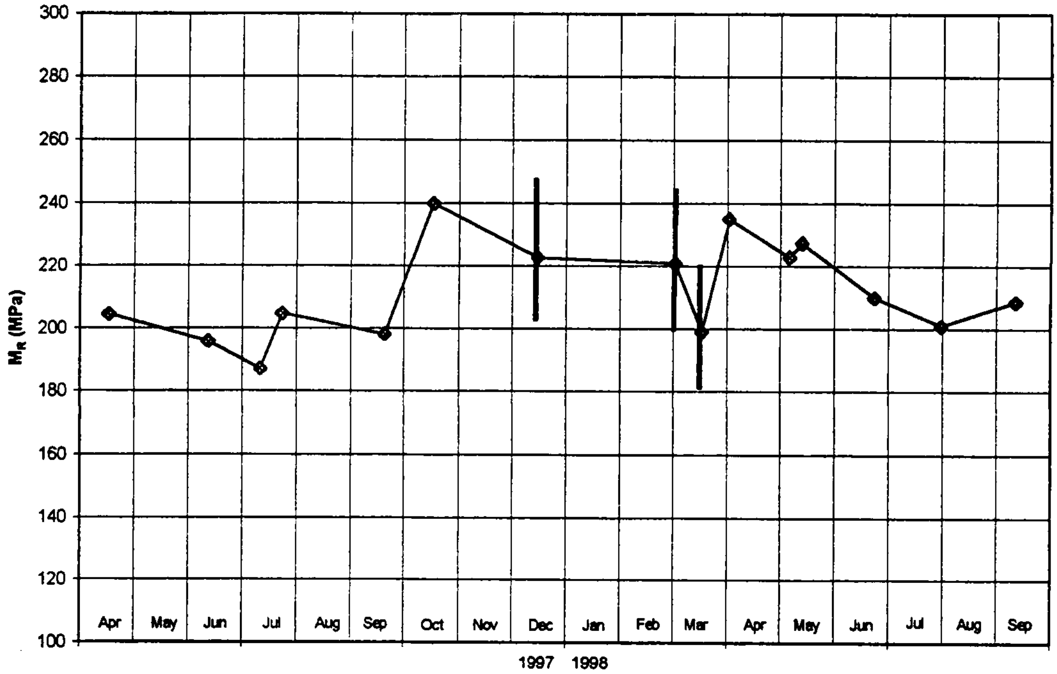

Figure 18 - Blount County FWD Backcalculated Subgrade Modulus

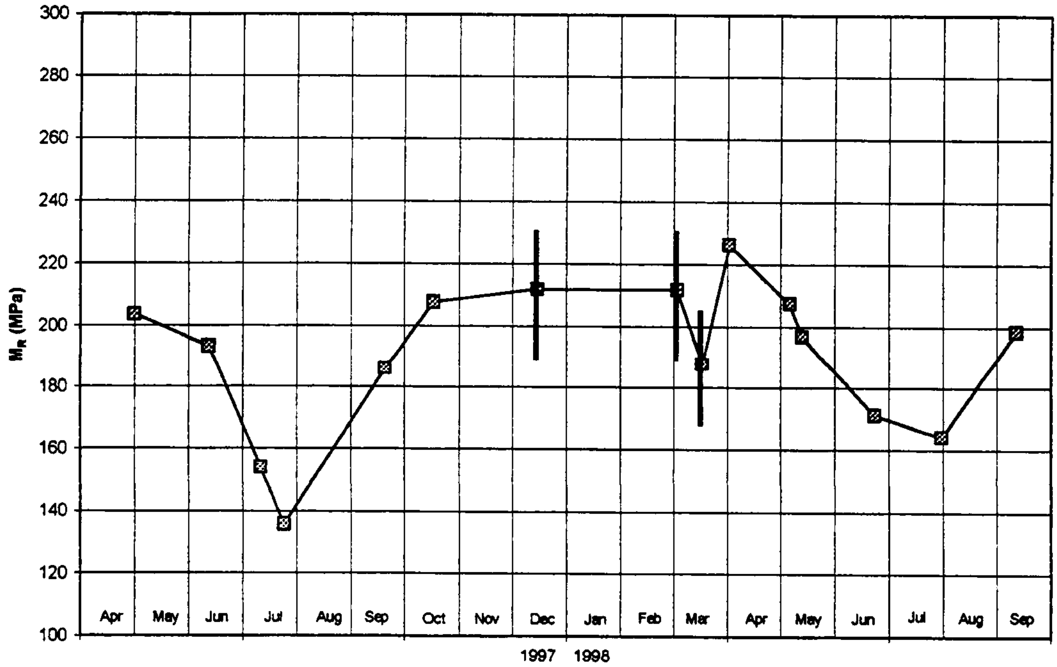

Figure 19 - Overton County FWD Backcalculated Subgrade Modulus

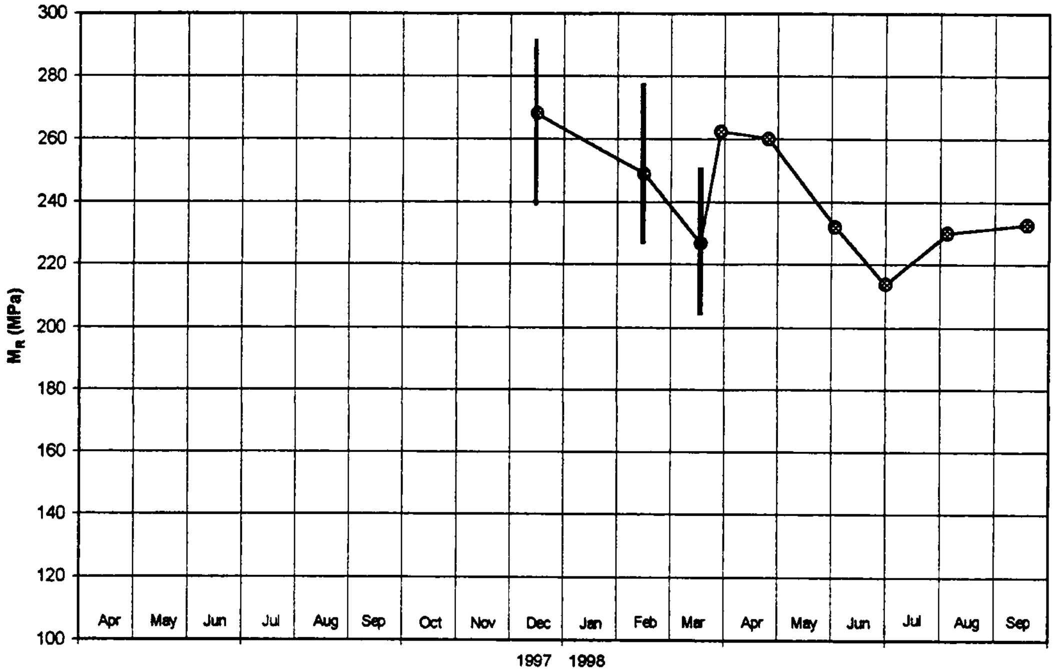

Figure 20 - Sumner County FWD Backcalculated Subgrade Modulus

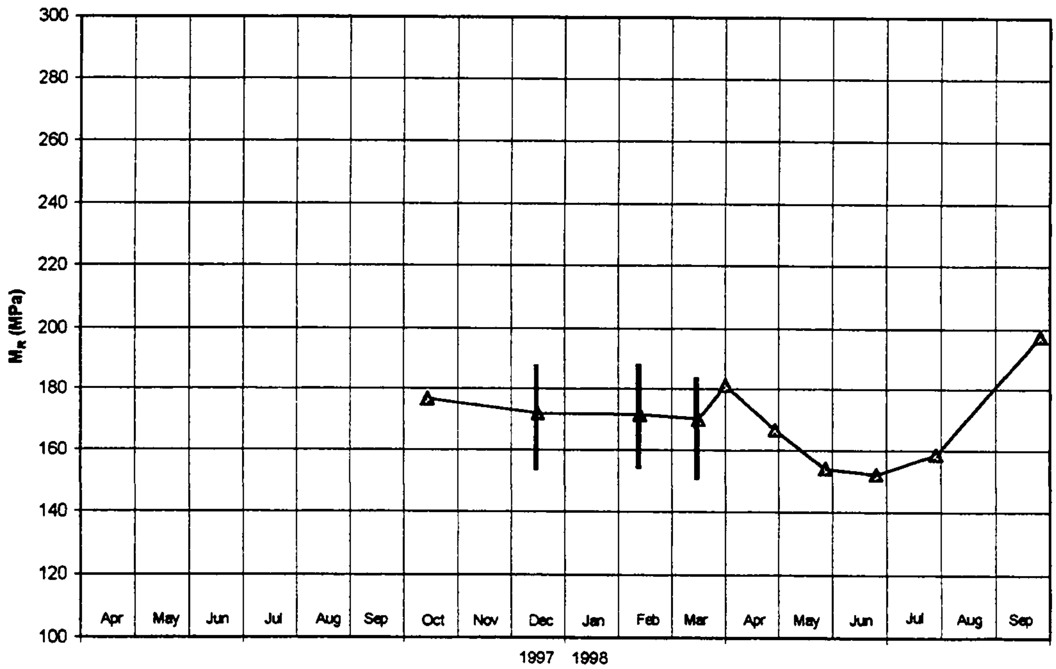

Figure 21 - McNairy County FWD Backcalculated Subgrade Modulus

There are no apparent environmental factors related to the drop in modulus value at all four sites during the latter part of March 1998. However, inaccurate FWD test data can make interpretation difficult. An equipment malfunction resulted in erroneous values for the FWD drop load during the tests performed in December 1997, February 1998, and March 1998. An estimated drop load was input to the DARWin procedure based on an average of known loads for these tests. Therefore, error bars that represent a modulus calculated from the minimum and the maximum drop load have been included on the plots of M_R for these months. Also, FWD tests were not performed at any of the test sites during the months of August 1997, November 1997, January 1998 and August 1998.

The spatial variability in FWD backcalculated subgrade modulus values between the five stations tested at the Blount County site in September 1997 is presented in Figure 22, and represents a typical site variability. The range in modulus values across five stations approximately 6 m (20 ft) apart for the September Blount County middle drop was over 43 Mpa (6 ksi), or 22% of the reported average value. The range in average subgrade modulus values that were reported for the Blount County site for the entire analysis period was approximately 53 MPa (8ksi), 25% of the average value. This degree of spatial variation, while significant, is low compared to the variation encountered by Newcomb et al. (1989) in the Nevada study. The coefficient of variation (COV) for the September 1997 Blount County modulus values is 10%, whereas the COV in the Nevada study of 26 sites ranged from 11% up to 98%, with an average COV of 28%.

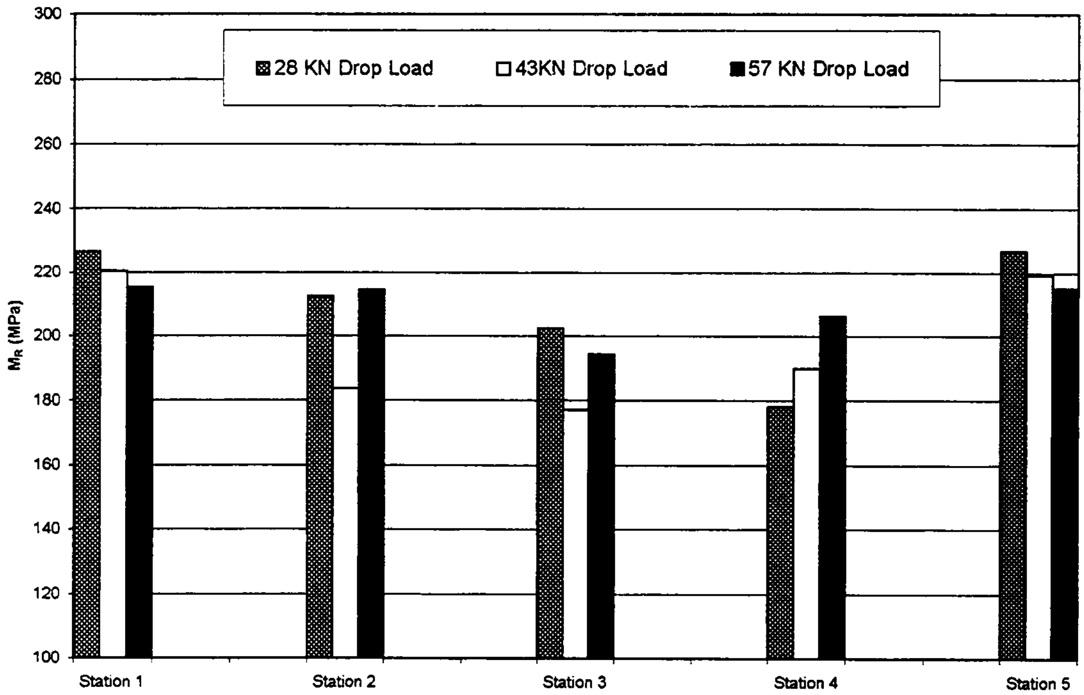

Figure 22 - Blount County Sept'97 FWD M_R : Spatial Variability

Figure 22 also demonstrates the inconsistent response of the subgrade to increasing stress. As the drop load (deviator stress) increases, the backcalculated subgrade resilient modulus (response) decreases at two stations, increases at one station, and changes from decreasing to increasing at the other two stations. Spatial variability and variation of the FWD drop load can complicate establishing seasonal trends for M_R. The importance of consistently testing at the same location using a similar load should be evident. FWD tests were performed at the same location for each test interval during this study, however the drop load could only be estimated for the tests conducted from November 1997 through March 1998.

5. ANALYSIS OF RESULTS FROM THE FIRST YEAR

Subgrade Moisture Content

The subgrade moisture content measured by the TDR probes does demonstrate seasonal variability. Previous studies have recognized that subgrade moisture tends to increase until equilibrium with the surrounding soil is achieved (Russam, 1970; Vaswani, 1975). There appears to be a general trend of increasing moisture content in each of the four subgrades analyzed in this project, as demonstrated in Figure 14. However, it would be premature to define a long-term trend with data from only one year. Although there are some obvious discrepancies in the TDR probe data, the seasonal variation would appear to most closely resemble the sinusoidal pattern typical of seasonal temperature variation (Figure 16). As temperatures rise in the summer and fall in the winter, subgrade moisture responds in a similar fashion. Figure 23 illustrates the relationship between air temperature and moisture content at TDR probe 3, located in the upper portion of the subgrade. Table 4 lists the correlation between monthly mean ambient air temperature and subgrade moisture content for each site. It should be noted that the Overton County site recorded some erratic subgrade moisture data, and the Sumner County site has data from less than one full year. Regardless, there appears to be a strong correlation between air temperature and subgrade moisture content based on the available data.

Table 4 - Subgrade Moisture Content & Air Temperature Correlation

	Blount	Overton	Sumner	McNairy
Correlation Coefficient	0.82	0.68	0.95	0.84

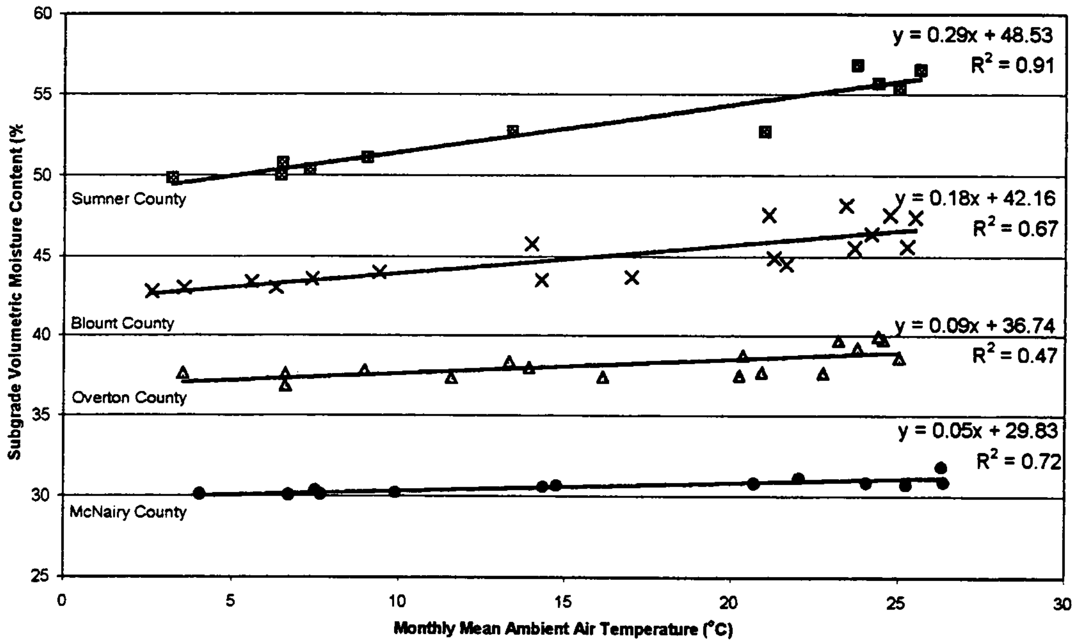

Figure 23 - Subgrade Moisture Content vs. Air Temperature

As illustrated in Figure 15, there is not a strong correlation between precipitation and subgrade moisture content. However, there are some indications that significant precipitation events do influence subgrade moisture content, perhaps several weeks later. Intensity and duration of the precipitation complicate the impact on subgrade moisture content. An intense storm of short duration may produce a large volume of water that has less effect on the pavement system than a less intense storm of longer duration. Permeability of the pavement layers and the drainage provided also have significance that is difficult to quantify. Data from the first year of this study indicates that precipitation does not directly affect the moisture content of the subgrade soils.

Aggregate Base Moisture Content

The aggregate base layers, at the sites where probe 4 is functioning, demonstrate more variability in moisture content than the subgrade iayers. Changes of moisture content in the base layer should be more closely related to precipitation events than the subgrade layers beneath. The correlation coefficient representing the relationship between monthly total precipitation at the Blount County site and the aggregate base layer moisture content is 0.64. The aggregate base layer is more porous than the underlying subgrade layer and moisture will generally move more rapidly through the base. However it should be apparent that high moisture content in the base layer will eventually permeate to the subgrade layer. Pan lysimeters located in the aggregate base layer indicate that moisture can infiltrate the pavement system more readily through the longitudinal joint than through the travel lanes. The data from the pan lysimeters at the McNairy County site, where the pavement surface layers are absent, demonstrate the importance of maintaining the impermeable nature of the pavement surface in order to minimize infiltration to the aggregate base layer (Figure 12). Brown (1996) points out that changes in the resilient modulus of the unbound granular base will have a more significant effect on the tensile strain in the asphalt layer than changes in subgrade modulus. The modulus of the aggregate base layer was not a focus of this study. The influence of changing moisture content in the unbound aggregate base layer on flexible pavement performance does, however, warrant further study.

FWD Backcalculated Modulus Values

The FWD device impacts the pavement system with a load that effectively simulates an Equivalent Single Wheel Load (ESWL). The process of backcalculating layer modulus values from the resulting deflections is complicated by the temperature dependent nature of the asphaltic concrete and the non-ideal nature of the unbound base and subgrade layers. The magnitude of the variation in M_R in this study was examined by inserting the maximum and minimum values of subgrade modulus from each site into the AASHTO flexible design equation with all other parameters as constants. The correction factor used by TDOT (0.33) was applied to the backcalculated values of M_R. This value of M_R was then used to solve for the required thickness of pavement for full-depth asphaltic concrete with a layer coefficient of 0.4. Table 5 summarizes the estimated pavement thickness required for each case. The importance of selecting a value of M_R that best represents the subgrade response for all seasons should be evident from the last column of Table 5. For most of the sites, the difference is 9% of the maximum thickness, while in the case of the Overton County site, with the lowest reported value of M_R, the difference is 17% of the maximum thickness. Designing a pavement system using the minimum value of M_R will result in premature failure, and designs based on the maximum value will be uneconomical. The optimum value is somewhere in between.

Table 5 – Variation of M_R & Required Pavement Thickness

	Maximum M_R (MPa)	Min. Thick. (mm)	Minimum M_R (MPa)	Max. Thick. (mm)	Difference (mm)
Blount	80	243	62	267	24
Overton	75	249	45	299	50
Sumner	89	232	71	254	22
McNairy	66	262	51	288	26

Figure 17 illustrates that the effective modulus values for the pavement are generally increasing with time in the first year to year and a half of the pavement life. The increase of E_P will decrease the amount of stress transmitted to the underlying subgrade, and for stress-softening cohesive subgrade material, lower stress levels result in higher modulus values. The effect on the pavement system of the increase in E_P may be offset by the increasing trend of subgrade moisture content.

The most critical situation for subgrade modulus will occur during the hot summer season, after a period of above normal rainfall. Critical periods, such as the period experienced at the Overton County site in July of 1997, will occur in some years and not in others, and cannot be predicted. Deviations from a predictable pattern will result in random variability. The reliability and variance factors in a design should reflect consideration of unpredictable environmental variation.

Subgrade resilient modulus values vary seasonally, as can be seen in Figures 18 and 19. This seasonal variation can be generally approximated as sinusoidal; modulus values are at a maximum in the winter and a minimum in the summer. This overall trend reflects the influence of temperature on the stiffness of the pavement and on the moisture content of the subgrade (as temperature and subgrade moisture content increase in the summer, subgrade modulus decreases, conversely in the winter subgrade modulus increases as temperature and subgrade moisture decrease). In summary, seasonal fluctuations of M_R are most closely related to seasonal variation of air temperature in Tennessee.

6. ESTIMATING SEASONAL FLUCTUATIONS IN M_R

As previously noted, Hudson et al. (1994) presented a technique for estimating optimum M_R for Tennessee soils based on correlating index properties and soil classifications. Drumm et al. (1997) followed up this work with a study of changes in M_R (ΔM_R) resulting from change in degree of saturation (ΔS), and developed values for the slope of $\Delta M_R/\Delta S$. These methods for estimating M_R at optimum and $\Delta M_R/\Delta S$ have previously been applied to the data collected in this study (Andrew et al., 1998).

Hudson/Drumm et al. (1997) Technique

A value of optimum M_R for a soil tested by Hudson et al. (1994) that best fits the soil type found at each of the four Tennessee sites was selected. The variation in M_R with change in degree of saturation was estimated on the basis of AASHTO soil type as suggested by Drumm et al. (1997). Table 6 summarizes the values of optimum M_R and $\Delta M_R/\Delta S$ selected in the process of estimating seasonal subgrade modulus values for each site.

Table 6 – Estimated Modulus Values

	Blount	Overton	Sumner	McNairy
Opt. M_R(Mpa)	200	180	125	110
$\Delta M_R/\Delta S$	-1900	-1900	-810	-300

While the subgrade layers experience only small seasonal changes in moisture content, these small changes in moisture content correspond to significant changes in degree of saturation. The degree of saturation for each period was calculated from the measured subgrade volumetric moisture content using Equation 1.

$$S = \frac{\theta G_s \rho_w}{(G_s \rho_w - \rho_d)} \quad (1)$$

Where:
S = Saturation,
θ = Volumetric Moisture Content,
G_s = Specific Gravity of Soil Solids,
ρ_w = Density of Water, and
ρ_d = Dry Density of Soil

ρ_d is the in-situ dry density, and 85% to 90% of optimum was assumed for these calculations to account for erroneously high values of S. ΔS is the difference between S at optimum moisture content and S for the time period of interest. ΔM_R, the reduction from optimum, is equal to ΔS multiplied by the slope of $\Delta M_R/\Delta S$. The subgrade modulus at a particular time can be estimated as the difference between M_R at optimum and ΔM_R. Figures 24 and 25 provide a comparison of the values of M_R estimated using this approach to the FWD backcalculated values for the Blount and Overton County sites. For the first half of the analysis period, the estimated modulus values derived using this technique correlate reasonably well with the FWD modulus values. For the second half of the analysis period, the estimated values decrease rapidly before a slight increase, while the FWD values decrease only slightly and then increase again. The estimated values change in relation to subgrade moisture content, and the subgrade moisture content is gradually increasing throughout the analysis period, while the FWD modulus values reflect the decrease in air temperature.

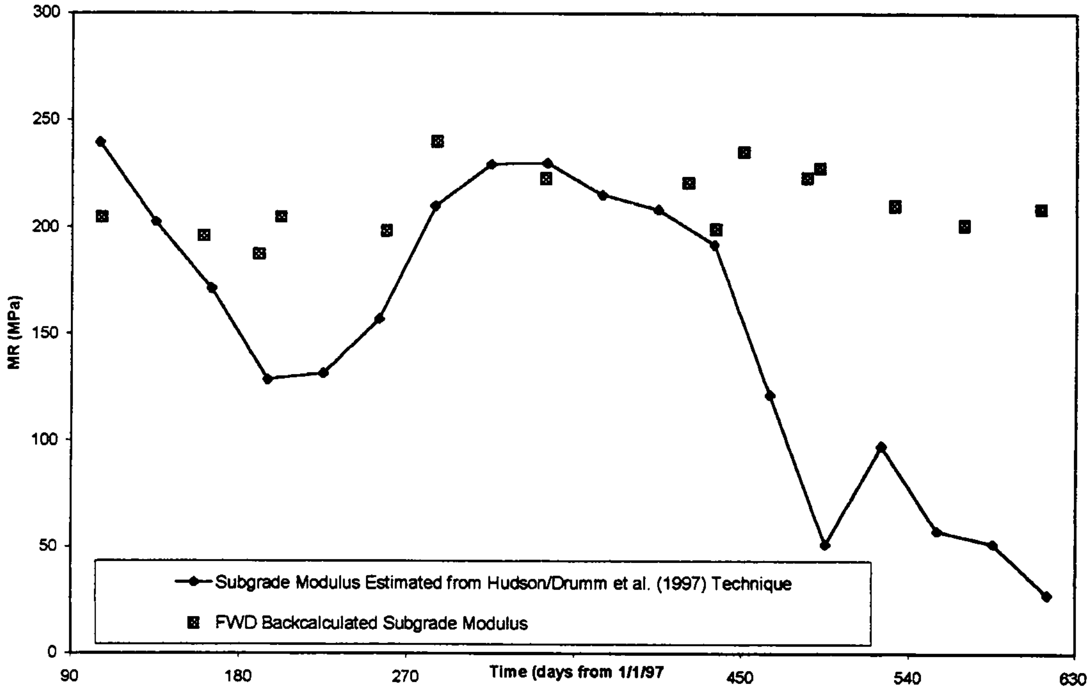

Figure 24 - Blount County Estimated Subgrade Modulus

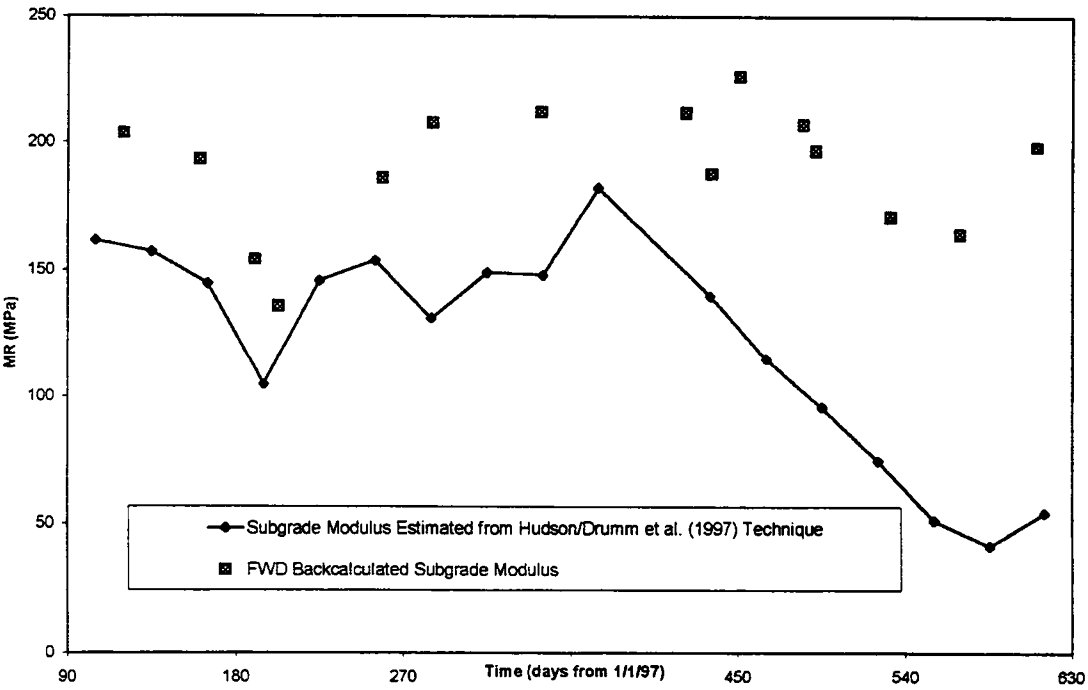

Figure 25 - Overton County Estimated Subgrade Modulus

Li and Selig (1994) Technique

A comparison study of four different mathematical models designed for predicting M_R of fine-grained soils was conducted by Li and Selig (1994). All four models were capable of closely estimating M_R from model parameters available from previous studies. The four models compared by Li and Selig were:

The bilinear model

$$M_R = K_1 + K_2\sigma_d \qquad \text{when } \sigma_d < \sigma_{di} \tag{2a}$$

$$M_R = K_3 + K_4\sigma_d \qquad \text{when } \sigma_d > \sigma_{di} \tag{2b}$$

Where:

K_1, K_2, K_3, and K_4 = model parameters dependent on soil type and physical state

σ_d = repeated deviator stress ($\sigma_1 - \sigma_3$), and

σ_{di} = deviator stress where the slope of M_R vs. σ_d changes

The power model

$$M_R = k\sigma_d^n \tag{3}$$

Where:

k and n = model parameters dependent on soil type and physical state

The semilog model

$$M_R = 10^{(k - n\sigma_d)} \tag{4}$$

And the hyperbolic model

$$M_R = \frac{k + n\sigma_d}{\sigma_d} \tag{5}$$

The coefficients of correlation for these models ranged from 0.89 to 1.0. The investigators in this study emphasize the importance of selecting the correct values for the model parameters. They suggest that the parameters for dry density and moisture content of the soil may have as much or more influence on the resulting value of M_R as stress level.

Li and Selig (1994) went on to develop two equations for estimating changes of M_R from a correlation of repeated load triaxial test results by others. These equations are based on the assumption that changes in M_R can be related to changes in the subgrade soil physical state (basically moisture content and dry density). Seed et al. (1962) noted that these subgrade soil parameters might change after construction and the importance of the changes on subgrade resilient modulus. The two equations developed by Li and Selig predict the variation of M_R for the case of changing moisture content with constant dry density and changing moisture content with constant compaction effort. These equations are noted below:

$$R_{m1} = 0.98 - 0.28(w - w_{opt}) + 0.029(w - w_{opt})^2 \qquad (6)$$

$$R_{m2} = 0.96 - 0.18(w - w_{opt}) + 0.0067(w - w_{opt})^2 \qquad (7)$$

Where: $R_{m1} = {M_R}/{M_{R(opt)}}$ for constant dry density;

$R_{m2} = {M_R}/{M_{R(opt)}}$ for constant compaction effort.

$(w - w_{opt})$ = change of moisture content from optimum

They propose that one of these equations, or some combination of the two can represent changes of M_R. Optimum M_R at the Overton County site was estimated using the power model with parameters determined for Tennessee soils by Drumm et al. (1995); $k = 374.1$ MPa and $n = -0.4620$. Then Equation 7 was used with the change of moisture content measured during each time period to determine the value of M_R for that period. Figure 26 illustrates the results of this model and compares them to the backcalculated M_R values from the Overton County site, and the Hudson/Drumm et al. (1997) technique.

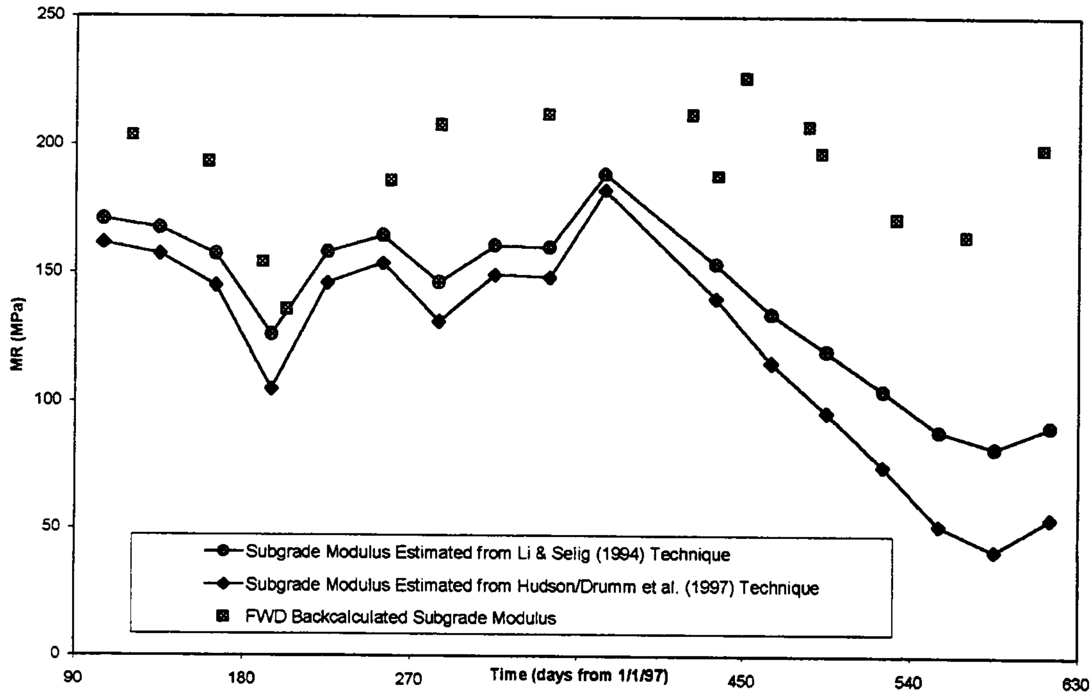

Figure 26 - Overton County Subgrade Modulus Calculated from Model

As illustrated in Figure 26, the Li and Selig (1994) technique yields results that are similar to the Hudson/Drumm et al.(1997) technique. This similarity stems from the fact that both techniques derive the change of M_R from the change of moisture content.

Ali and Parker (1996) Technique

Ali and Parker (1996) have approached estimation of fluctuations in pavement modulus values from a different direction. Their approach recognizes that seasonal variations of M_R can be modeled as a periodic sinusoidal function that reflects the annual influence of environmental conditions in the region of study, particularly in the absence of a freeze/thaw cycle. Freeze/thaw cycling has a severe influence on subgrade properties that Ali and Parker (1996) suggest may be better represented by polynomial or exponential functions. The test sites in this study are not subjected to freeze/thaw cycling. The general equation for the sinusoidal function suggested by Ali and Parker (1996) is:

$$M_R = A + B\sin(2\pi f \mathrm{T} + C) \tag{8}$$

Where: A = Average value

B = Amplitude of the wave

f = Frequency

T = Time of observation

C = Phase angle

Figure 27 demonstrates the sinusoidal function fit to the Overton County test site data, along with the FWD backcalculated values from the Overton County site. In this solution, A = 192 MPa, B = 48 MPa, f = 365 days, T = day of the year, and C = 1.2. Additionally, a factor has been added to this prediction equation to include the trend of increasing modulus values that occurred throughout this analysis period. The slope of this trend at the Overton County site was 0.03, derived by fitting a linear trend line to the Overton County plot of M_R over time. This factor can be modified or deleted as more data is collected.

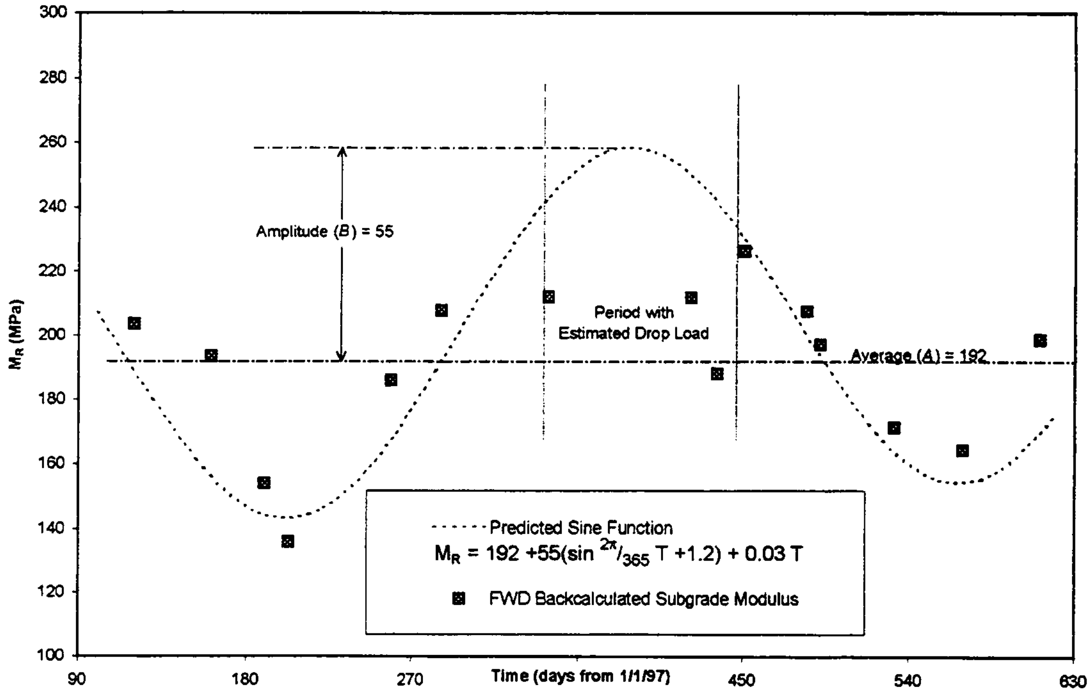

Figure 27 - Overton County Predicted Sine Function

Sine functions fitted to the data from all four study sites are included in Appendix E. Table 7 provides a comparison of the correlation between the values predicted by each of these techniques and the subgrade modulus values backcalculated from the FWD tests. As shown in Table 7, the Ali and Parker (1996) model (sinusoidal function) appears to provide the best overall correlation with the test site data collected in this study. However, the sinusoidal function was derived from the FWD data, whereas the values of M_R derived using the other two techniques are independent of the FWD data.

Table 7 – Correlation between Predicted and Backcalculated M_R

	Correlation Coefficient			
Method	**Blount**	**Overton**	**Sumner**	**McNairy**
Hudson/Drumm et al.	0.19	0.32	0.66	0.50
Li & Selig	0.21	0.32	0.67	0.50
Ali & Parker	0.56	0.72	0.62	0.64

7. RESOLVING SEASONAL FLUCTUATIONS IN M_R

AASHTO Relative Damage Approach

The 1993 AASHTO Guide outlines a procedure to compensate for seasonal fluctuations in M_R. This procedure begins with the determination of the seasonal values of M_R and the length of the seasons. The length of the seasons need be no less than ½ month, in which case 24 values of M_R will be needed. If one-month intervals are used, only 12 values are required. The modulus value will be the same for each interval during longer seasons when the modulus value is constant. The next step in the AASHTO calculation of a single design value of M_R is the estimation of relative damage (u_f) for each season. Relative damage is reflected by an index determined from a chart provided in the Guide, or a value can be calculated from the equation:

$$u_f = 1.18 \times 10^8 \times M_R^{-2.32} \tag{9}$$

It is important to point out that this estimation of relative damage only applies to the AASHTO flexible pavement design equation. The relative damage is measured empirically in terms of serviceability loss as compared to the AASHO Road Test, conducted in Ottawa, Illinois. The values of u_f are then summed and divided by the number of seasons to find the average value of u_f. The chart can be used again to find the value of M_R corresponding to the average value of u_f, or the equation for relative damage can be solved for M_R using the average value of u_f. This process determines the Effective Roadbed Soil Resilient Modulus, a value that reflects the sum of the cumulative damage from each season.

The AASHTO approach can be demonstrated by determining the Effective Modulus of Subgrade Reaction for the Blount County site as an example. A value of M_R (psi) is determined for each season from FWD test results, or through one of the techniques described in the previous chapter. For example, the modulus value from the September 1997 FWD test (28,866-psi) is used to determine a relative damage value.

$$u_f = 1.18 \times 10^8 \times (28{,}866)^{-2.32}$$

$$u_f = 0.005294$$

Then the relative damage is calculated for each month using Equation 9.

Month	**M_R (psi)**	**u_f**
January	29,646	0.004976
February	28,404	0.005496
March	27,146	0.006105
April	29,690	0.004959
May	28,732	0.005351
June	34,802	0.003431
July	32,280	0.004085
August	32,020	0.004162
September	28,866	0.005294
October	34,105	0.003595
November	32,337	0.004068
December	32,991	0.003883
Average Value	30,918	0.004617

Finally, the average of all relative damage values is used to solve Equation 9 for the Effective Modulus of Subgrade Reaction. The average relative damage value of 12 intervals for the Blount County site is 0.004617. Solving Equation 9 for M_R:

$$M_R = 10^{\frac{\log \frac{0.004617}{1.18 \times 10^8}}{-2.32}}$$

M_R = 30,619 psi (211 MPa)

Weighting Factor Approach

Another approach developed by Gomez-Achecar and Thompson (1984) with respect to environmental conditions, and refined by Guan et al. (1998) to address M_R, assigns weighting factors to each season. The general form of the equation developed to quantify environmental effects (Gomez-Achecar and Thompson, 1984) is:

$$WF_i = \frac{N_f}{N_{ai}} \tag{10}$$

Where: WF_i = Weighting Factor for a given month,
N_f = number of load repetitions to failure,
f = number of years to failure, and
N_{ai} = allowable number of load repetitions under prevailing conditions of the given month.

Guan, et al. (1998) proposed that this equation be applied to the seasonal variation of M_R, and assigned weighting factors based on the AASHTO flexible pavement serviceability criteria to the seasonal subgrade modulus values with the following equation:

$$WF_i = \frac{nM_{Ri}^{-2.32}}{\sum_{i=1}^{n} M_{Ri}^{-2.32}} \tag{11}$$

Where: M_{Ri} = resilient modulus of subgrade for ith month, and
n = number of months (intervals) used

In this approach the annual mean value of the weighting factors will always be 1. Solving equation 11 for M_R with WF equal to 1 will yield the effective annual subgrade modulus to be used for design.

Using the September 1997 FWD modulus again:

$$WF_i = \frac{(12)\times(28{,}866)^{-2.32}}{4.695\times10^{-10}}$$

$$WF_i = 1.147$$

Solving for M_R with WF equal to 1:

$$M_R = 10^{\frac{\log\frac{4.695\times10^{-10}}{12}}{-2.32}}$$

$$M_R = 30{,}620 \text{ psi } (211 \text{ MPa})$$

This approach, like the relative damage approach, is also applicable only to designs based on the AASHTO serviceability criteria.

Table 8 compares the results of the AASHTO approach to the weighting factor approach for the backcalculated values from Blount County and Overton County.

Table 8 - Effective Subgrade Resilient Modulus

Blount County			Overton County		
Annual Mean (Mpa)	Eff. M_R (u_f) (Mpa)	Eff. M_R (WF) (Mpa)	Annual Mean (Mpa)	Eff. M_R (u_f) (Mpa)	Eff. M_R (WF) (Mpa)
213	211	211	192	184	185

These two approaches to quantifying the seasonal variation of M_R yield similar results. Both equations are derived from the AASHTO serviceability criteria and Miner's hypothesis of cumulative linear damage (Guan et al., 1998; AASHTO, 1986). The approach suggested by Guan et al. offers a somewhat less complicated procedure. In addition, for a mechanistic design, the general equation for weighting factors can be modified to incorporate the failure criteria specified for that design.

8. RECOMMENDED DESIGN APPROACH

The analysis of the data collected in this study indicates that seasonal fluctuations of flexible pavement subgrade response to dynamic load are most closely related to sinusoidal patterns of air temperature. Therefore it should be possible to predict these fluctuations with a sinusoidal function, and resolve them by assigning weighting factors to the values derived for each season. It should be noted that the procedure described here is limited to relatively new pavement systems constructed on embankment fill in climatic regions devoid of freeze/thaw cycles.

The first requirement is the determination of a maximum, minimum and mean value of M_R, and the time of occurrence of the maximum and minimum. These values can be determined from FWD tests, or from one of the techniques described earlier for estimating M_R from index properties or a mathematical model. The mean establishes the base line modulus value, the difference between the mean and the maximum or minimum (whichever is greater) determines the amplitude of the sine function, and the time of year where the maximum or minimum values occur sets the phase angle, or offset. Also, if a linear trend of increasing or decreasing values is evident, this trend can be incorporated by algebraically adding the time period multiplied by the slope of this trend. Once these parameters have been established, the sine curve representing seasonal fluctuations is generated using equation 8.

With an estimate of the seasonal values of M_R in hand, weighting factors are then assigned to each modulus value. The weighting factor should represent the magnitude of the damage to the pavement system during that particular season. The weighting factor equation should reflect the failure criteria employed in the design procedure that will be used. For the AASHTO serviceability criteria, equation 11 is applicable. Each incremental damage value is multiplied by the number of increments, and divided by the sum of all the incremental damages to determine the weighting factor for that increment. Then the design value of M_R that represents the cumulative damage for the entire year is at the point where the weighting factor is equal to 1.

With careful application of this procedure, the period of time when the weighting factor is equal to 1 can be determined for a particular region, and future testing of the pavement system can be concentrated at that time of the year. From the data collected so far in this study, that time of year would most likely be in the early part of the fall season for the Tennessee test sites. At this time of the year, significant precipitation events are less likely, the air temperature is near a median range, and the seasonal fluctuations of subgrade moisture content are ebbing.

9. CONCLUSIONS

The moisture content of subgrade soils under nearly impervious pavements demonstrates a seasonal pattern, with an increase of moisture content in the upper layers in the warm season and a decrease in the cold season. This pattern has been related to the annual fluctuations of air temperature at the four test sites in Tennessee. Furthermore, the moisture content of the subgrade under pavements constructed on embankments appears to be increasing with time, perhaps toward equilibrium with the moisture content of the surrounding soils.

While the pavement surface remains relatively impervious, precipitation generally has little effect on the subgrade moisture content. However, it has been demonstrated that when the semi-impervious surface layer is not intact, a greater percentage of the moisture produced by precipitation events will infiltrate the pavement system, resulting in significant increases in the moisture content of the aggregate base layer. The aggregate base layer experienced greater variation of moisture content than the subgrade at the three sites where TDR probe 4 data was available. The increased moisture content of the base layer can eventually influence the moisture content of the underlying subgrade, although this influence may be delayed by several weeks. The results of this study indicate that the most critical period of time for the pavement system subgrade is the warm summer season following a spring season with above normal amounts of precipitation.

It has been demonstrated that the fluctuations of subgrade modulus recorded over the analysis period are significant, and can be translated as a 10% to 20% difference in required pavement depth. Seasonal variation of M_R was not significantly greater than the combined spatial and systemic variability of the FWD test results in this study. With this fact in mind, it should be understood that attempts to confirm methods for predicting changes of M_R with FWD testing will have a certain margin of error. This process is further complicated by the early time stiffening of the asphaltic concrete layers as a result of aging and traffic-induced densification.

In the absence of extreme environmental conditions, such as a freeze/thaw cycle, the seasonal fluctuations of subgrade response can be predicted using a sinusoidal function with a reasonable amount of confidence. Based on the data from this study, this approach offers a better fit to the FWD data than prediction models based on index properties and moisture content change.

With values of M_R from each season, a weighting factor can be assigned to each season that represents the level of damage sustained by the pavement system during that season. Then the value of M_R that corresponds to the mean weighting factor (1) is the value to be used in the design of a pavement system or the overlay of a pavement system supported by that subgrade soil.

10. RECOMMENDATIONS FOR FURTHER STUDY

The following recommendations are made for further study:

- Pavement sections constructed in cuts should be instrumented and FWD tests conducted on these sections to supplement the knowledge gained from the sites constructed on embankments that were analyzed in this study.
- Moisture content of the uncovered soil near the pavement should be monitored.
- The construction of the pavement system should be well documented, including observations about environmental conditions during the construction process.
- FWD testing should be performed on each layer of the pavement system as it is constructed to develop an initial value of resilient modulus for each material.
- A journal should be maintained by the FWD technicians to document environmental conditions during the test procedure, as well as any other unusual circumstances, such as standing water, overgrown drainage outlets, etc.
- FWD testing should be performed on a more frequent basis (twice monthly), for at least the first two years, and especially during the months when M_R is at a maximum and minimum. This will better determine the values that determine the average and amplitude of the sine function. After the first two years, testing can be concentrated in the months with modulus values close to the mean, and every five years the seasonal pattern can be re-evaluated.

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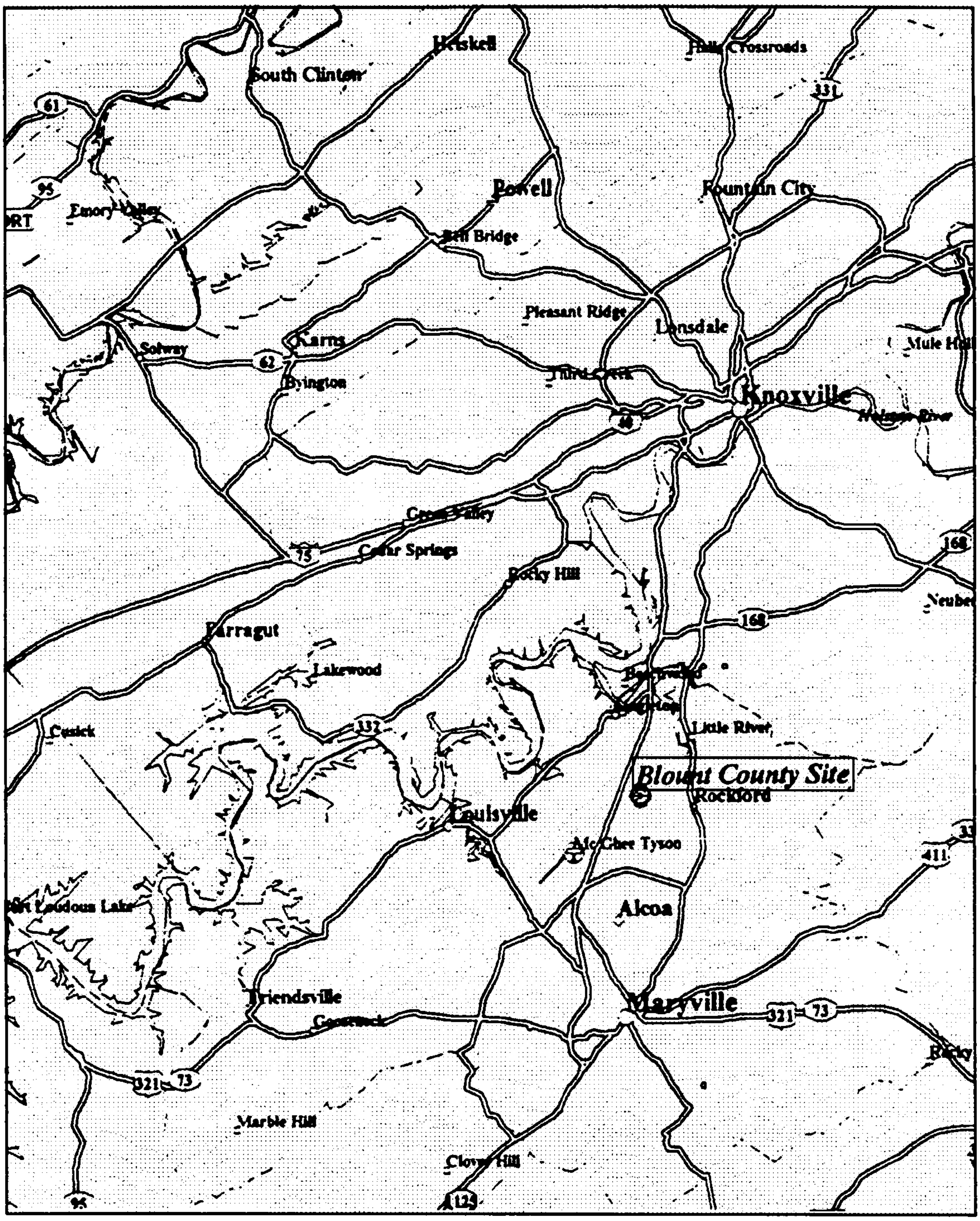
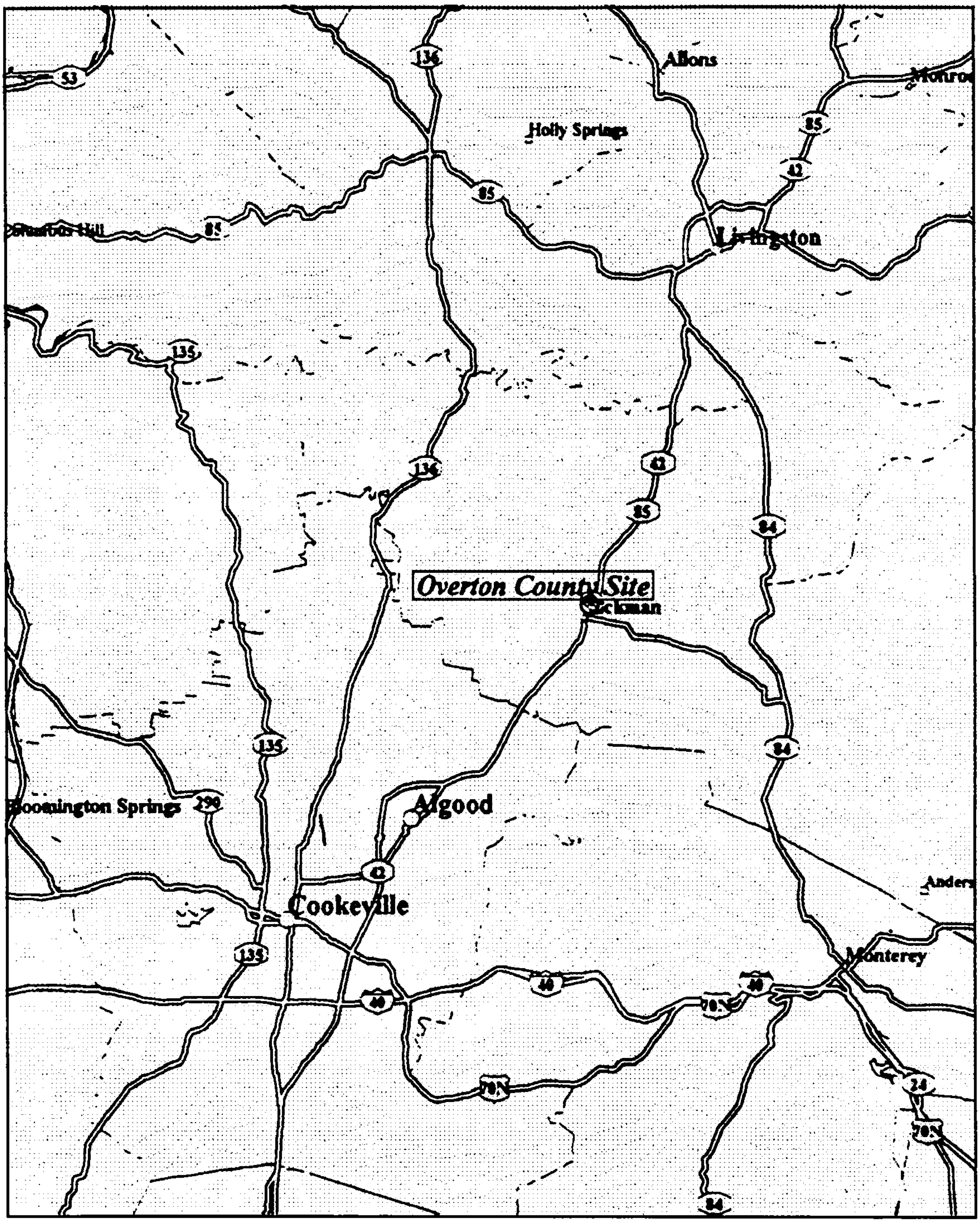
APPENDICES

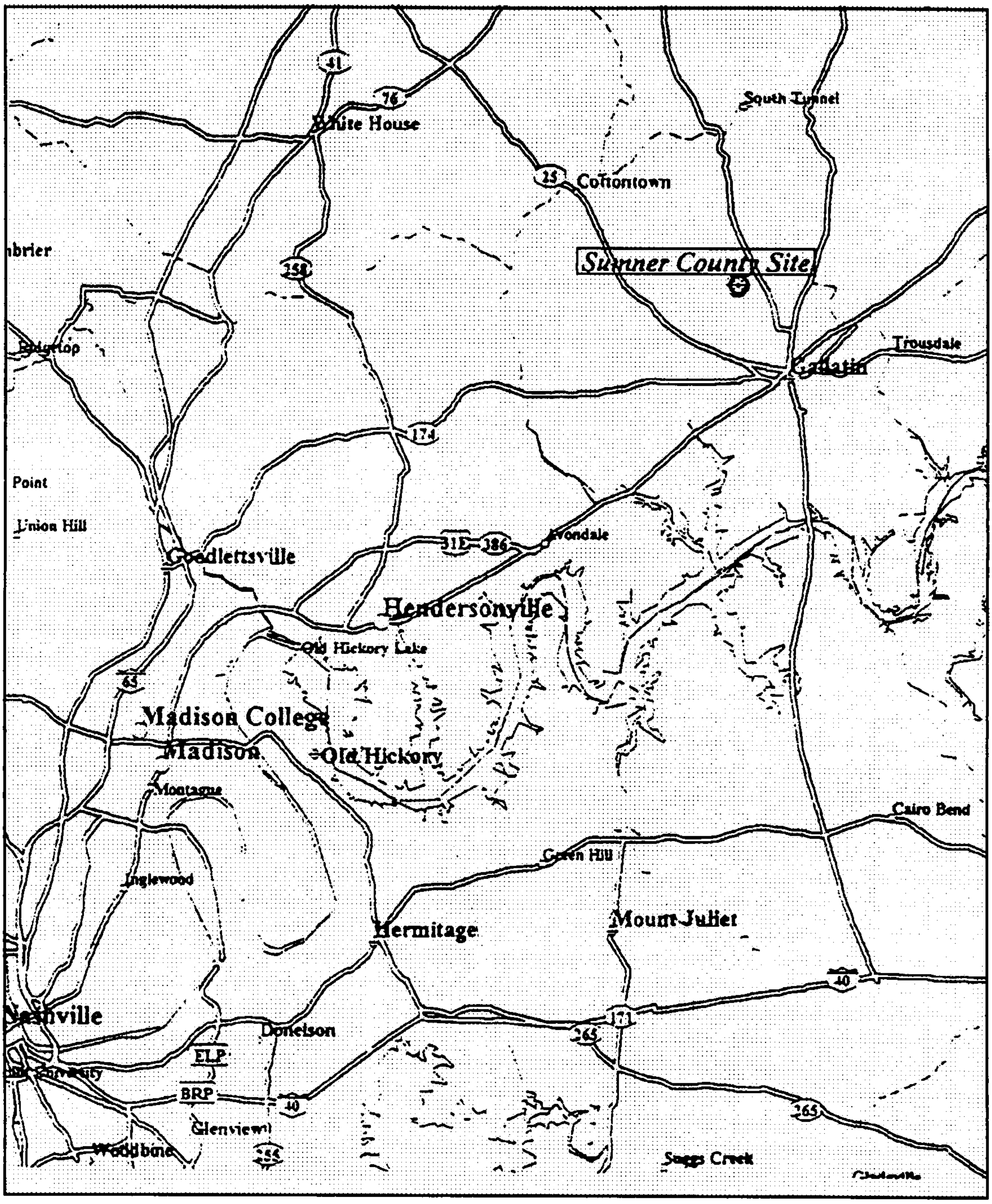
APPENDIX A
TEST SITE VICINITY MAPS



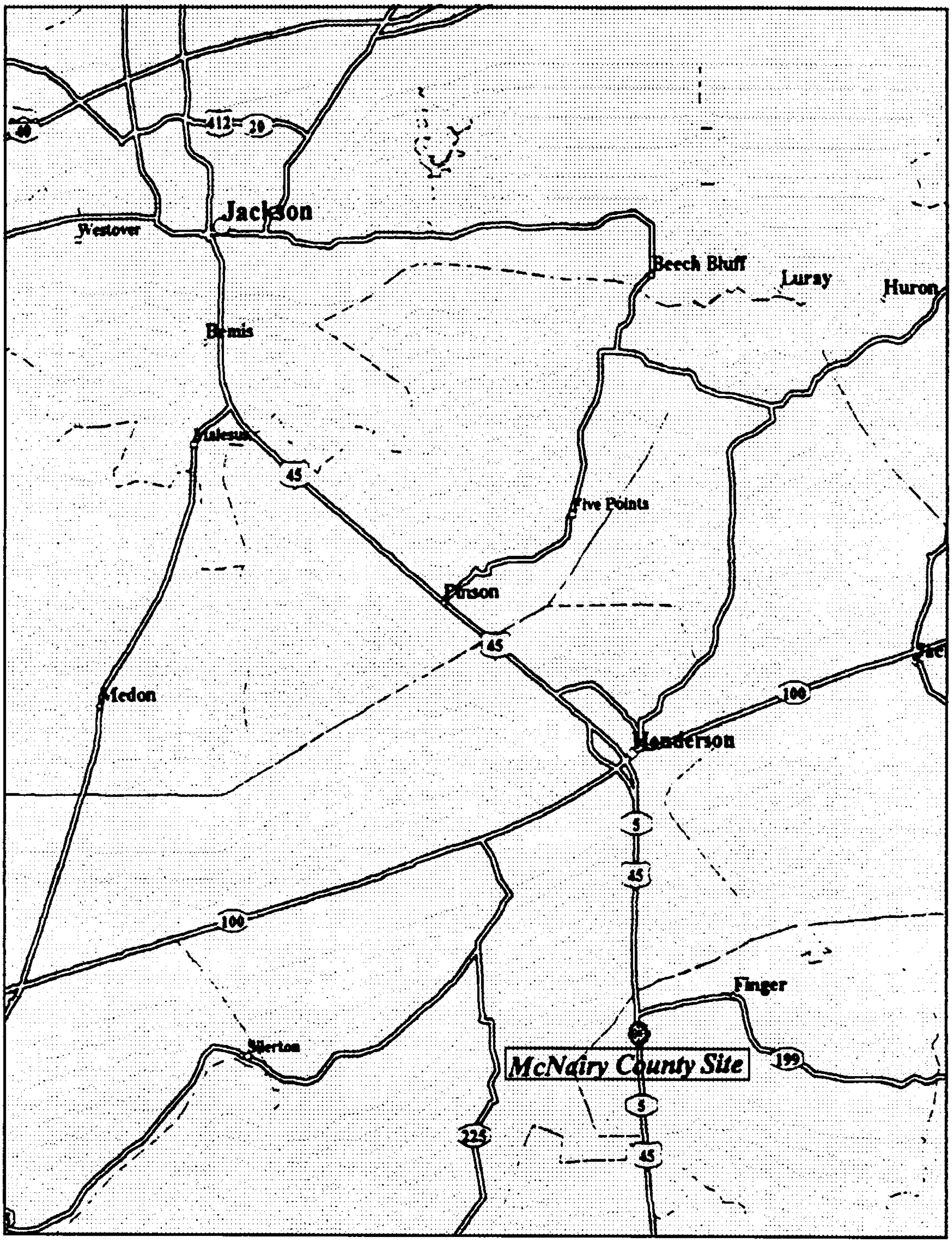
A.1 – Blount County Site



A.2 – Overton County Site



A.3 – Sumner County Site



A.4 – McNairy County Site

APPENDIX B
TEST SITE PAVEMENT DESIGN DATA

Original TDOT Design Parameters

Blount County Site

CBR = 5.00 SSV = 2.20 Design Period = 20 yrs ADL = 277.0 SN = 5.38

Layer	Description	Coefficient	Thickness (in)	SN
411-01	Polymer Mod. Surf. Grade D	0.40	1.25	0.50
307-04	Polymer Mod. Grade B-Mod2	0.40	2.00	0.80
307-04	Polymer Mod. Grade A	0.40	4.00	1.60
303-01	Mineral Agg. Base Grade D	0.14	10.00	1.40

Overton County Site

CBR = 9.00 SSV = 3.56 Design Period = 20 yrs ADL = 440.0 SN = 4.37

Layer	Description	Coefficient	Thickness (in)	SN
411-01	Surface Grade D	0.40	1.25	0.50
307-03	Binder Grade B-Mod2	0.40	2.00	0.80
307-03	Black Base Grade A	0.40	3.00	1.20
307-01	Black Base Grade A-S	0.30	3.00	0.90
303-01	Mineral Agg. Base Grade D	0.14	10.00	1.40

Sumner County Site

CBR = 4.00 SSV = 1.68 Design Period = 20 yrs ADL = 247.0 SN = 5.63

Layer	Description	Coefficient	Thickness (in)	SN
411-01	Surface Grade D	0.40	1.25	0.50
307-03	Binder Grade B-Mod2	0.40	2.00	0.80
307-03	Black Base Grade A	0.40	3.50	1.20
303-01	Mineral Agg. Base Grade D	0.14	10.00	1.40

McNairy County Site

CBR = 6.77 SSV = 2.90 Design Period = 20 yrs ADL = 761.0 SN = 5.69

Layer	Description	Coefficient	Thickness (in)	SN
411-01	Surface Grade D	0.40	1.25	0.50
307-03	Binder Grade B-Mod2	0.40	2.00	0.80
307-01	Black Base Grade A	0.40	6.00	2.40
307-01	Black Base Grade A-S	0.30	3.00	0.90
303-01	Mineral Agg. Base Grade D	0.10	10.00	1.00

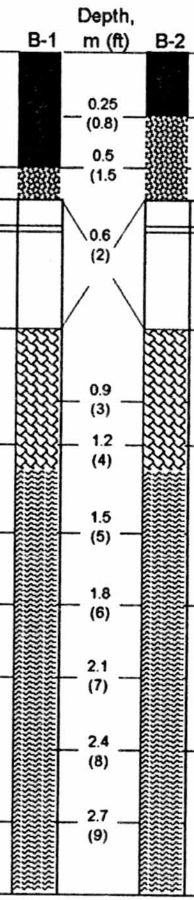
APPENDIX C
TEST SITE SOIL BORING LOGS

C.1 - Blount County Field Boring Logs

B-1

Asphaltic Concrete Pavement / Unbound Mineral Aggregate Base / Subgrade Soil

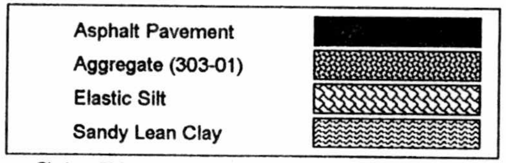
USCS Class.	AASHTO Class.	Plastic Index	Liquid Limit	In-Situ Water Content (%)	In-Situ Density (Mg/m^3)
MH	A-7-5 (20)	17	55	32.1	1.43
ML					
	A-7-6 (14)	15	44	26	1.63



B-2

Asphaltic Concrete Pavement / Unbound Mineral Aggregate Base / Subgrade Soil

In-Situ Density (Mg/m^3)	In-Situ Water Content (%)	Liquid Limit	Plastic Index	AASHTO Class.	USCS Class.
		55	25	A-7-5(25)	MH
1.55	25.8	40	20	A-6(17)	CL
1.59	20.7	33	10	A-7-6(18)	
1.62	22.3	41	20	A-7-6(17)	

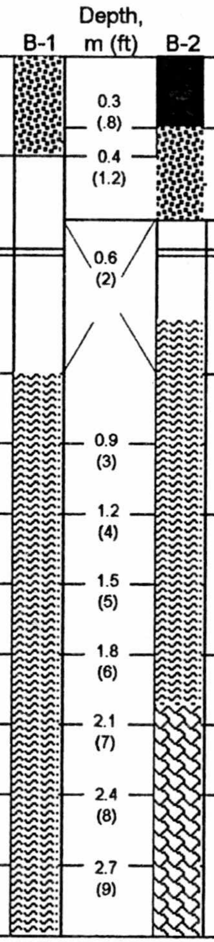


C.1 - Blount County Field Boring Logs

B-1

Layer					
Unbound Mineral Aggregate Base					
Subgrade Soil					

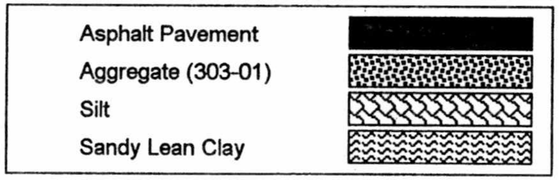
USCS Class.	AASHTO Class.	Plastic Index	Liquid Limit	In-Situ Water Content (%)	In-Situ Density (Mg/m^3)
CL	A-7-5(15)	17	45		
CL	A-6 (14)	18	40	29.3	1.55
	A-4 (16)	18	29	19.4	1.68



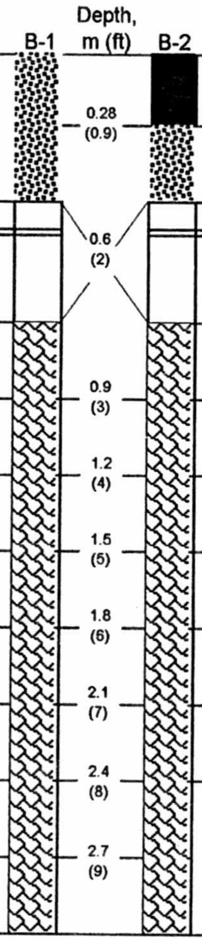
B-2

Layer					
Asphaltic Concrete Pavement					
Unbound Mineral Aggregate Base					
Subgrade Soil					

In-Situ Density (Mg/m^3)	In-Situ Water Content (%)	Liquid Limit	Plastic Index	AASHTO Class.	USCS Class.
		44	25	A-7-6(20)	CL
1.69	19.0				
1.57	24.5	42	23	A-7-6(19)	
1.60	22	24	7	A-4 (3)	CL-ML
1.72	18.6	18	1	A-4 (0)	ML



C.2 - Overton County Field Boring Logs



B-1

Unbound Mineral Aggregate Base

Subgrade Soil					
USCS Class.	AASHTO Class.	Plastic Index	Liquid Limit	In-Situ Water Content (%)	In-Situ Density (Mg/m³)
	A-7-6 (20)	25	50	22	1.58

B-2

Asphaltic Concrete Pavement

Unbound Mineral Aggregate Base

Subgrade Soil					
In-Situ Density (Mg/m³)	In-Situ Water Content (%)	Liquid Limit	Plastic Index	AASHTO Class.	USCS Class.
1.58	24	42	19	A-7-5 (13)	
1.56	26	46	21	A-7-6 (17)	
1.59		49	21	A-7-6 (17)	
1.36	25	41	18	A-7-6 (14)	
	22				

Legend:
- Asphalt Pavement
- Aggregate (303-01)
- Silty Clay

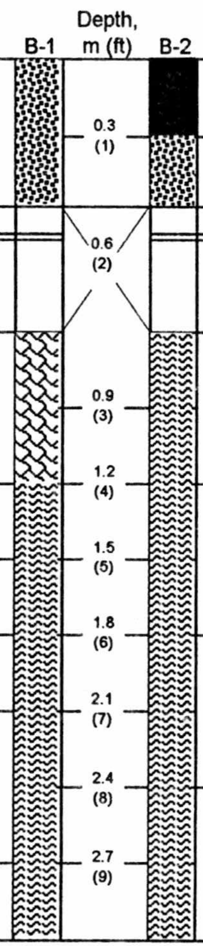
C.3 - Sumner County Field Boring Logs

Boring B-1

Unbound Mineral Aggregate Base

Subgrade Soil

USCS Class.	AASHTO Class.	Plastic Index	Liquid Limit	In-Situ Water Content (%)	In-Situ Density (Mg/m^3)
ML	A-4 (2)	9	34	16.9	1.75
CL-ML	A-4 (1)	6	27		
CL	A-6 (4)	12	27	17.3	1.84



Boring B-2

Asphaltic Concrete Pavement

Unbound Mineral Aggregate Base

Subgrade Soil

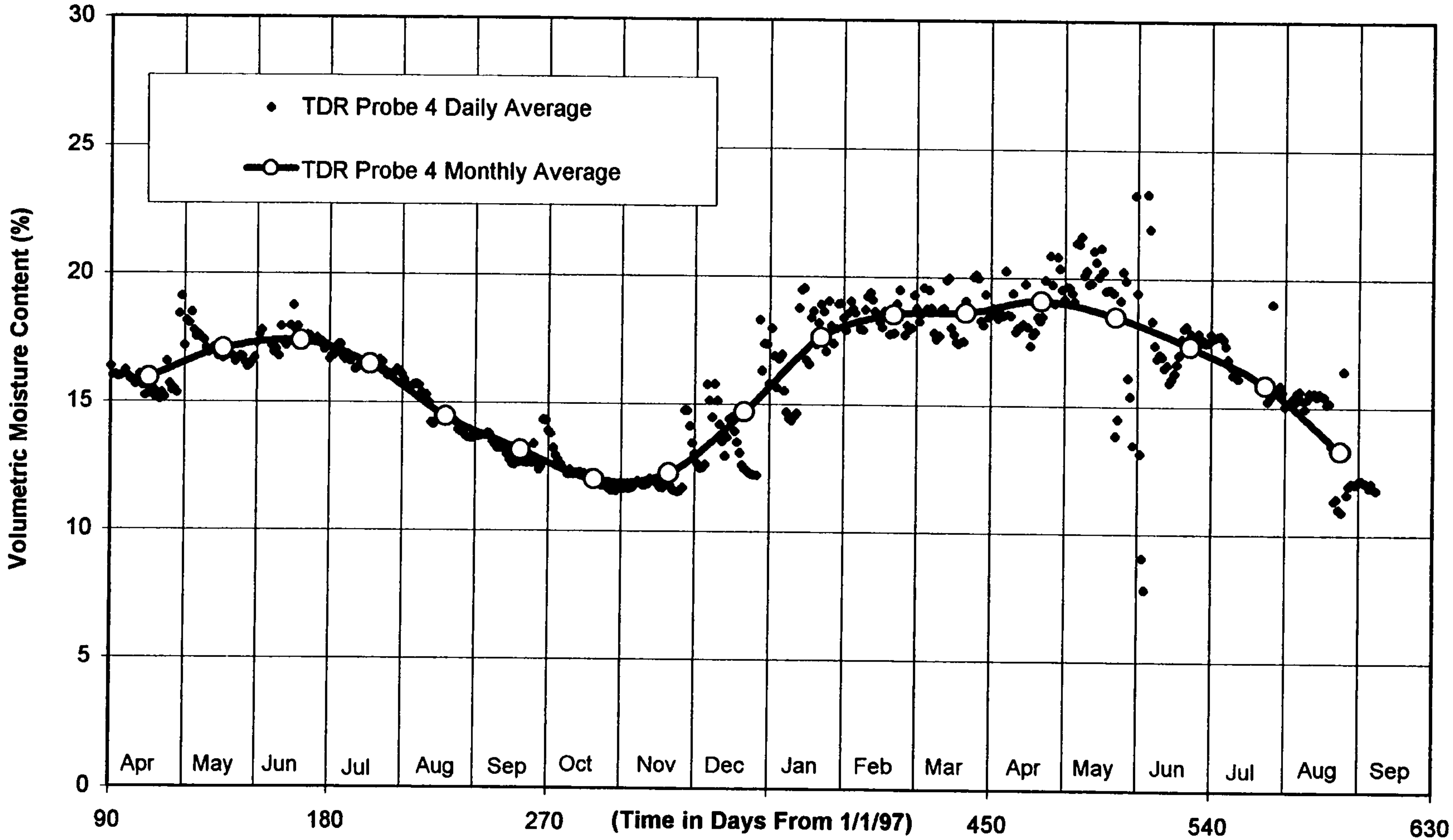
In-Situ Density (Mg/m^3)	In-Situ Water Content (%)	Liquid Limit	Plastic Index	AASHTO Class.	USCS Class.
		25	10	A-4 (2)	CL
1.84	16.1	29	14	A-6 (5)	
1.80	17.6	32	17	A-6 (5)	
1.72	14.6	26	11	A-6 (2)	

Asphalt Pavement
Aggregate (303-01)
Silty Clay
Sandy Lean Clay

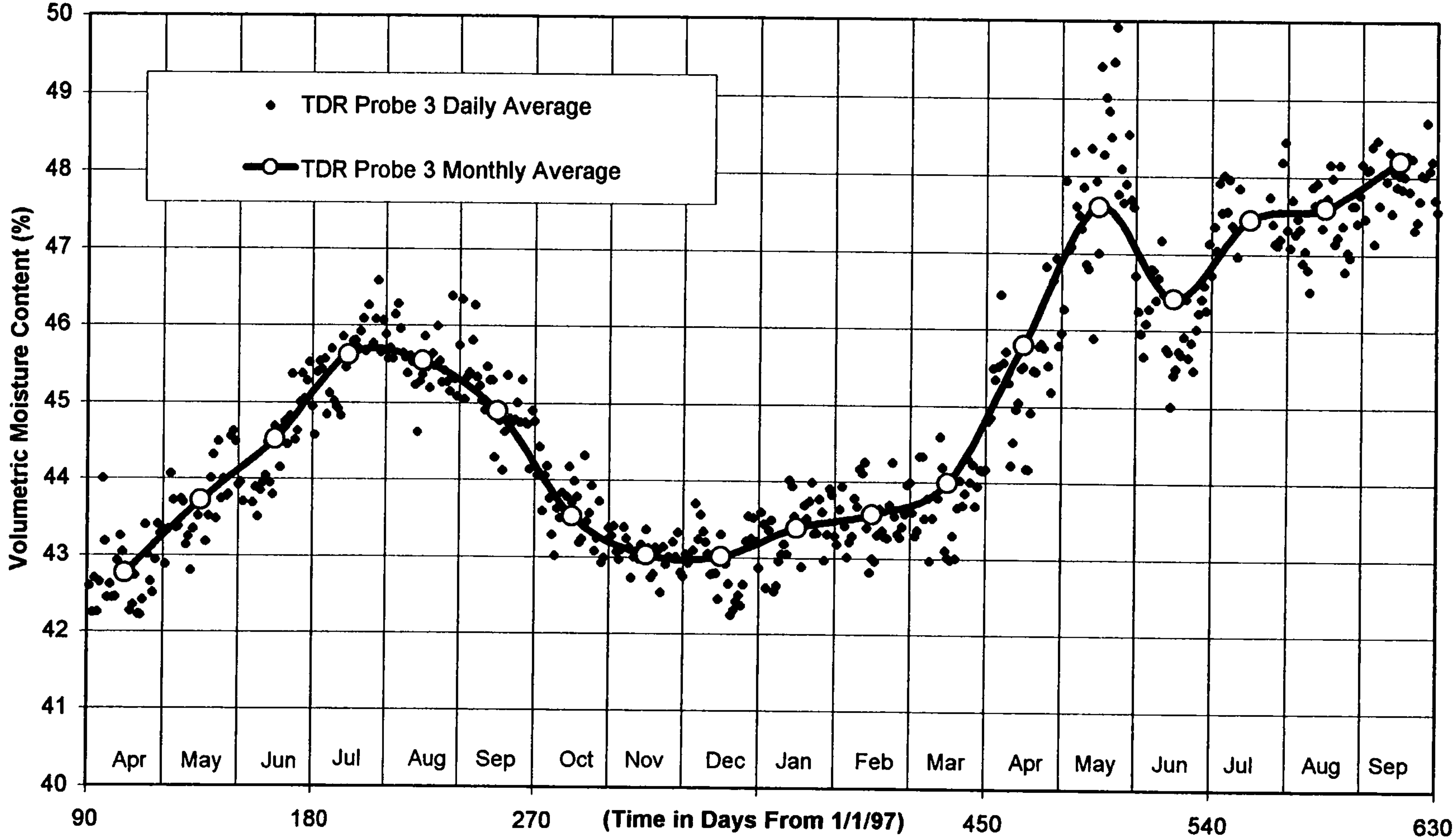
C.4 - McNairy County Field Boring Logs

APPENDIX D
DATA COLLECTED FROM TEST SITES

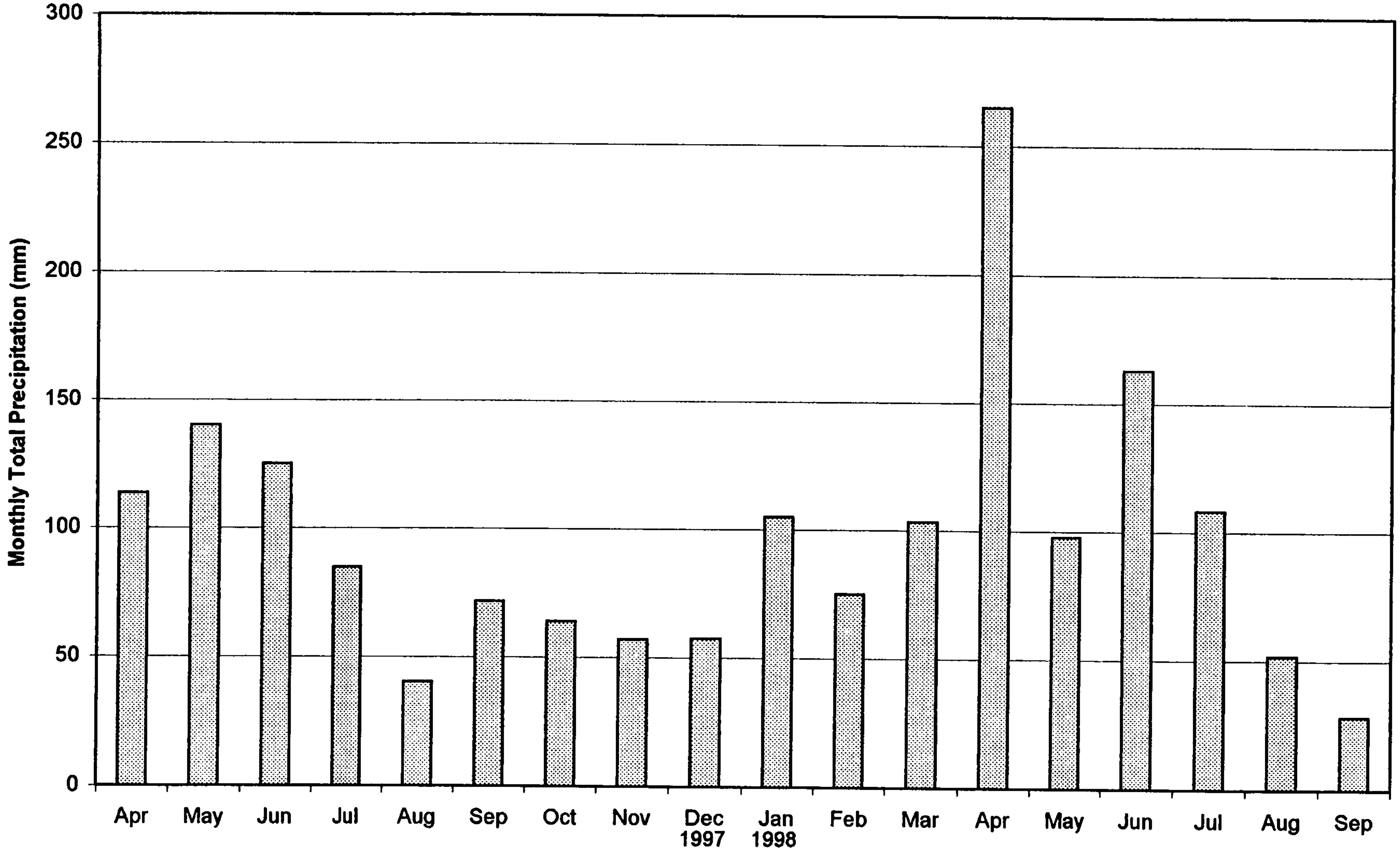
Blount County Average Monthly Moisture Content and Precipitation						
		Probe 3		Probe 4		
		Monthly Ave.		Monthly Ave.		Monthly Ave.
		Volumetric		Volumetric		Precip.
Month	day	Moisture (%)		Moisture (%)		(mm)
Apr'97	105	42.77		15.94		113.5
May'97	135	43.72		17.08		140
Jun'97	165	44.52		17.38		125
Jul'97	195	45.62		16.47		84.7
Aug'97	225	45.54		14.46		40
Sep'97	255	44.89		13.14		71.6
Oct'97	285	43.53		12.02		63.9
Nov'97	315	43.03		12.27		57
Dec'97	345	43.01		14.70		57.4
Jan'98	375	43.39		17.62		104.9
Feb'98	405	43.57		18.52		75.1
Mar'98	435	44.00		18.61		103.4
Apr'98	465	45.79		19.09		264.9
May'98	495	47.60		18.49		97.8
Jun'98	525	46.41		17.32		162.7
Jul'98	555	47.44		15.84		108.1
Aug'98	585	47.59		13.31		51.8
Sep'98	615	48.21				28.2



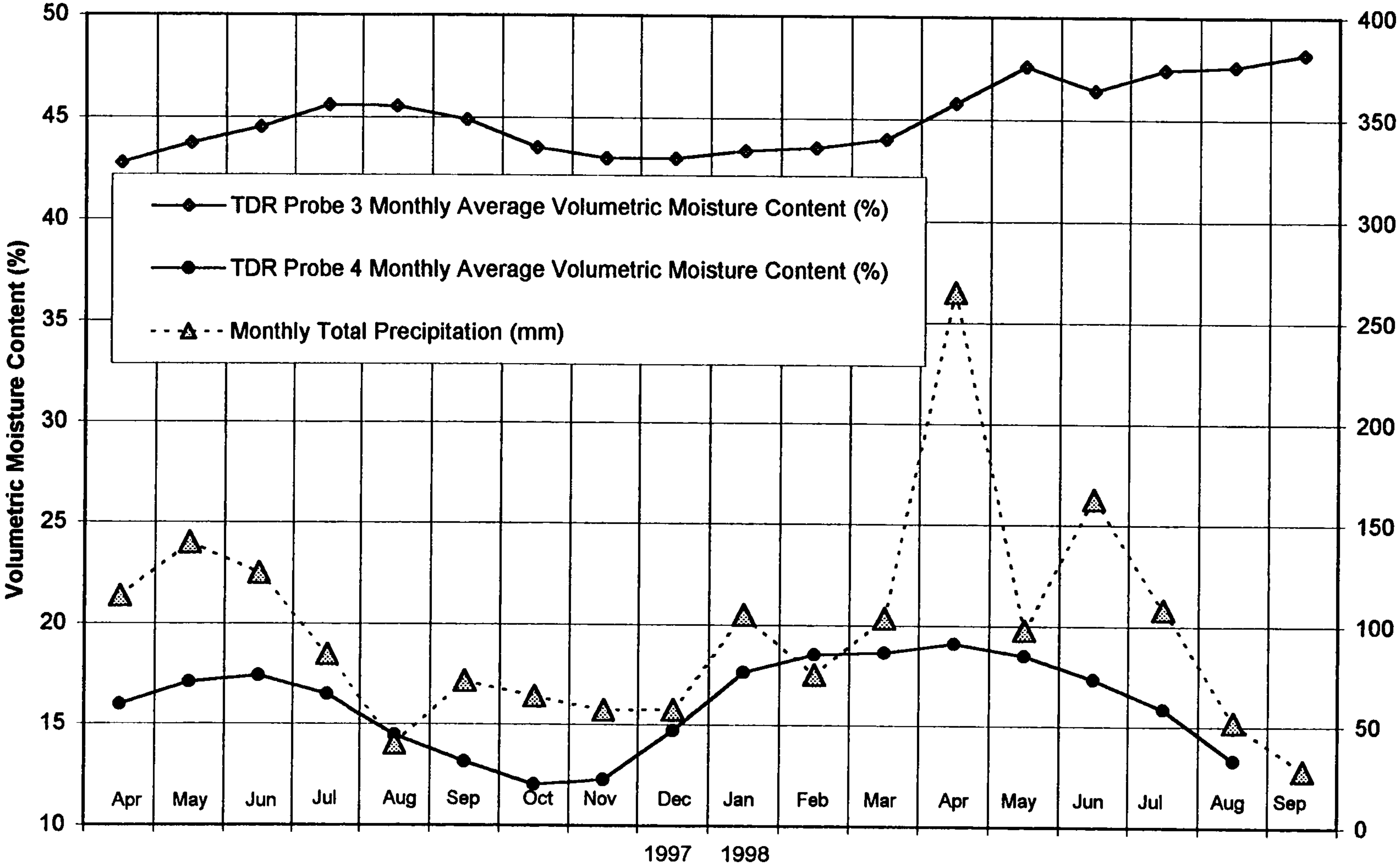
D.1 - Blount County Aggregate Base Volumetric Moisture Content



D.2 - Blount County Subgrade Volumetric Moisture Content



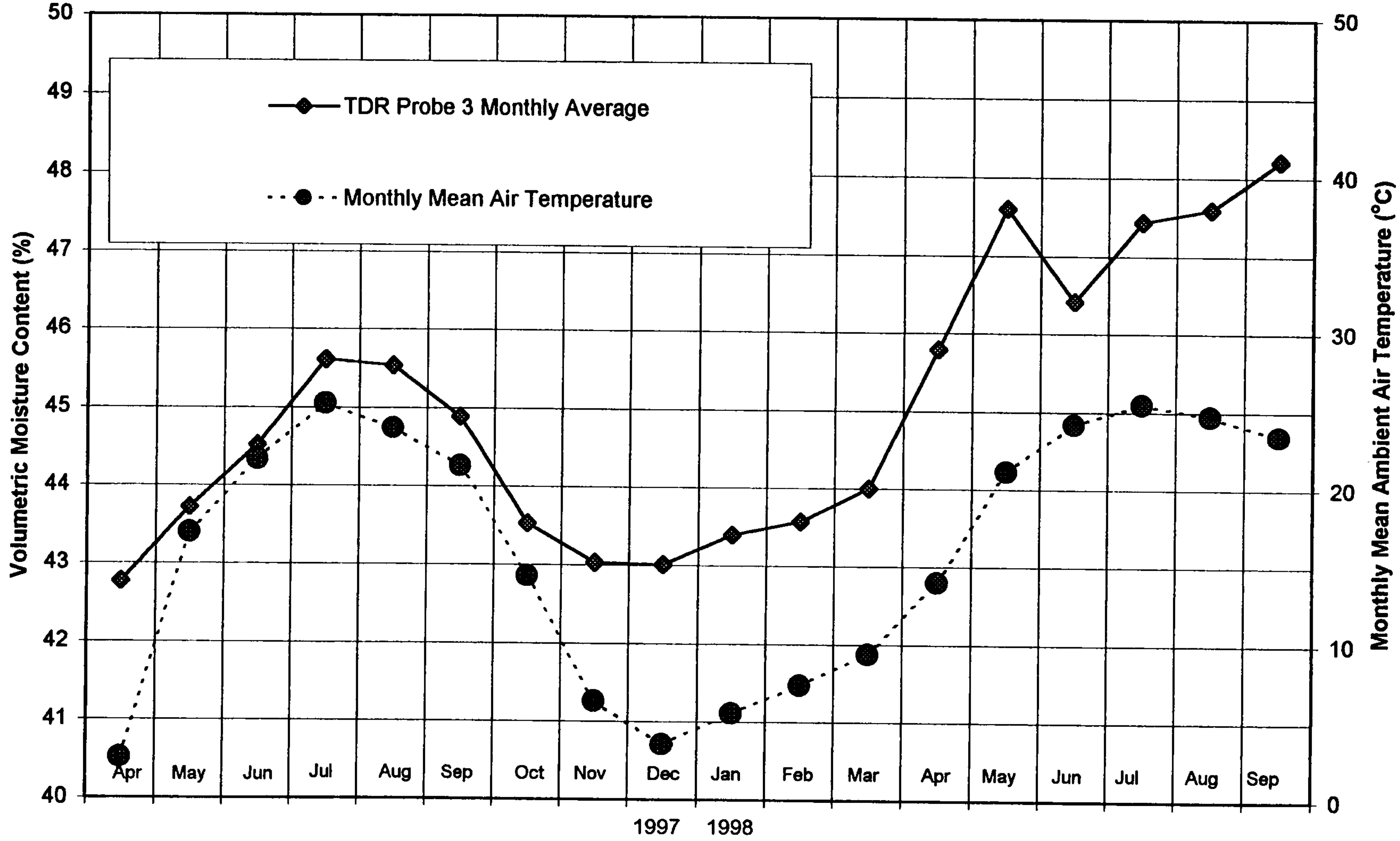
D.3 - Blount County Monthly Total Precipitation



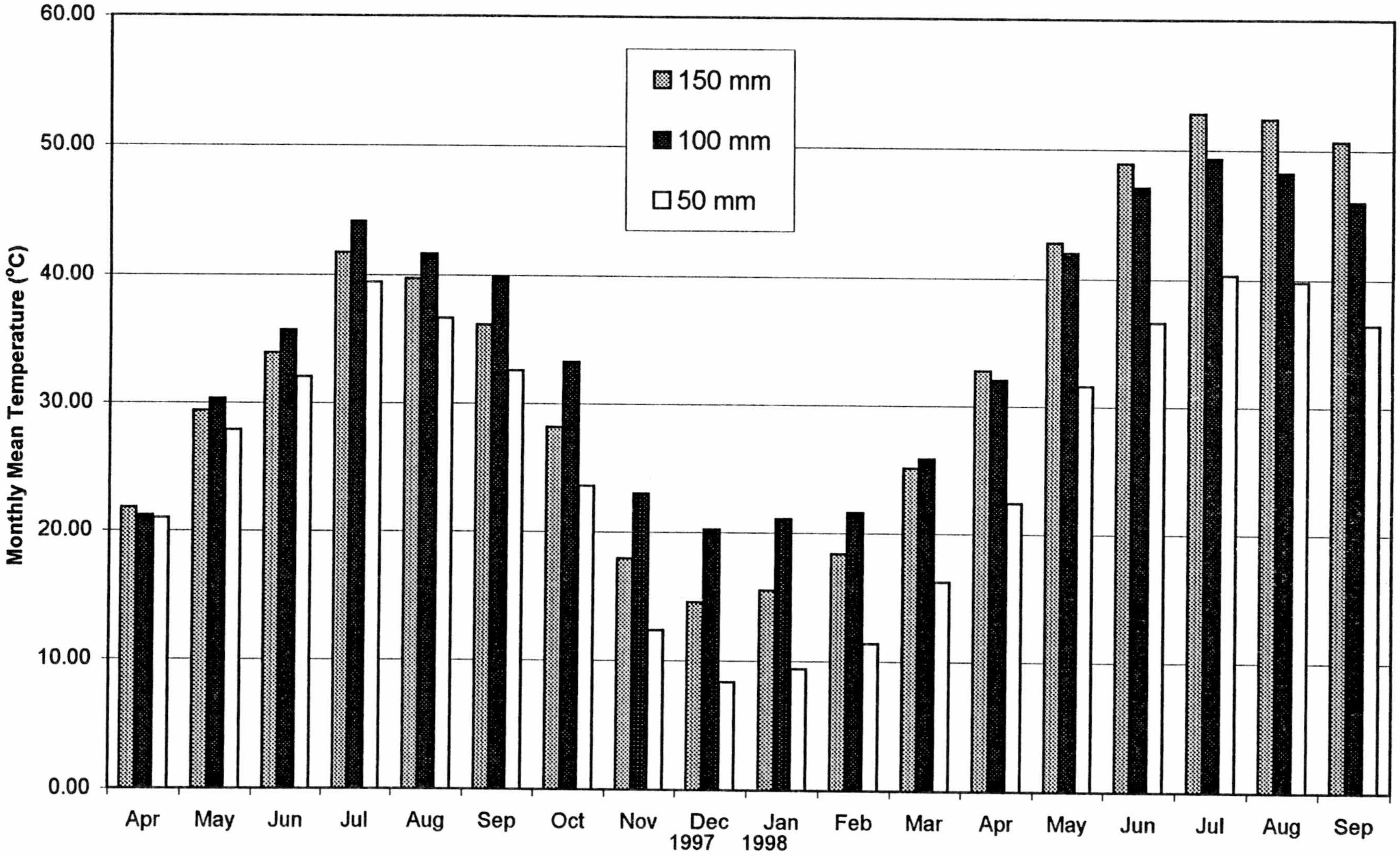
D.4 - Blount County: Precipitation and Moisture Content

Blount County Monthly Mean Temperature (°C)

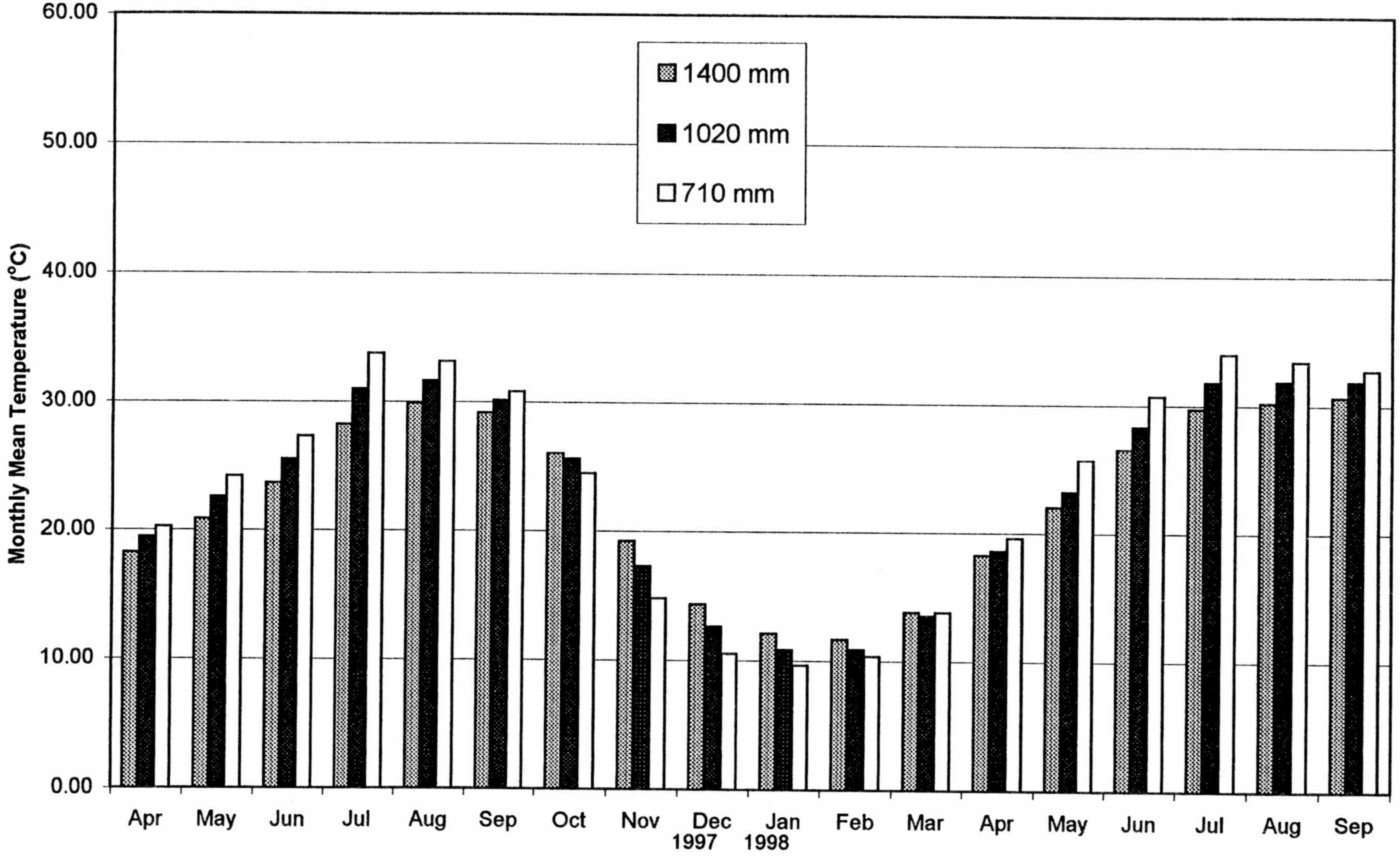
	Subgrade			Aggregate		AC Pavement			Ambient
Month	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5	Probe 6	Probe 7	Probe 8	Air
Apr	18.24	19.44	20.25	20.61	20.94	21.79	21.17	21.00	2.60
May	20.88	22.57	24.18	24.77	25.55	29.40	30.33	27.91	16.99
Jun	23.67	25.48	27.31	27.99	29.06	33.91	35.69	32.02	21.65
Jul	28.23	30.96	33.72	34.73	35.89	41.71	44.17	39.41	25.26
Aug	29.86	31.61	33.13	33.83	34.07	39.69	41.63	36.65	23.70
Sep	29.17	30.11	30.82	31.15	30.67	36.16	39.87	32.55	21.28
Oct	26.01	25.54	24.47	24.16	22.76	28.20	33.24	23.57	14.28
Nov	19.23	17.31	14.79	14.10	12.26	17.94	23.00	12.33	6.31
Dec	14.36	12.60	10.51	10.02	8.37	14.55	20.23	8.34	3.56
Jan	12.08	10.84	9.62	9.52	8.41	15.51	21.07	9.39	5.56
Feb	11.65	10.87	10.35	10.46	9.72	18.41	21.59	11.34	7.37
Mar	13.77	13.49	13.78	14.03	13.64	25.11	25.85	16.24	9.38
Apr	18.28	18.61	19.62	19.95	19.61	32.77	32.00	22.42	13.98
May	22.04	23.22	25.68	26.56	27.12	42.78	42.02	31.59	21.12
Jun	26.54	28.31	30.67	31.56	31.55	48.92	47.11	36.59	24.19
Jul	29.73	31.77	33.97	34.88	34.15	52.79	49.34	40.30	25.49
Aug	30.21	31.85	33.38	34.28	33.40	52.39	48.23	39.79	24.73
Sep	30.65	31.87	32.71	33.39	32.06	50.67	46.01	36.43	23.43



D.5 - Blount County: Air Temperature and Moisture Content

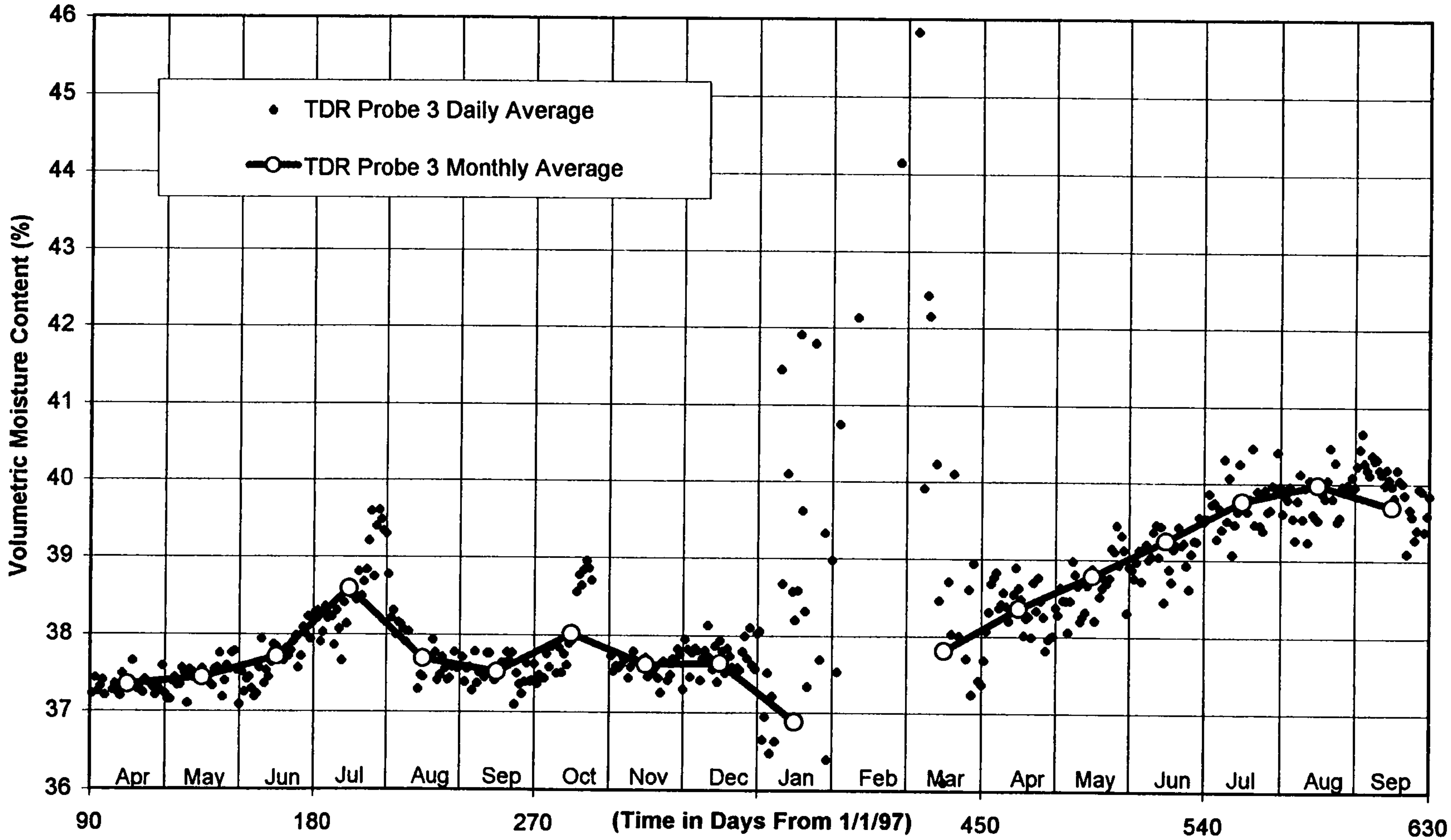


D.6 - Blount County Monthly Mean AC Pavement Temperature

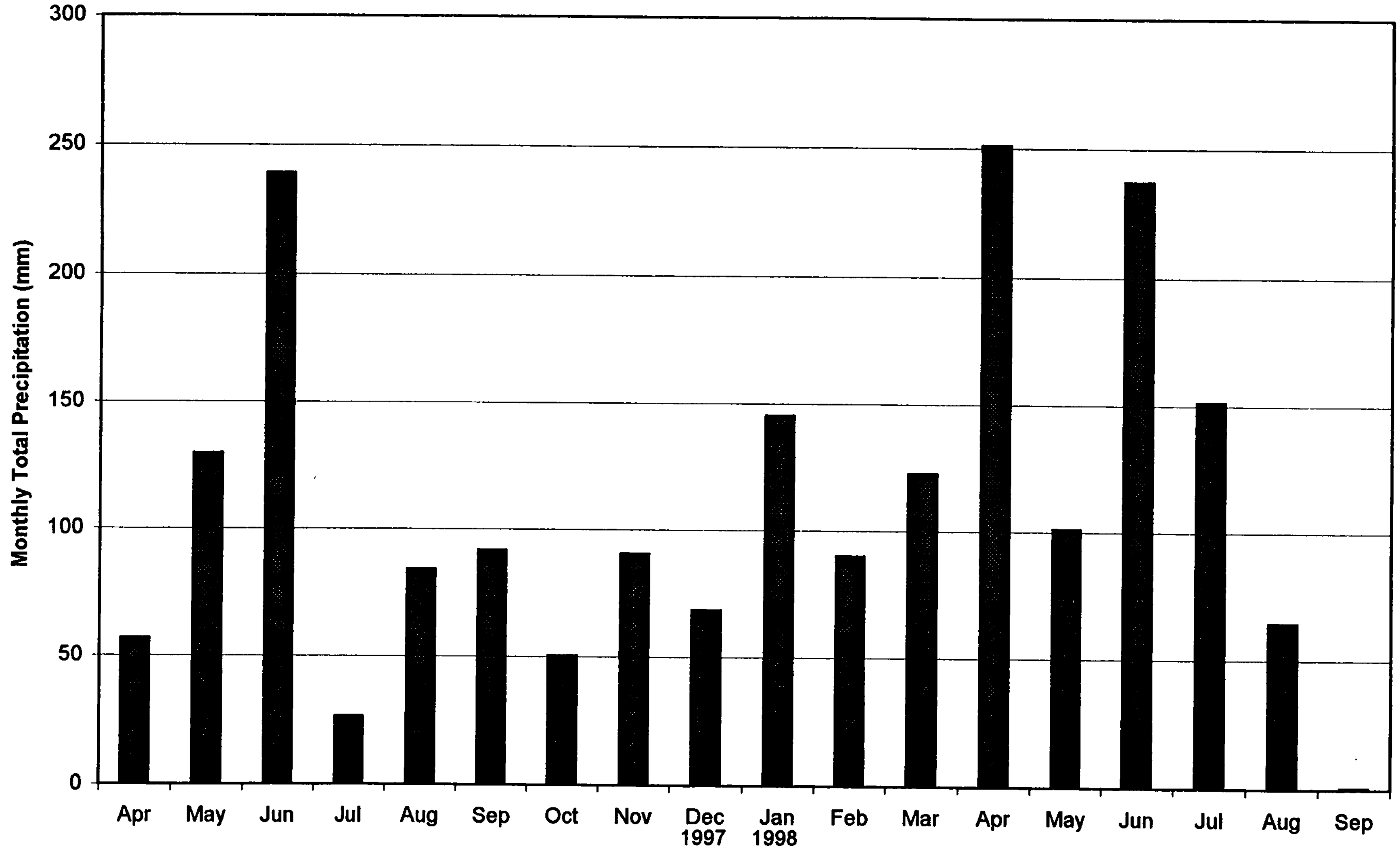


D.7 - Blount County Subgrade Monthly Mean Temperature

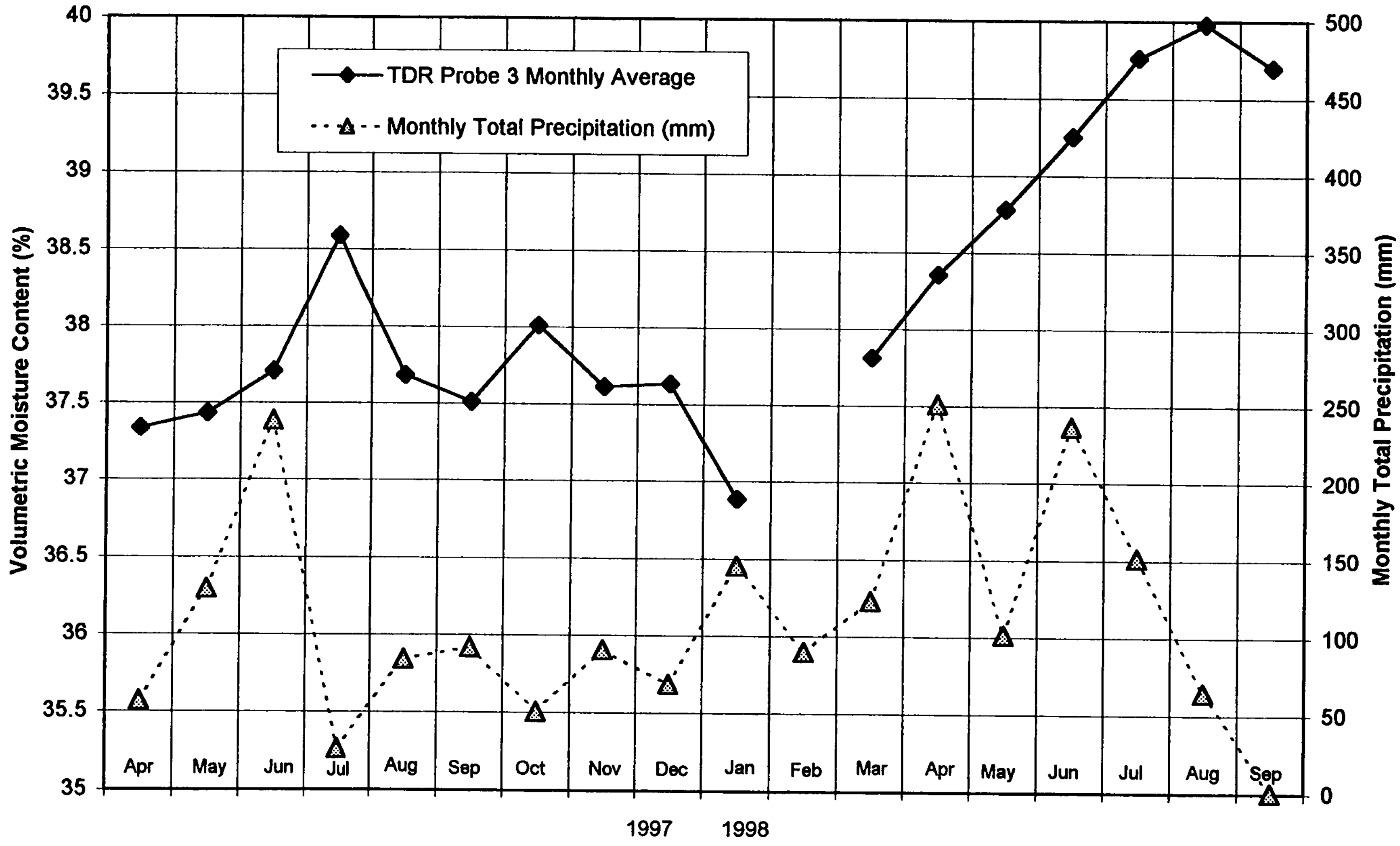
Overton County Average Monthly Moisture Content and Precipitation						
		Probe 3				
		Monthly Ave.				Monthly Ave.
		Volumetric				Precip.
Month	day	Moisture (%)				(mm)
Apr'97	105	37.34				56.9
May'97	135	37.43				129.5
Jun'97	165	37.71				239.1
Jul'97	195	38.59				26.5
Aug'97	225	37.68				84.1
Sep'97	255	37.51				91.7
Oct'97	285	38.01				50.3
Nov'97	315	37.61				90.5
Dec'97	345	37.63				68.5
Jan'98	375	36.89				145.3
Feb'98	405					89.9
Mar'98	435	37.81				122.7
Apr'98	465	38.36				251.1
May'98	495	38.78				101.1
Jun'98	525	39.25				237.1
Jul'98	555	39.76				151.4
Aug'98	585	39.98				64.5
Sep'98	615	39.70				0.7



D.8 - Overton County Subgrade Volumetric Moisture Content



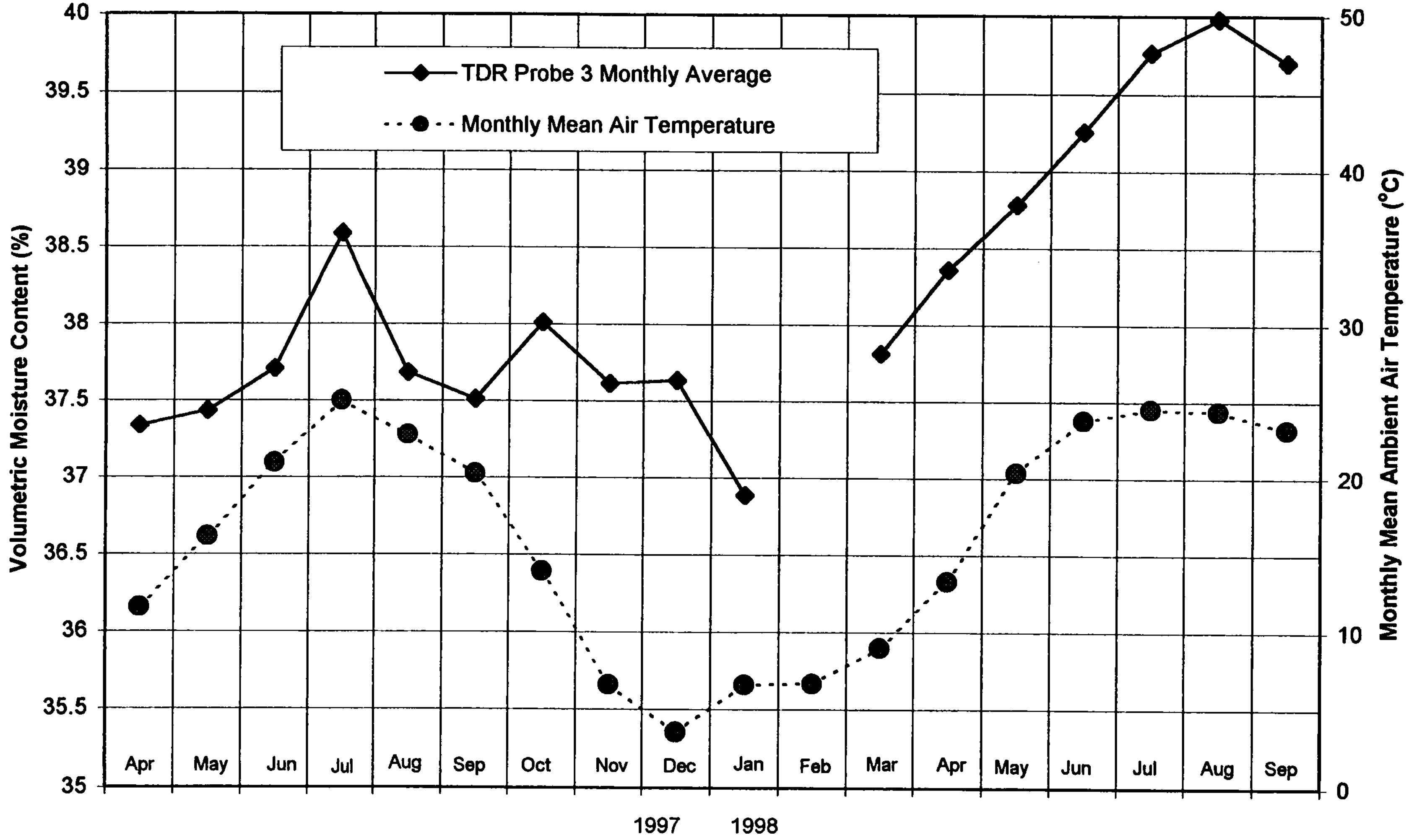
D.9 - Overton County Monthly Total Precipitation



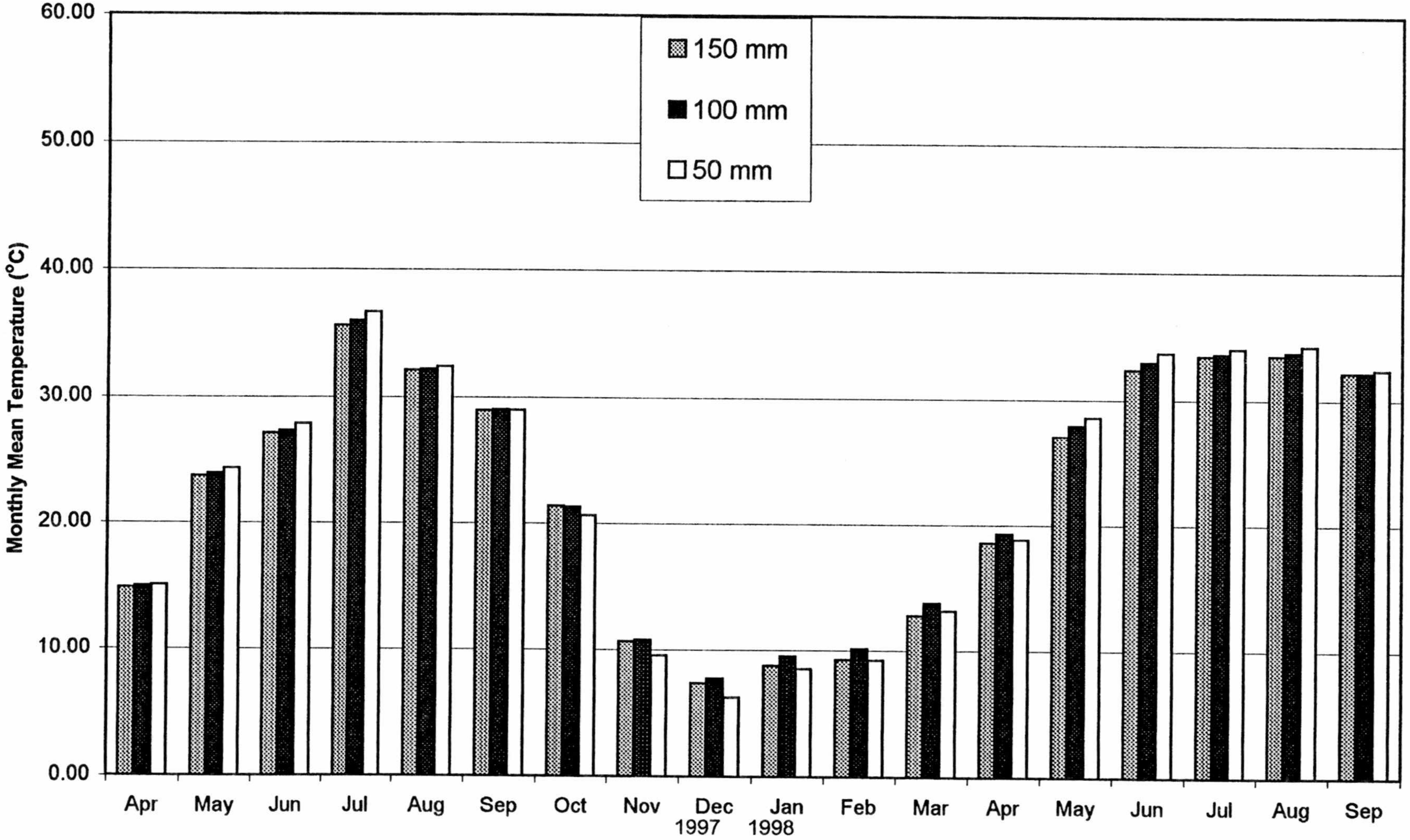
D.10 - Overton County: Precipitation and Moisture Content

Overton County Monthly Mean Temperature (°C)

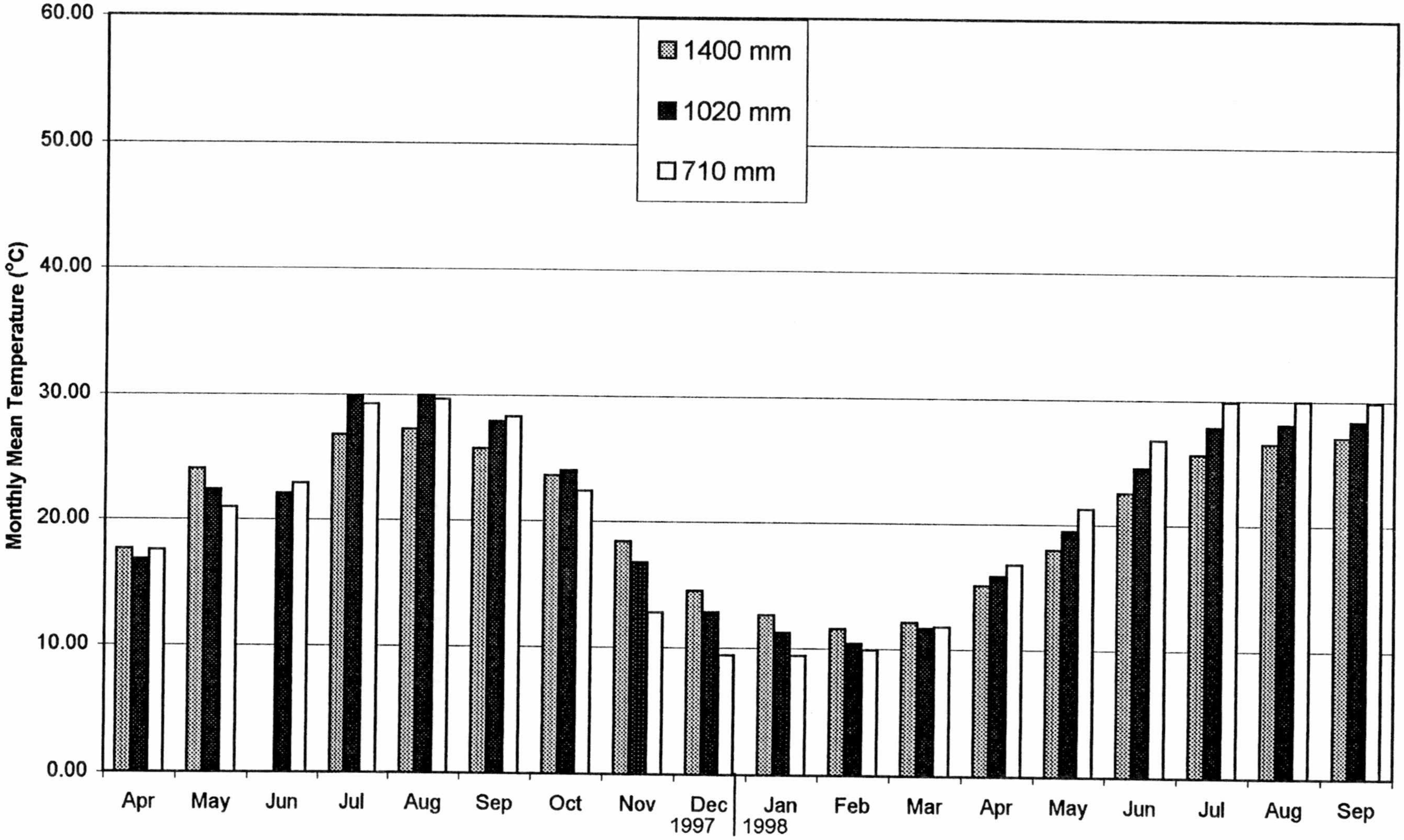
	Subgrade			Aggregate		AC Pavement			Ambient
Month	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5	Probe 6	Probe 7	Probe 8	Air
Apr	17.64	16.81	17.56	18.19	20.15	14.86	14.97	15.06	11.56
May	24.01	22.36	20.93	24.99	28.47	23.67	23.87	24.28	16.15
Jun		22.05	22.88	26.01	26.32	27.08	27.29	27.88	20.93
Jul	26.74	29.87	29.25	37.94	37.07	35.64	35.98	36.70	25.03
Aug	27.21	29.94	29.67	33.94	31.18	32.11	32.19	32.37	22.78
Sep	25.72	27.92	28.27	29.40	28.33	28.94	29.04	28.97	20.27
Oct	23.59	24.00	22.40	23.53	21.55	21.35	21.27	20.59	13.92
Nov	18.41	16.75	12.78	15.34	11.58	10.64	10.77	9.55	6.59
Dec	14.50	12.81	9.42	11.63	8.29	7.33	7.71	6.21	3.54
Jan	12.60	11.23	9.41	10.48	8.79	8.74	9.51	8.50	6.58
Feb	11.56	10.42	9.91	9.49	9.00	9.25	10.12	9.22	6.66
Mar	12.10	11.65	11.77	12.29	12.11	12.79	13.76	13.16	8.97
Apr	15.08	15.82	16.76	17.99	17.89	18.59	19.26	18.81	13.30
May	17.97	19.44	21.24	24.31	24.97	27.03	27.91	28.56	20.36
Jun	22.51	24.54	26.76	29.81	30.70	32.36	32.91	33.67	23.80
Jul	25.64	27.81	29.86	31.82	32.24	33.41	33.59	33.98	24.55
Aug	26.50	28.09	29.93	31.57	32.18	33.46	33.72	34.20	24.40
Sep	27.05	28.33	29.86	30.77	31.00	32.12	32.14	32.33	23.22



D.11 - Overton County: Air Temperature and Moisture Content

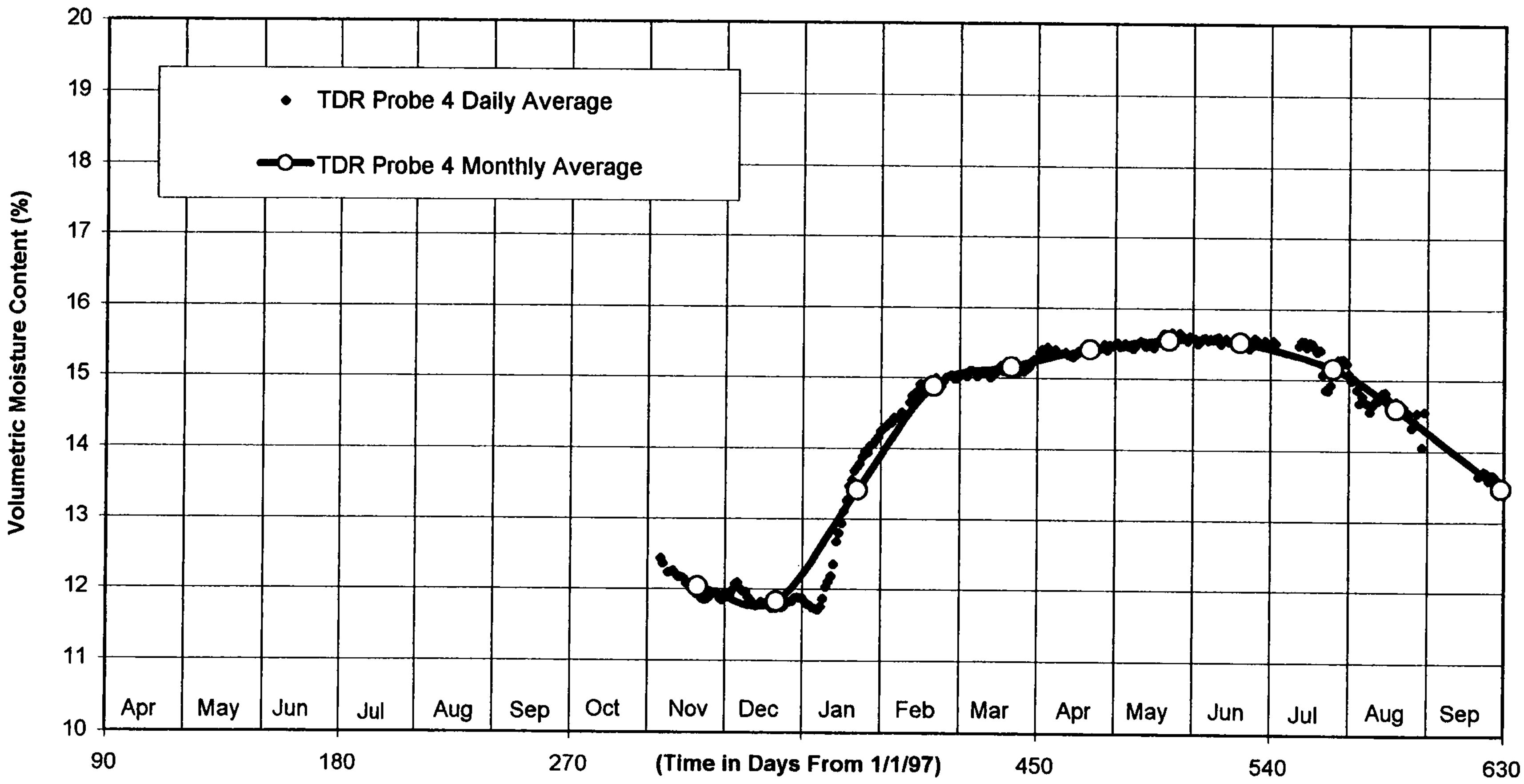


D.12 - Overton County Monthly Mean AC PavementTemperatures

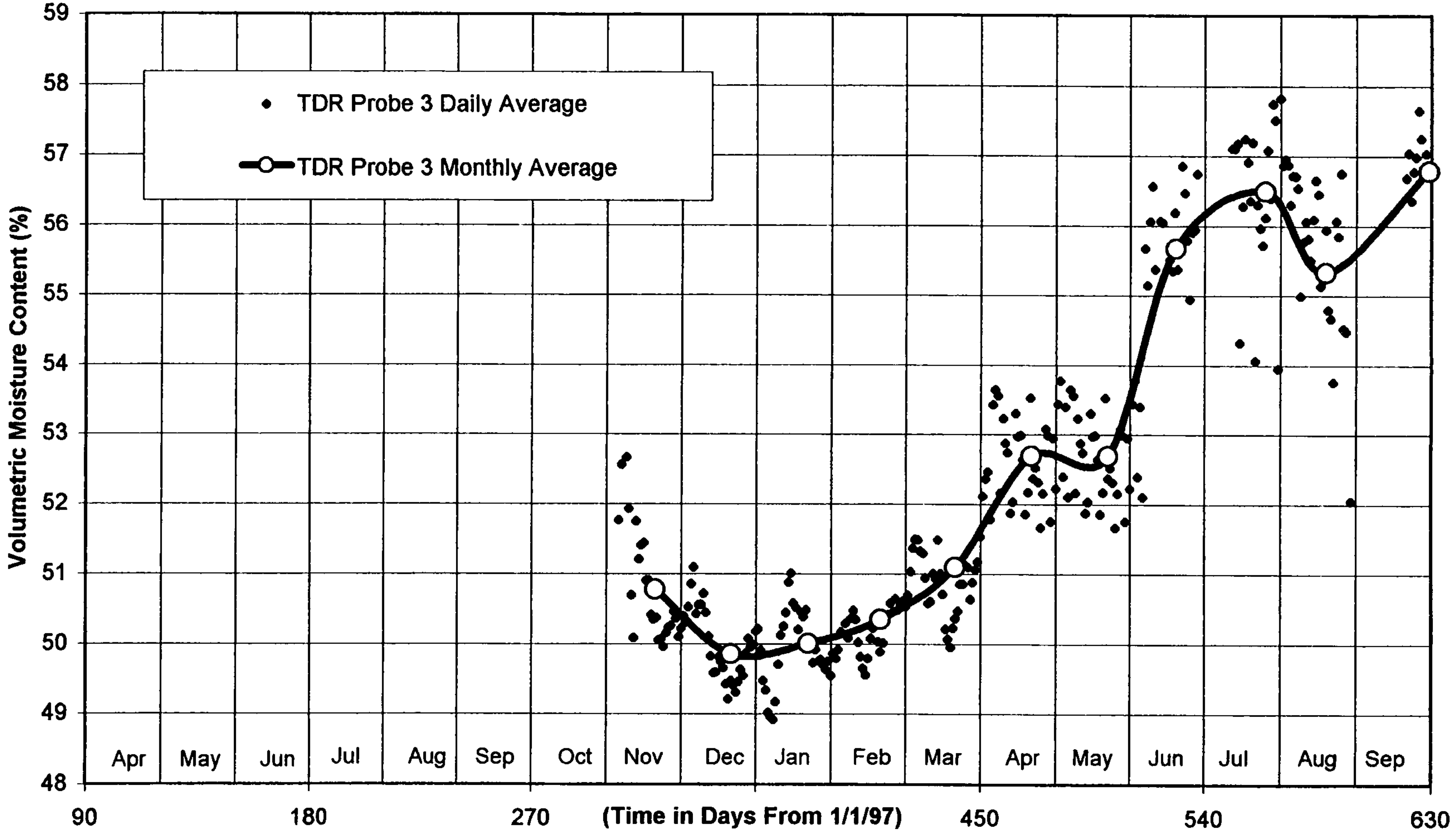


D.13 - Overton County Subgrade Monthly Mean Temperatures

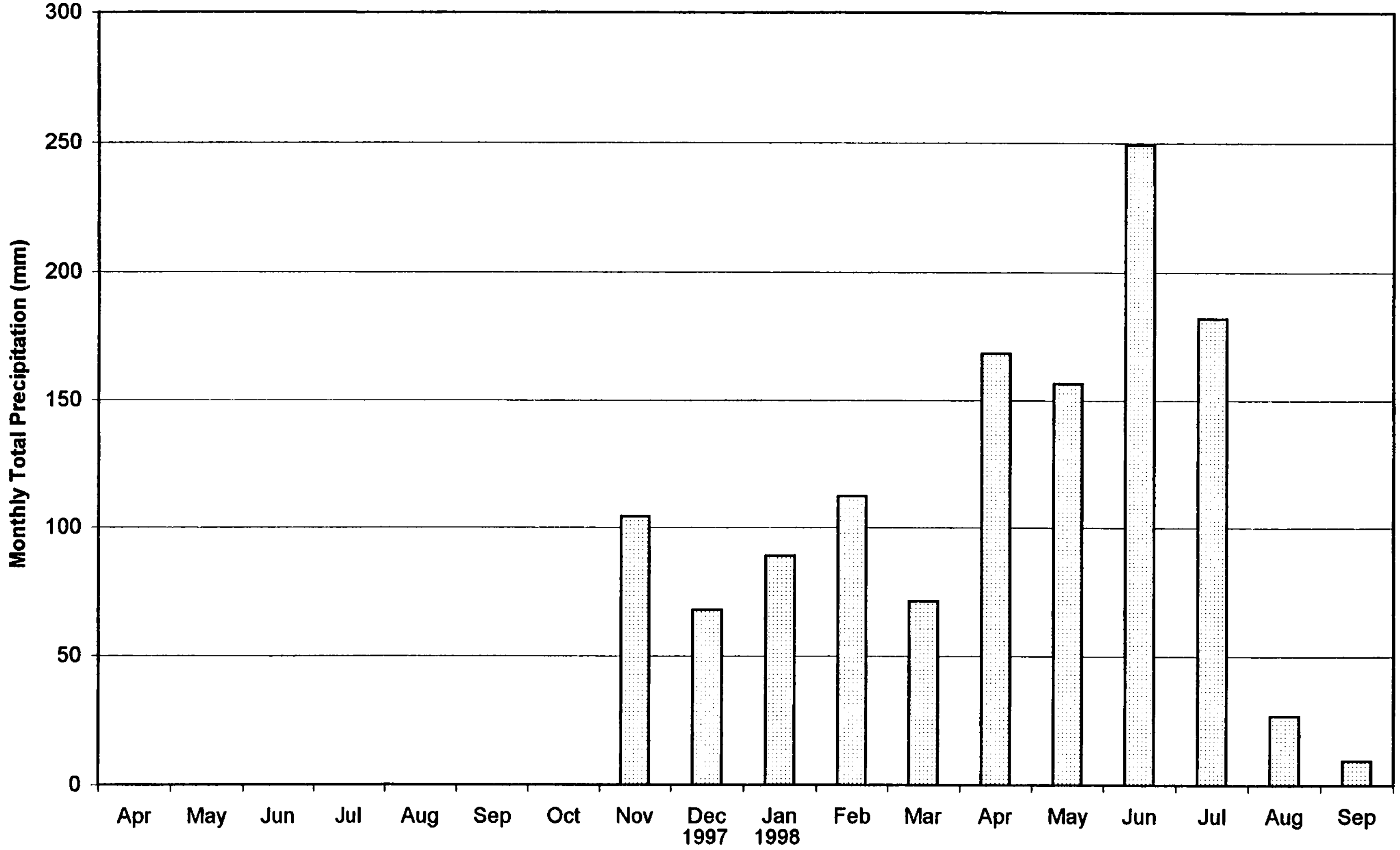
Sumner County Average Monthly Moisture Content and Precipitation						
		Probe 3		Probe 4		
		Monthly Ave.		Monthly Ave.		Monthly Ave.
		Volumetric		Volumetric		Precip.
Month	day	Moisture (%)		Moisture (%)		(mm)
Apr'97						
May'97						
Jun'97						
Jul'97						
Aug'97						
Sep'97						
Oct'97						
Nov'97	320	50.77		12.04		104.3
Dec'97	350	49.86		11.83		67.9
Jan'98	381	50.01		13.40		88.9
Feb'98	410	50.35		14.88		112.1
Mar'98	440	51.10		15.15		71.4
Apr'98	471	52.69		15.41		168.2
May'98	501	52.69		15.55		156.4
Jun'98	528	55.67		15.52		249.4
Jul'98	564	56.49		15.15		182
Aug'98	588	55.33		14.59		26.7
Sep'98	629	56.78		13.47		9.2



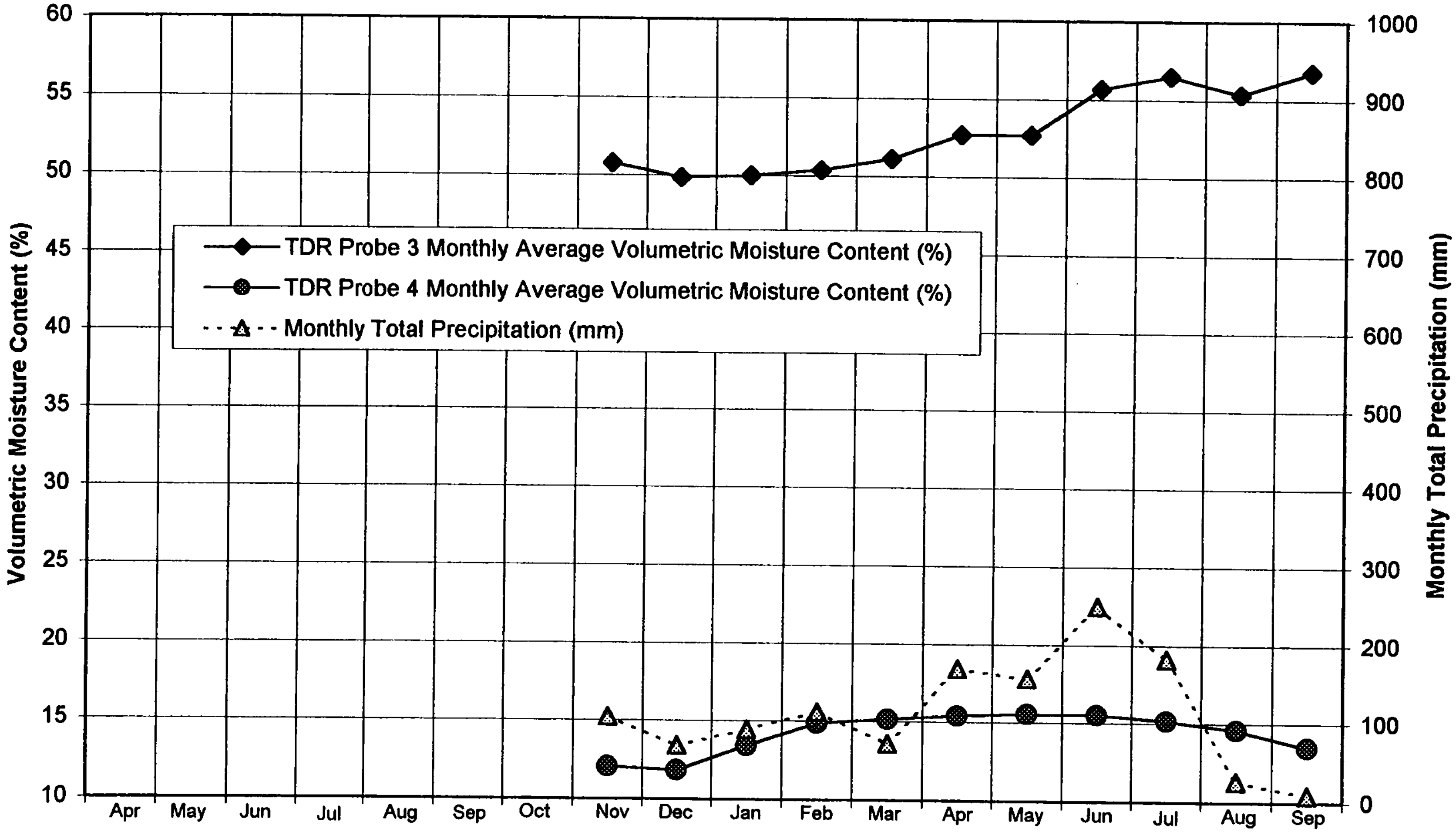
D.14 - Sumner County Aggregate Base Volumetric Moisture Content



D.15 - Sumner County Subgrade Volumetric Moisture Content



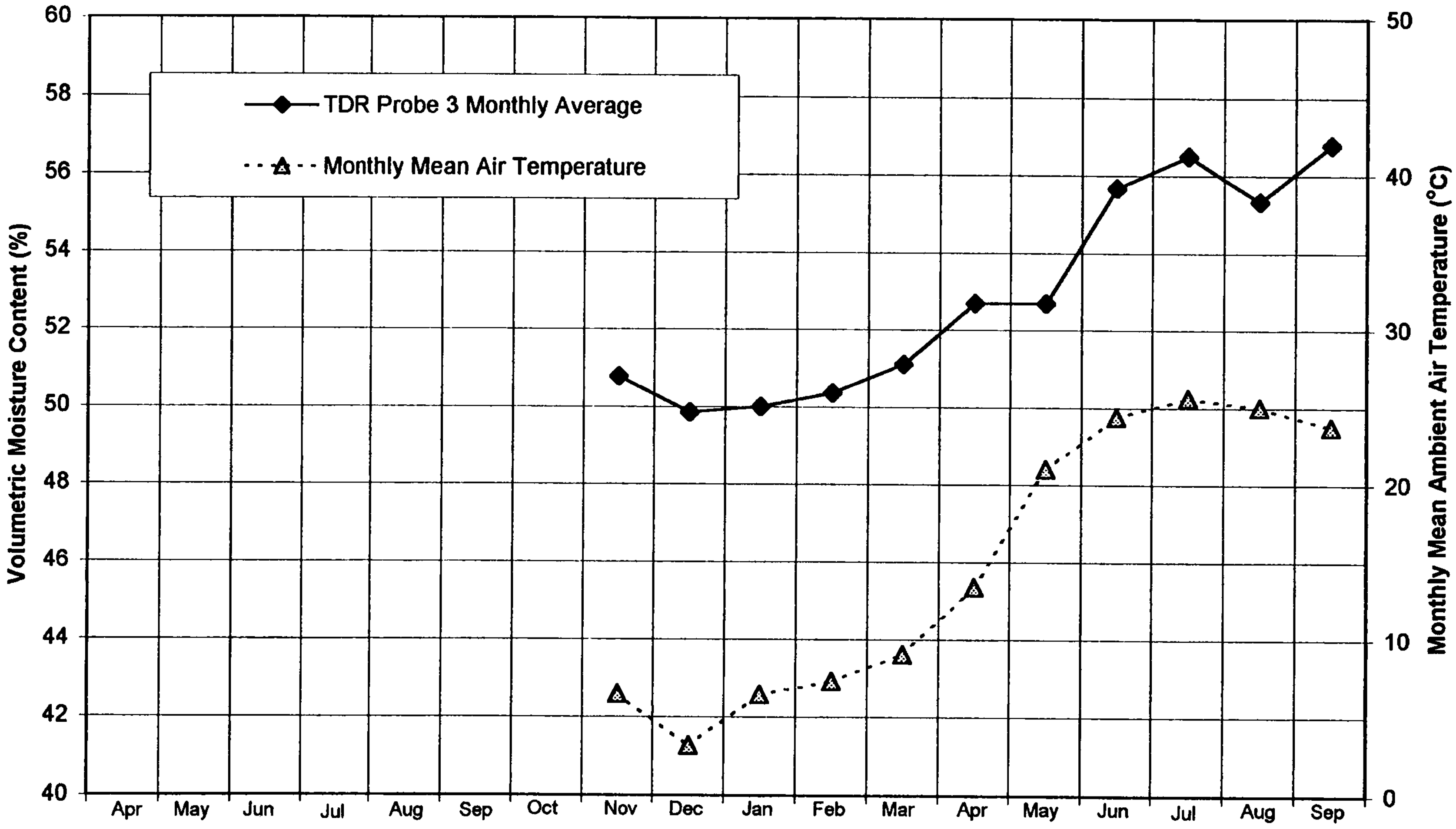
D.16 - Sumner County Monthly Total Precipitation



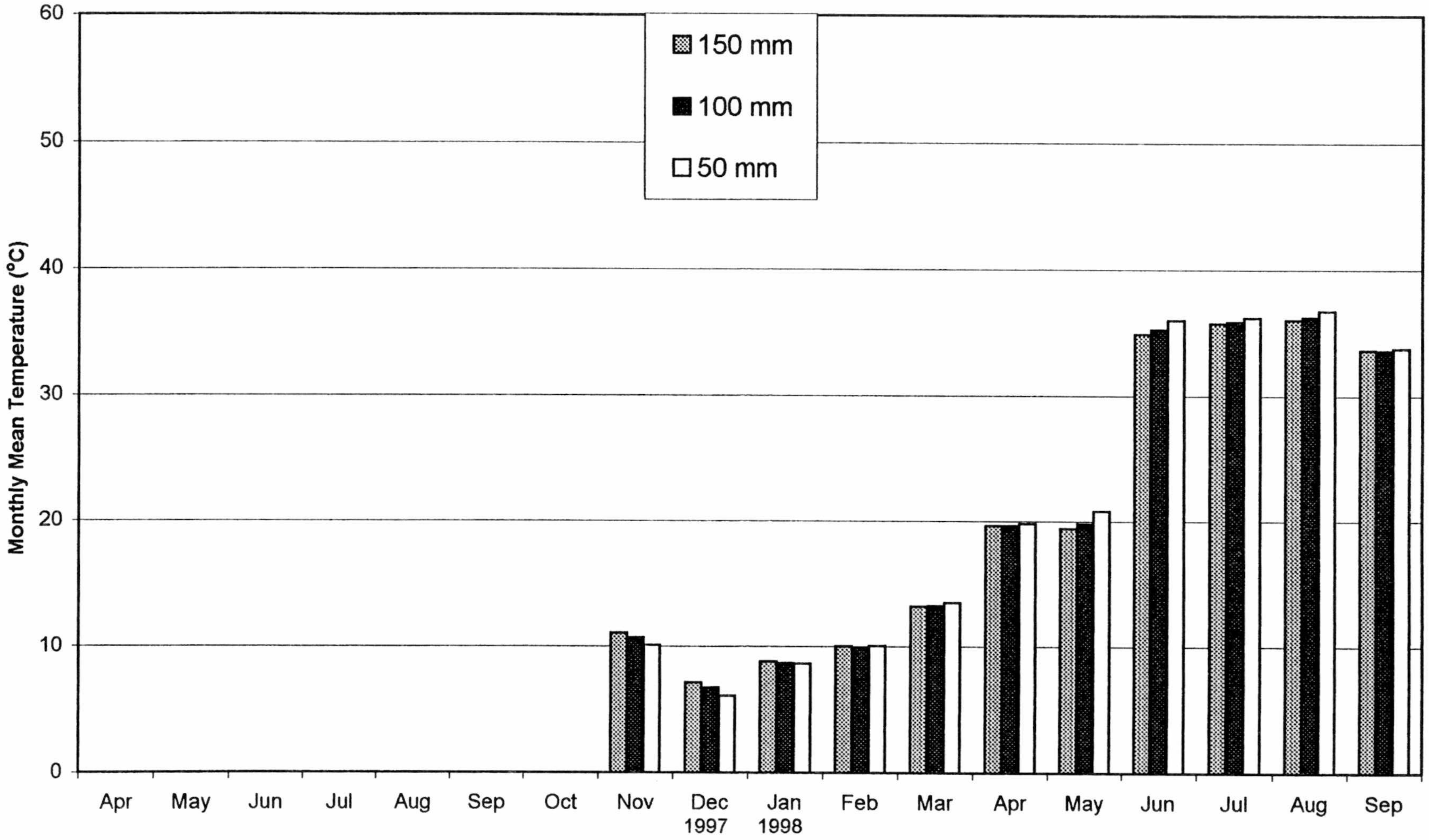
D.17 - Sumner County: Precipitation and Moisture Content

Sumner County Monthly Mean Temperature (°C)

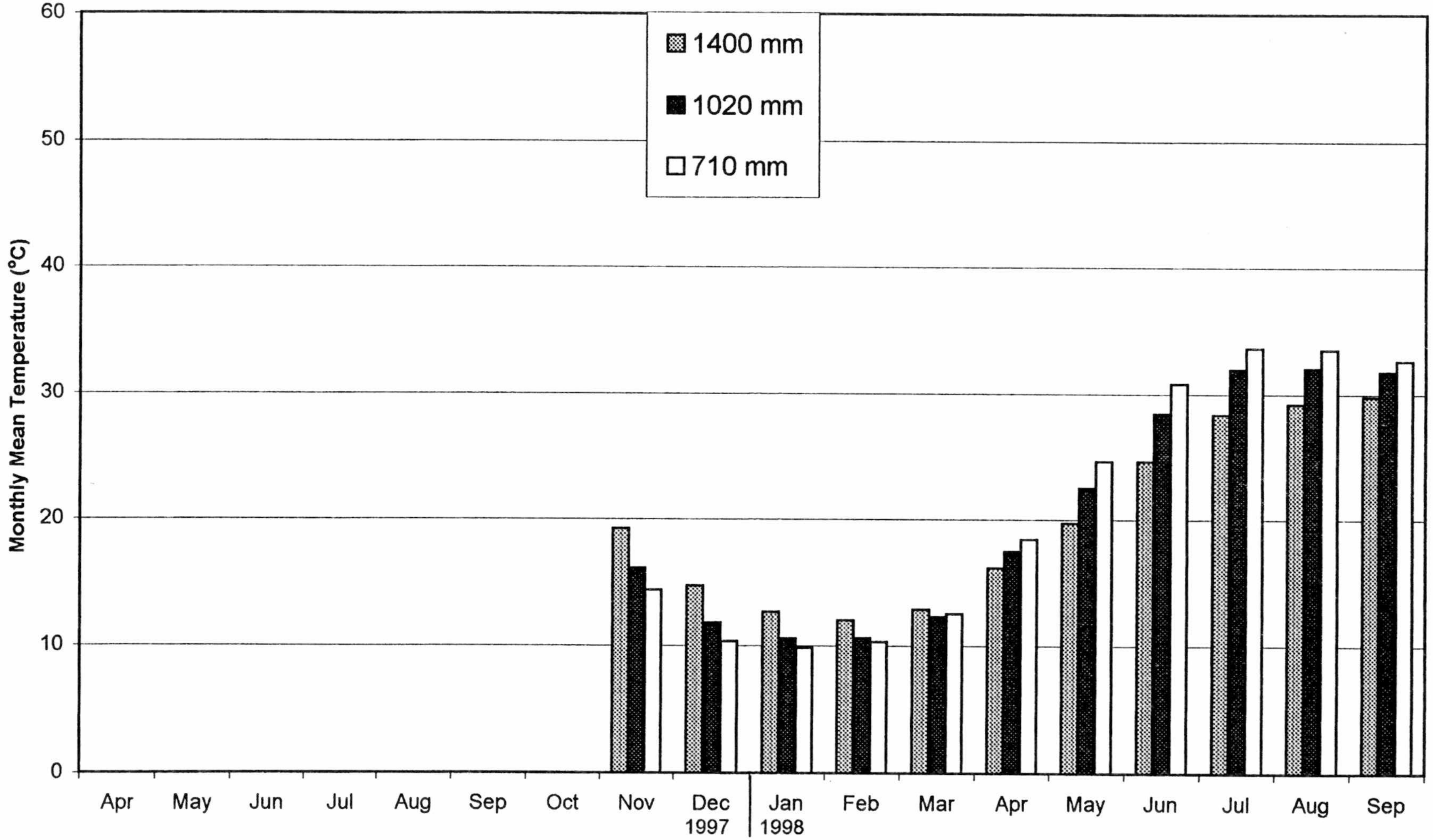
	Subgrade			Aggregate		AC Pavement			Ambient
Month	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5	Probe 6	Probe 7	Probe 8	Air
Apr									
May									
Jun									
Jul									
Aug									
Sep									
Oct									
Nov	19.26	16.11	14.37	12.62	12.05	11.03	10.66	10.07	6.48
Dec	14.72	11.80	10.33	8.75	8.20	7.13	6.72	6.09	3.20
Jan	12.66	10.56	9.83	9.29	9.20	8.77	8.64	8.59	6.44
Feb	12.02	10.58	10.29	10.20	10.26	9.99	9.92	10.03	7.30
Mar	12.85	12.28	12.51	12.95	13.22	13.21	13.24	13.48	9.01
Apr	16.16	17.46	18.44	19.15	19.53	19.62	19.64	19.80	13.39
May	19.69	22.50	24.60	26.76	27.78	19.42	19.81	20.81	21.00
Jun	24.60	28.43	30.80	33.01	33.95	34.90	35.23	36.00	24.38
Jul	28.34	31.93	33.63	34.83	35.40	35.76	35.87	36.19	25.62
Aug	29.19	32.03	33.52	34.79	35.46	36.04	36.23	36.75	25.00
Sep	29.80	31.76	32.62	33.05	33.44	33.61	33.61	33.74	23.76



D.18 - Sumner County: Air Temperature and Moisture Content

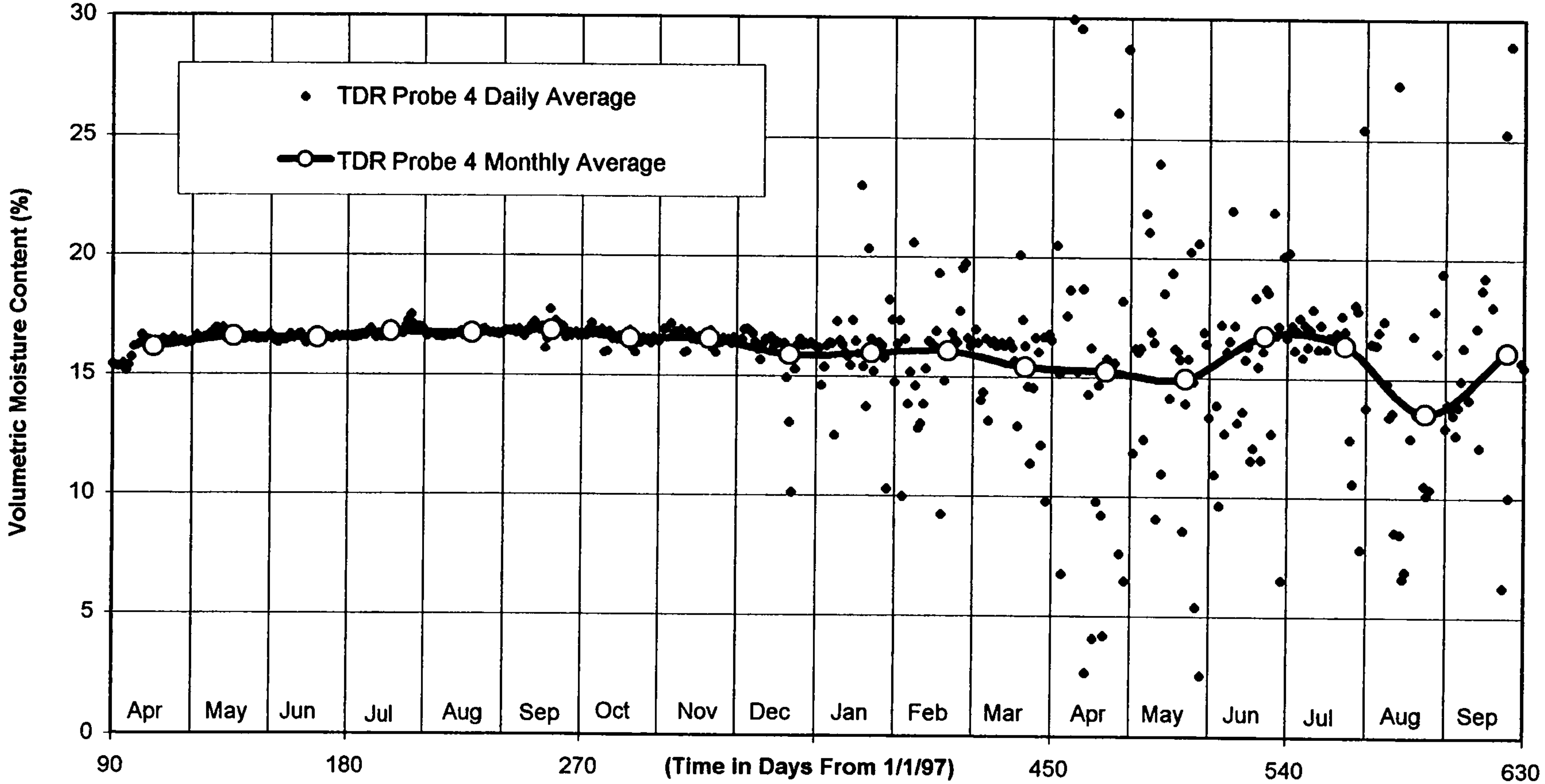


D.19 - Sumner County Monthly Mean AC PavementTemperatures

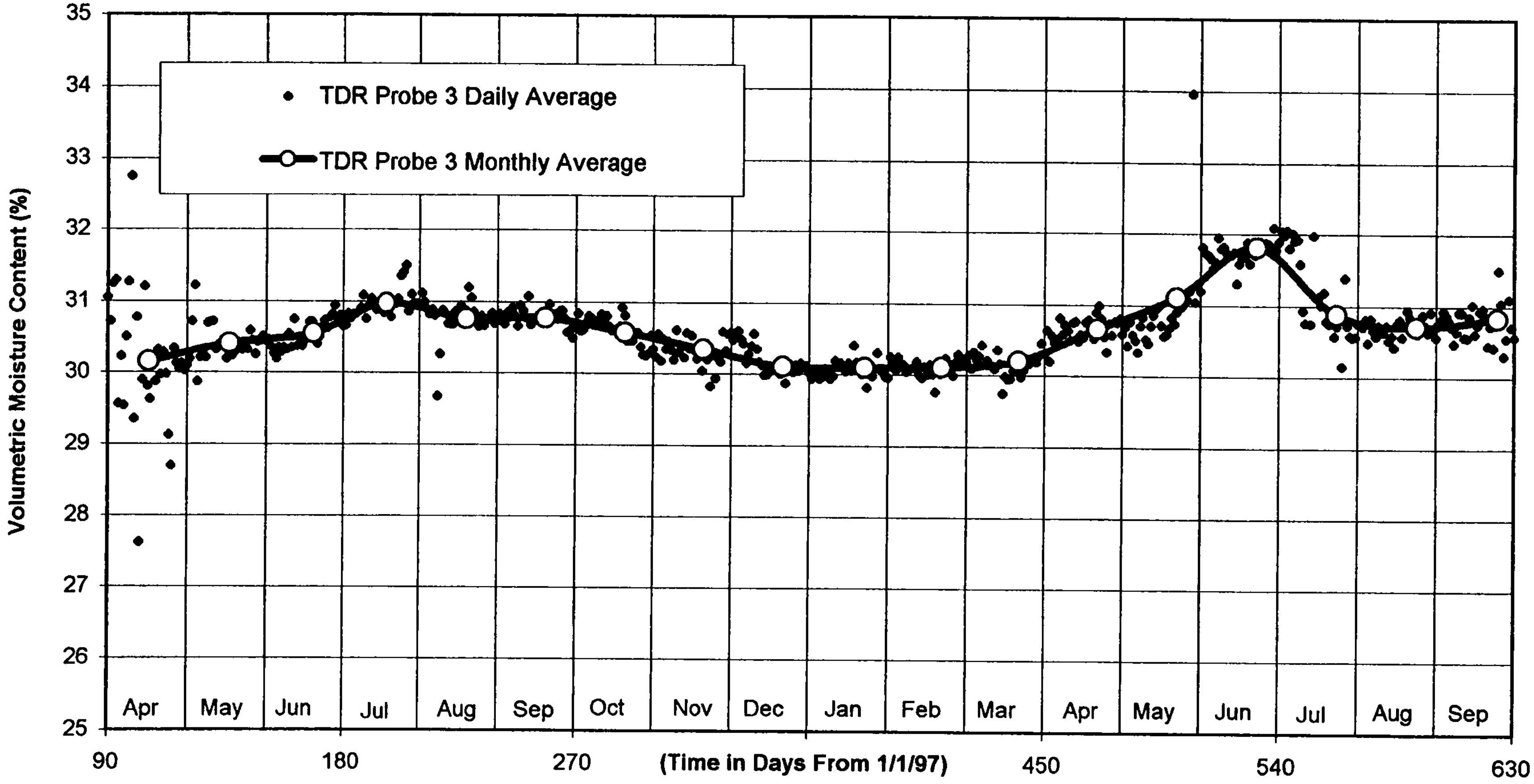


D.20 - Sumner County Subgrade Monthly Mean Temperatures

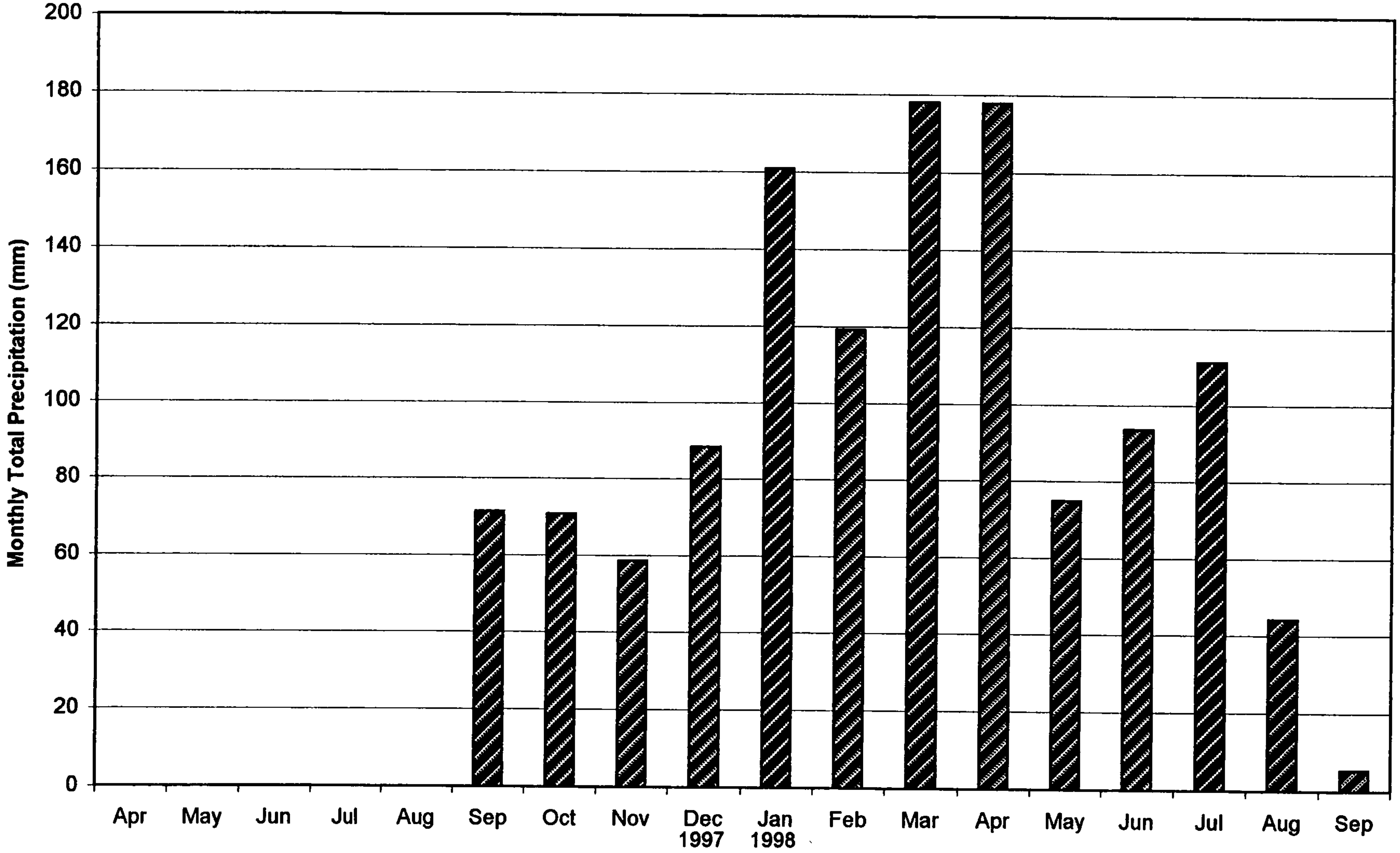
McNairy County Average Monthly Moisture Content and Precipitation						
		Probe 3		Probe 4		
		Monthly Ave.		Monthly Ave.		Monthly Ave.
		Volumetric		Volumetric		Precip.
Month	day	Moisture (%)		Moisture (%)		(mm)
Apr'97	106	30.15		16.14		
May'97	136	30.41		16.58		
Jun'97	168	30.55		16.53		
Jul'97	197	30.98		16.79		
Aug'97	228	30.76		16.76		
Sep'97	259	30.78		16.87		71.3
Oct'97	289	30.58		16.57		70.8
Nov'97	320	30.34		16.57		58.6
Dec'97	350	30.11		15.89		88.4
Jan'98	381	30.09		15.98		160.8
Feb'98	411	30.11		16.09		119.1
Mar'98	440	30.20		15.42		178
Apr'98	471	30.67		15.24		177.9
May'98	501	31.11		14.95		74.8
Jun'98	532	31.81		16.79		93.7
Jul'98	562	30.88		16.37		111.2
Aug'98	593	30.71		13.54		44.2
Sep'98	624	30.83		16.10		5.4



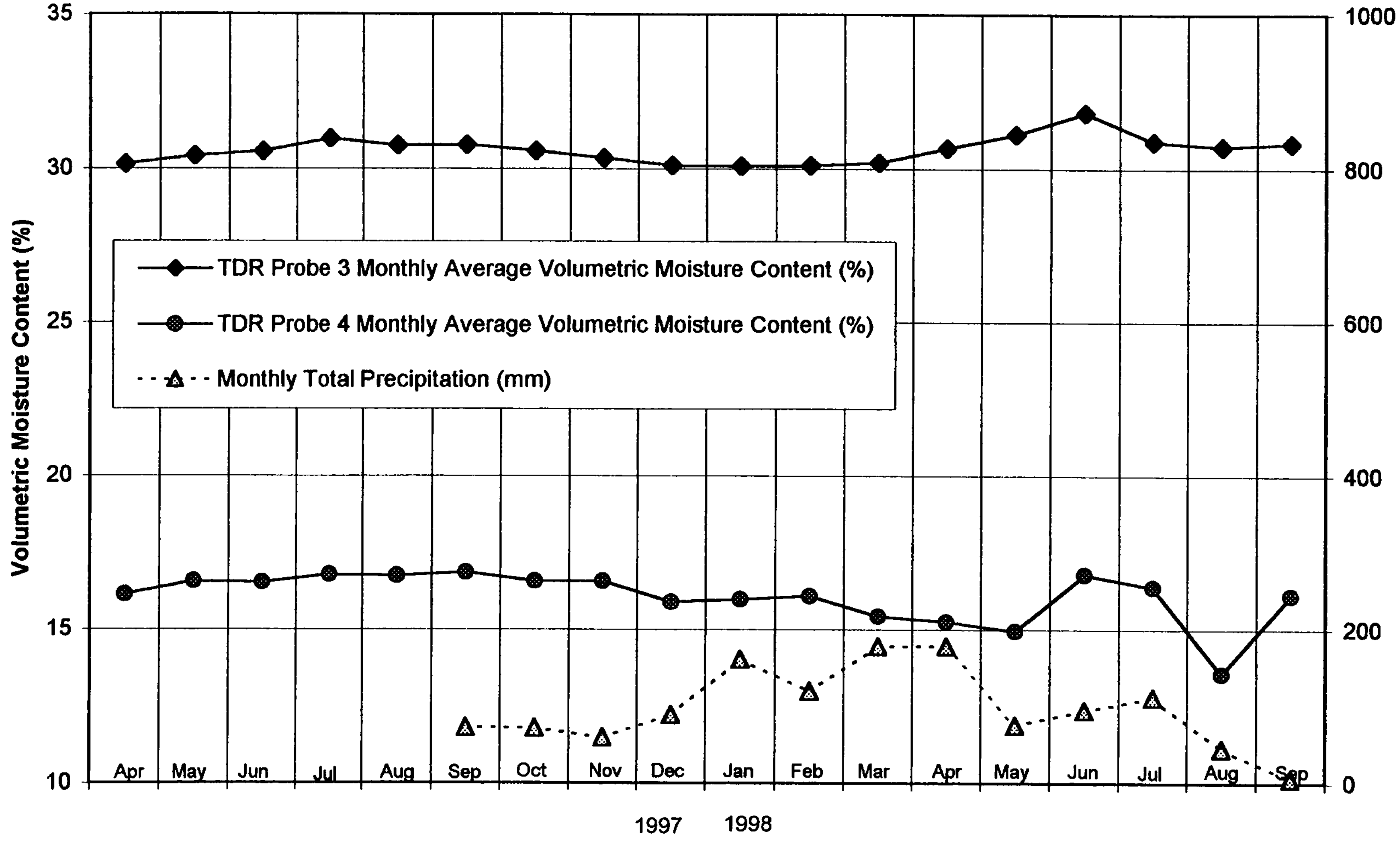
D.21 - McNairy County Aggregate Base Volumetric Moisture Content



D.22 - McNairy County Subgrade Volumetric Moisture Content



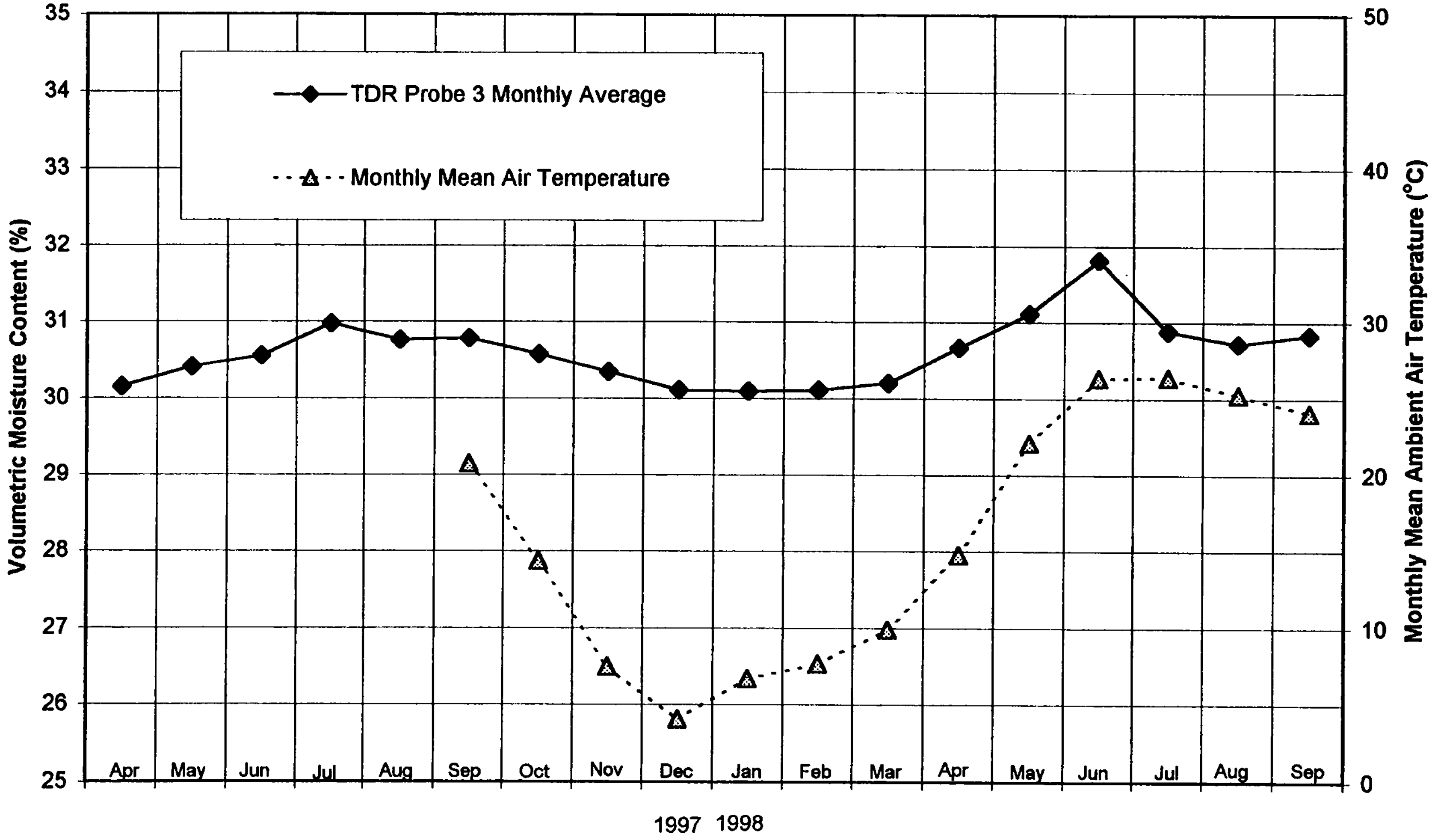
D.23 - McNairy County Monthly Total Precipitation



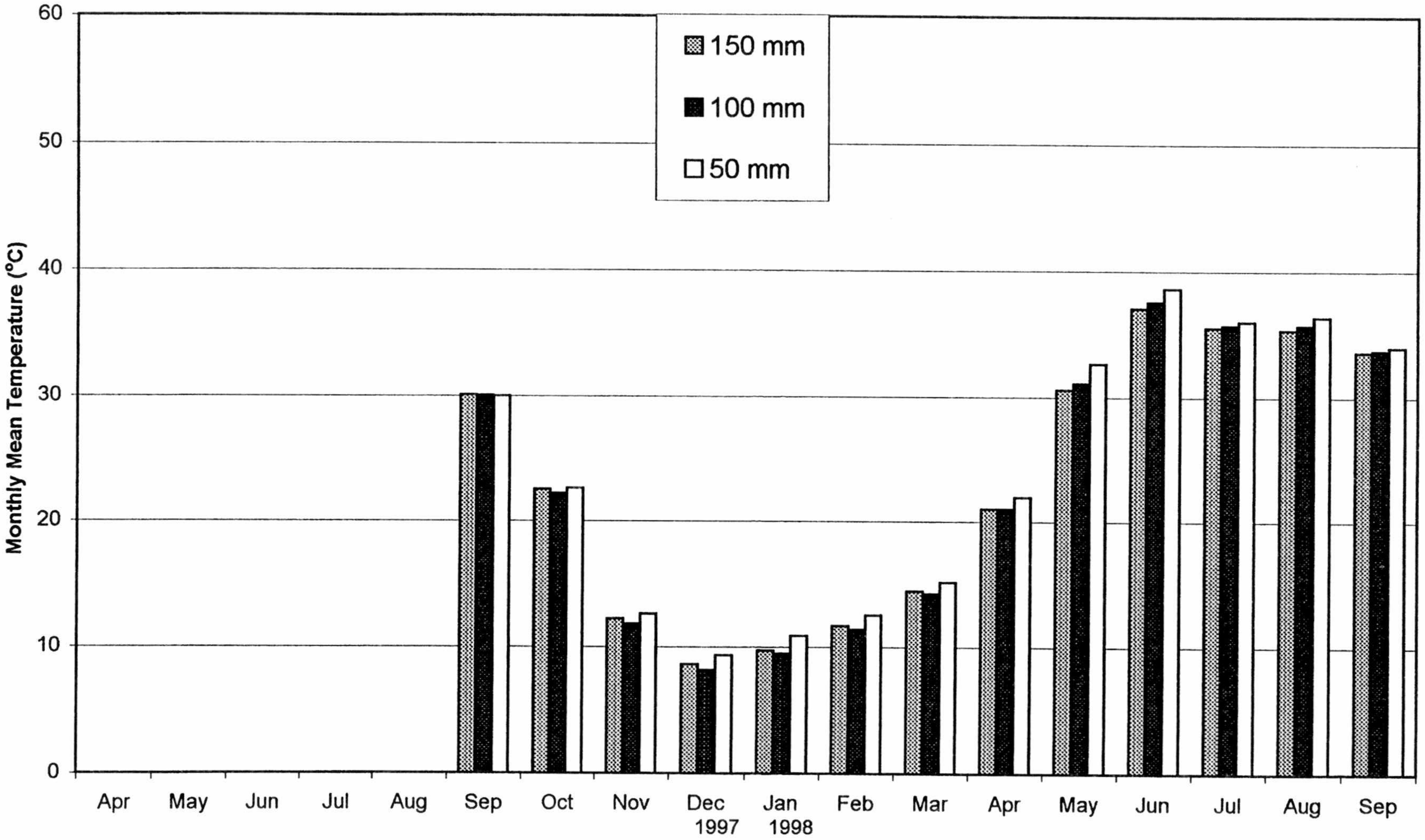
D.24 - McNairy County: Precipitation and Moisture Content

McNairy County Monthly Mean Temperature (°C)

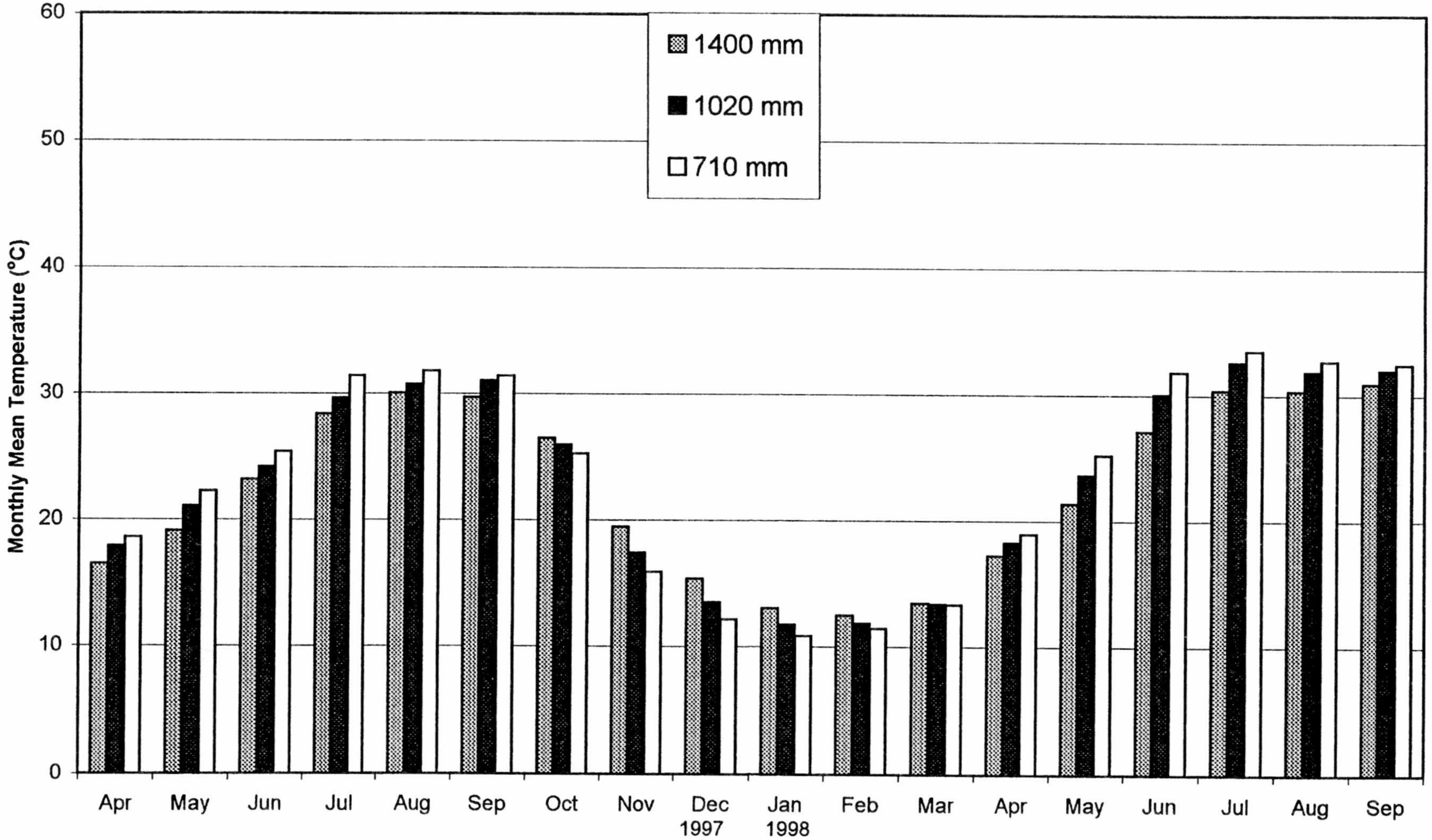
	Subgrade			Aggregate		AC Pavement			Ambient Air
Month	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5	Probe 6	Probe 7	Probe 8	
Apr	16.50	17.88	18.62	19.82	21.16				
May	19.10	21.06	22.22	23.79	25.43				
Jun	23.18	24.18	25.37	26.95	28.53				
Jul	28.35	29.62	31.40	33.47	35.39				
Aug	30.02	30.70	31.76	32.89	33.97				
Sep	29.72	31.02	31.41	31.78	32.08	30.10	30.04	30.01	20.71
Oct	26.47	25.96	25.21	24.62	24.35	22.53	22.20	22.62	14.36
Nov	19.44	17.44	15.90	14.81	14.02	12.25	11.83	12.63	7.48
Dec	15.37	13.51	12.15	11.15	10.37	8.59	8.13	9.34	4.05
Jan	13.05	11.73	10.84	10.40	10.19	9.68	9.45	10.90	6.69
Feb	12.47	11.86	11.44	11.37	11.47	11.70	11.38	12.55	7.66
Mar	13.46	13.37	13.33	13.58	13.96	14.41	14.23	15.16	9.89
Apr	17.27	18.29	18.95	19.76	20.73	21.01	21.02	21.93	14.77
May	21.34	23.62	25.21	27.11	29.00	30.59	31.12	32.67	22.06
Jun	27.09	30.05	31.80	33.77	36.28	37.03	37.56	38.59	26.31
Jul	30.37	32.55	33.50	34.66	37.36	35.52	35.69	35.99	26.36
Aug	30.35	31.86	32.72	33.90	37.62	35.38	35.69	36.36	25.24
Sep	30.94	31.98	32.43	33.20	37.16	33.57	33.70	33.95	24.07



D.25 - McNairy County: Precipitation and Moisture Content

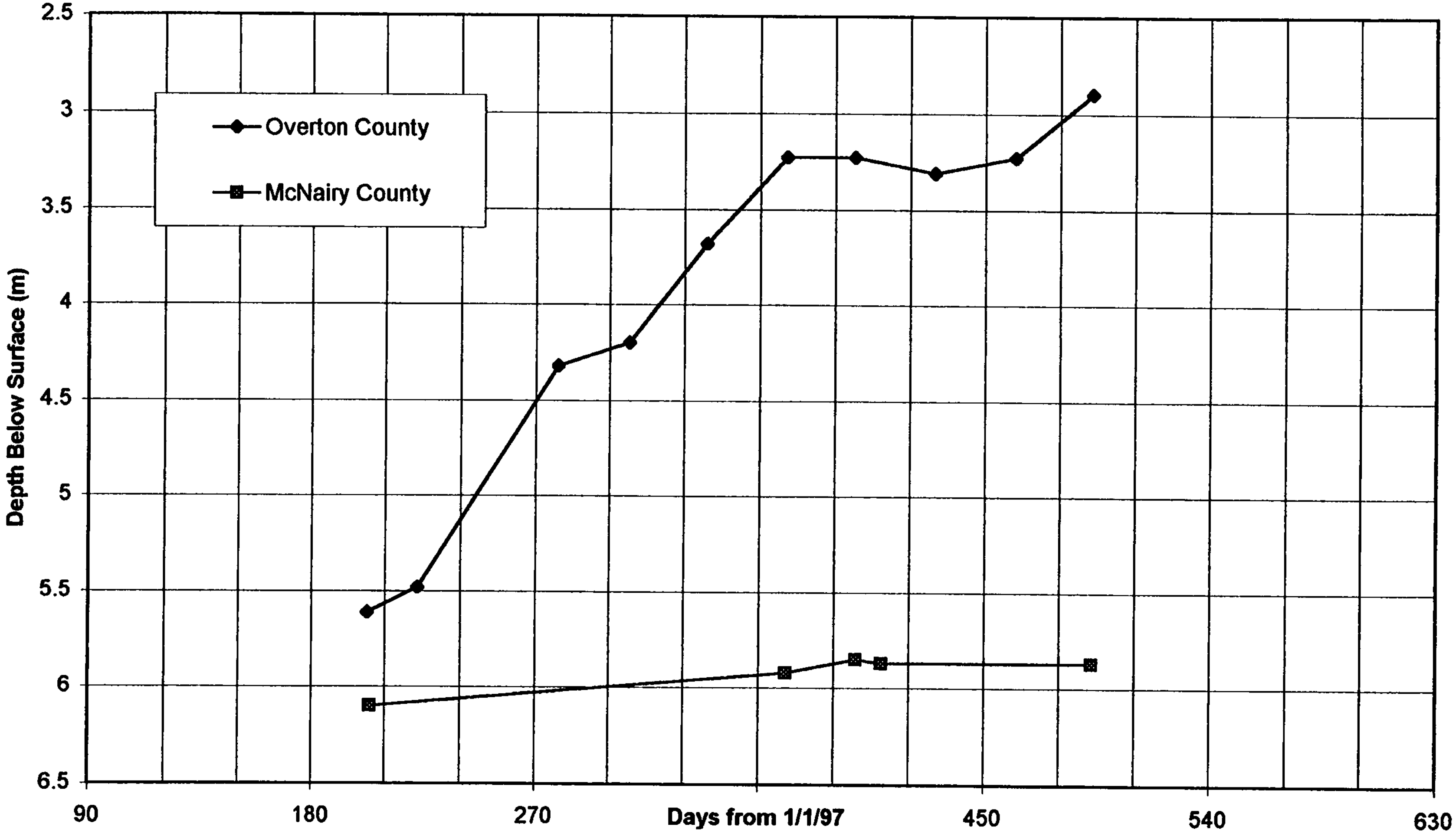


D.26 - Sumner County Monthly Mean AC PavementTemperatures



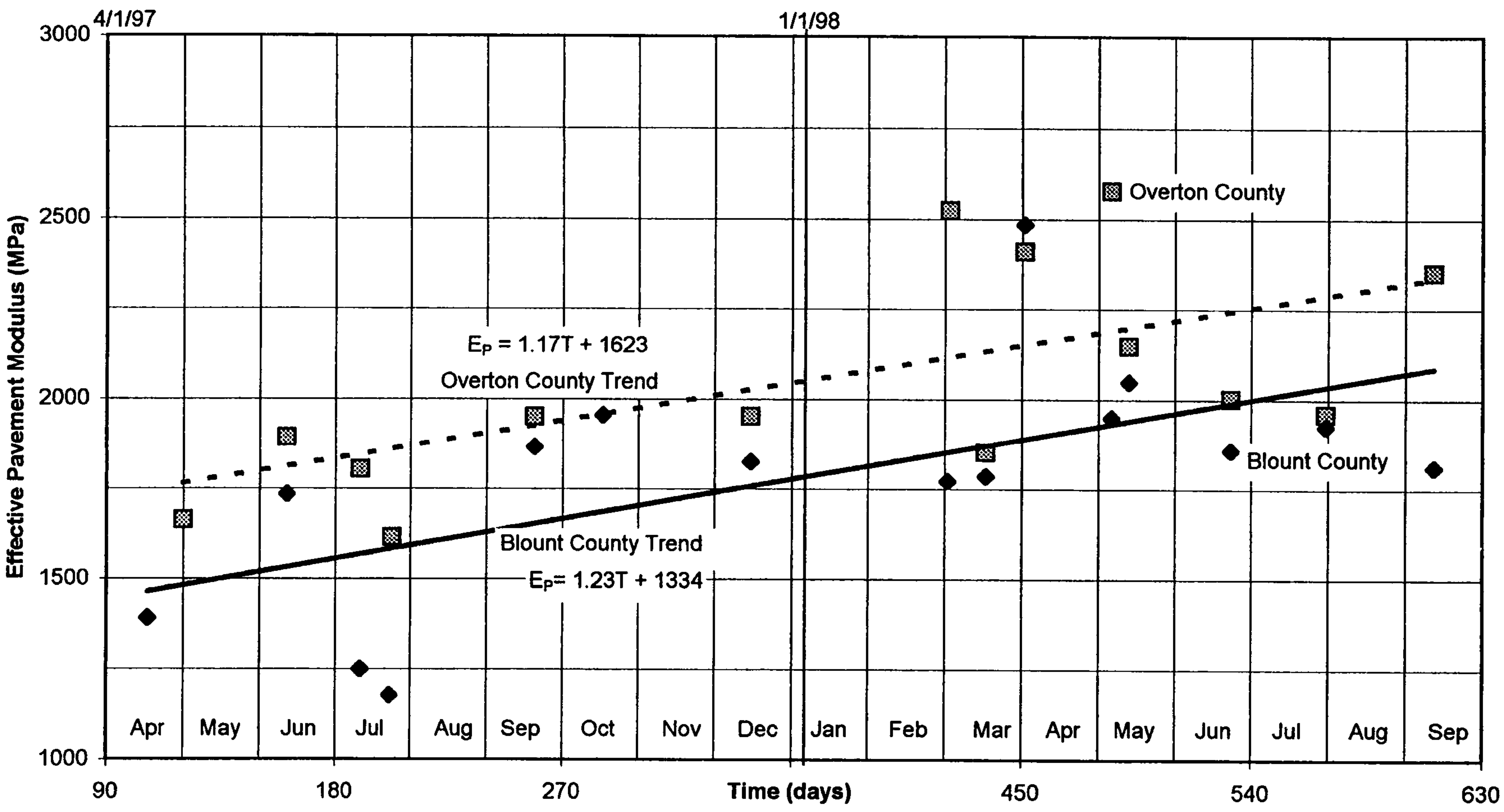
D.27 - McNairy County Subgrade Monthly Mean Temperatures

Water Table Monitoring Wells						
Overton County				McNairy County		
		depth to water table				depth to water table
date	day	(m)		date	day	(m)
7/22/97	203	5.61		7/23/97	204	6.1
8/11/97	223	5.48				
10/6/97	279	4.32				
11/4/97	308	4.2				
12/5/97	339	3.68				
1/6/98	371	3.23		1/6/98	371	5.92
2/2/98	398	3.23		2/3/98	399	5.85
3/6/98	430	3.31		2/13/98	409	5.87
4/7/98	462	3.23				
5/8/98	493	2.9		5/8/98	493	5.87

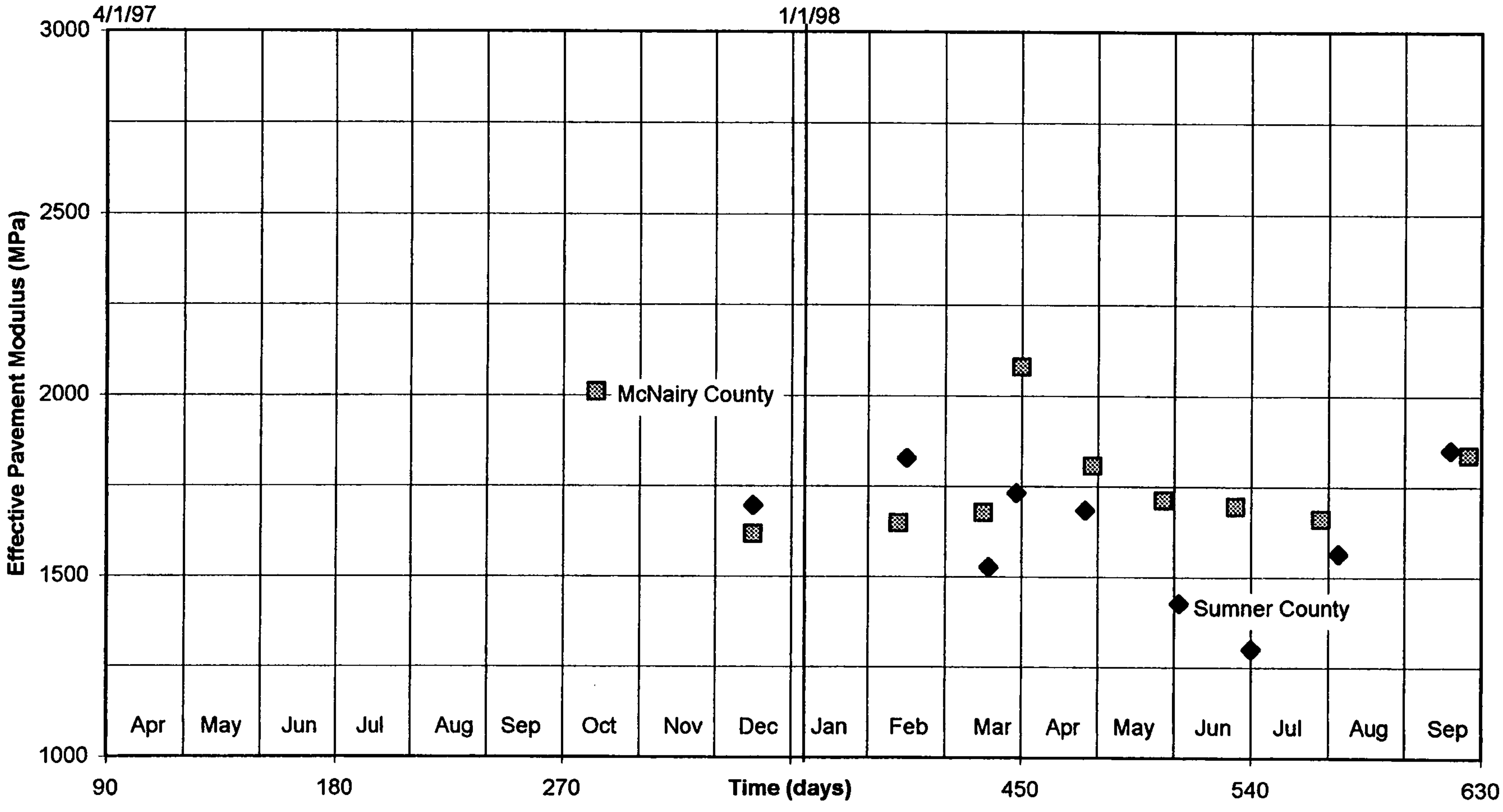


D.28 - Water Table Monitoring Wells

DARWin Backcalculated Pavement Modulus (E_P)								
Blount County						Overton County		
day	(ksi)	MPa		month		day	(ksi)	MPa
106	201.834	1390.64		May'97		120	241.215	1661.97
161	251.547	1733.16		June'97		161	274.584	1891.88
190	181.49	1250.47		July'97		190	261.767	1803.57
202	170.733	1176.35		Aug'97		203	234.397	1615.00
259	270.889	1866.43		Sept'97		259	282.857	1948.88
286	283.551	1953.67		Oct'97		286	313.114	2157.36
344	265.003	1825.87		Dec'97		344	283.088	1950.48
421	257.159	1771.83		Feb'98		422	366.239	2523.39
436	259.044	1784.81		Mar.12'98		436	268.681	1851.21
451	360.691	2485.16		Mar.27'98		451	349.734	2409.67
485	282.842	1948.78		Apr'98		485	374.054	2577.23
492	297.1	2047.02		May'98		492	311.619	2147.05
532	269.752	1858.59		June'98		532	290.42	2000.99
569	279.395	1925.03		July'98		569	284.259	1958.54
611	262.907	1811.43		Sept'98		611	341.482	2352.81
Sumner County						McNairy County		
day	(ksi)	MPa		month		day	(ksi)	MPa
				Oct'97		283	291.617	2009.24
345	245.925	1694.42		Dec'97		345	234.645	1616.70
405	265.253	1827.59		Feb'98		402	238.965	1646.47
437	221.589	1526.75		Mar.13'98		435	243.323	1676.50
448	251.2	1730.77		Mar.24'98		450	301.755	2079.09
475	244.138	1682.11		Apr'98		478	262.126	1806.05
512	206.962	1425.97		May'98		506	248.246	1710.41
540	188.502	1298.78		June'98		534	245.704	1692.90
574	226.821	1562.80		July'98		567	240.814	1659.21
618	268.637	1850.91		Sept'98		625	266.42	1835.63

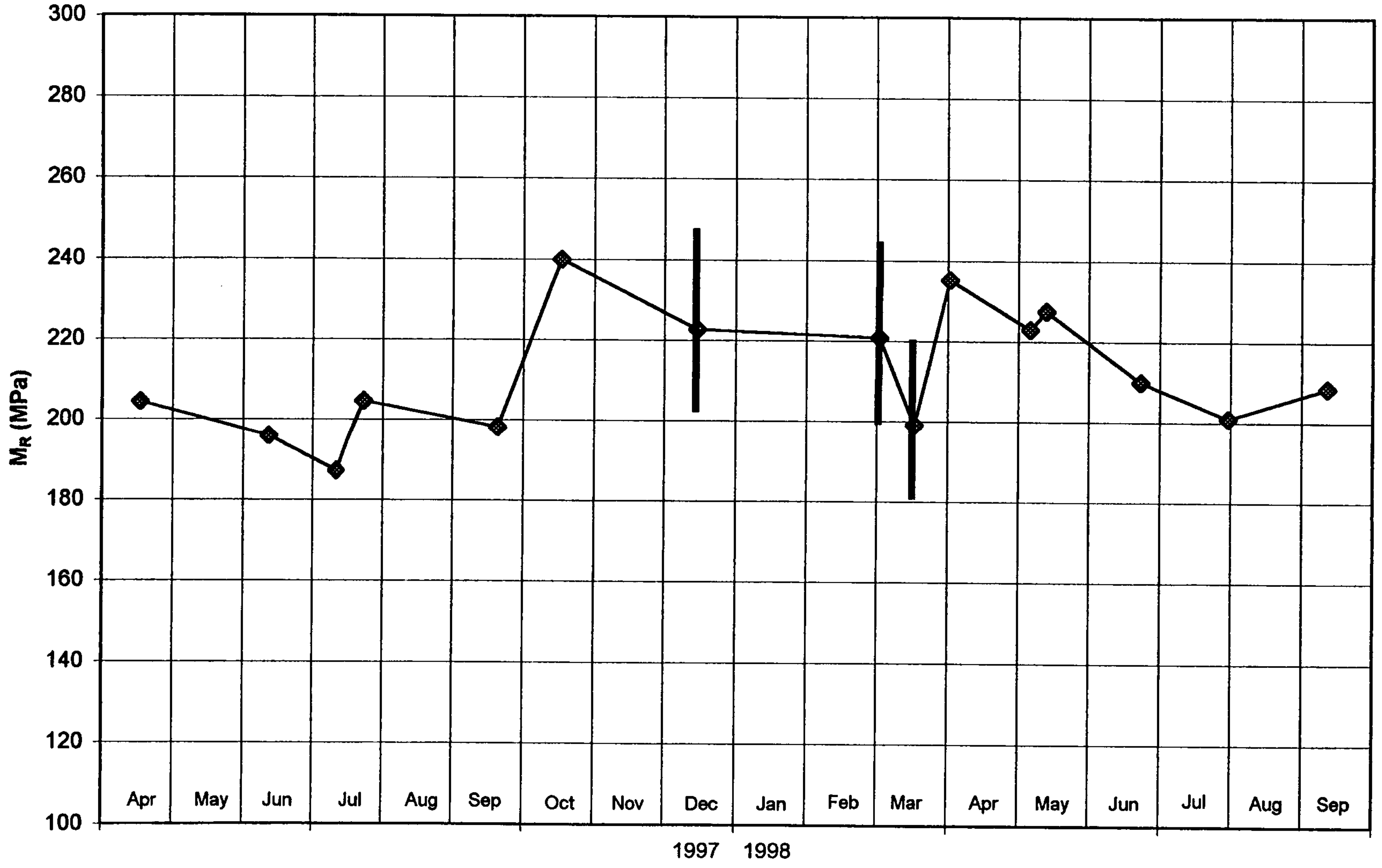


D.29 - Effective Pavement Modulus for Blount County & Overton County

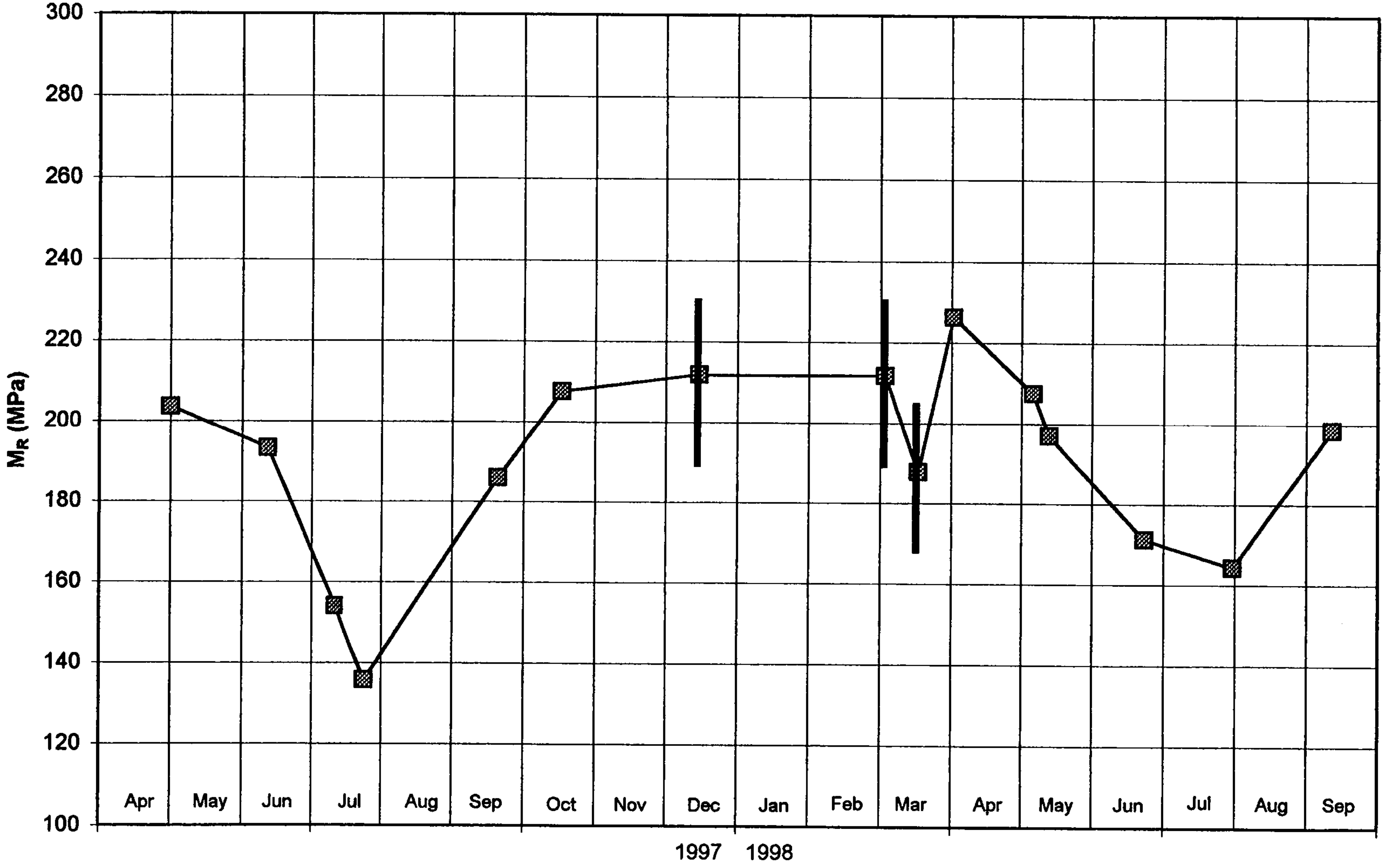


D.30 - Effective Pavement Modulus for Sumner County & McNairy County

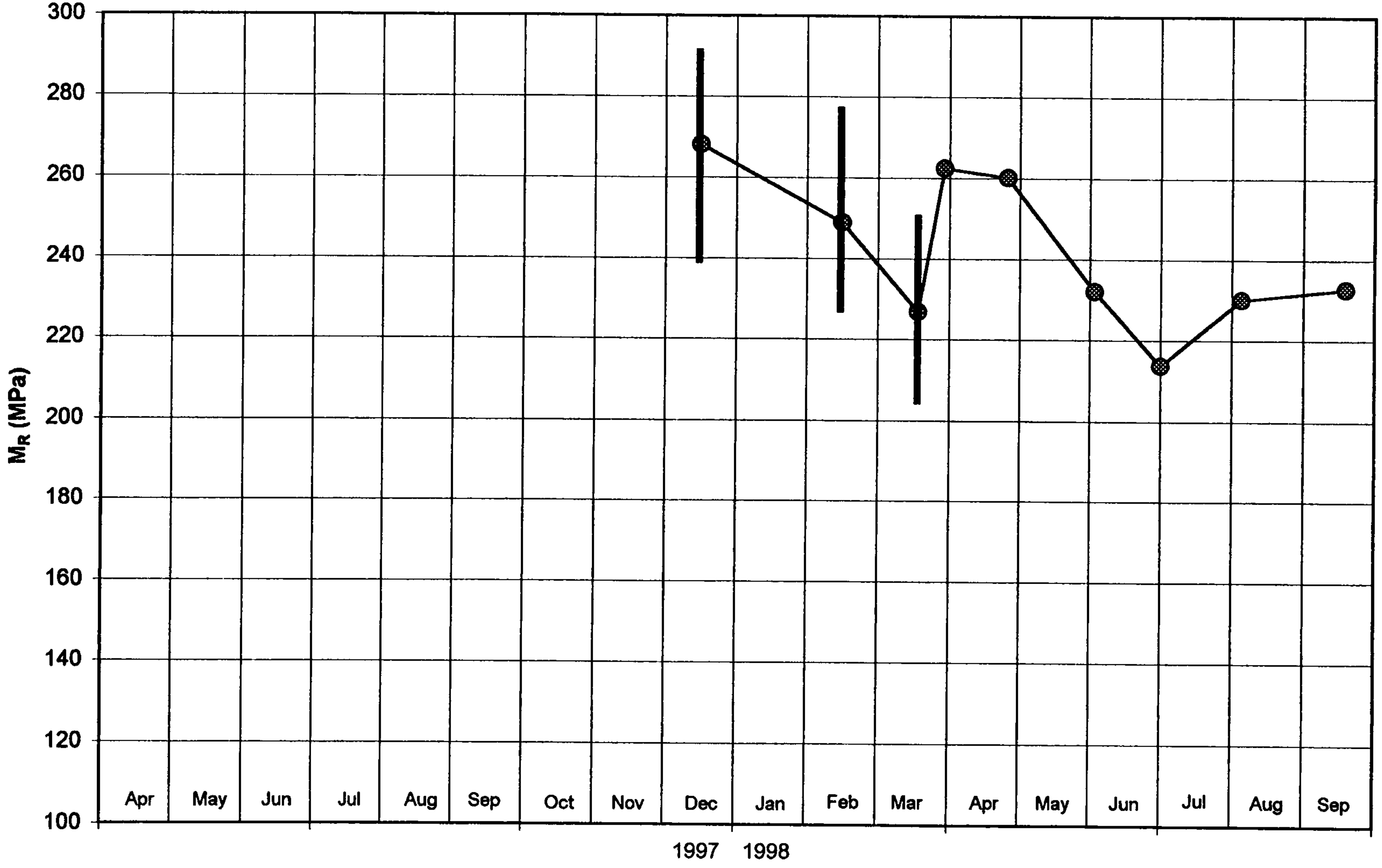
DARWin Backcalculated Subgrade Modulus (M_R)								
(Bold italic numbers were calculated using an average value for drop weight)								
Blount County					Overton County			
test date	day	(psi)	MPa		test date	day	(psi)	MPa
4/16/97	106	29,646	204.41		4/30/97	120	29,520	203.54
6/10/97	161	28,404	195.85		6/10/97	161	28,047	193.38
7/9/97	190	27,146	187.17		7/9/97	190	22,346	154.08
7/21/97	202	29,690	204.71		7/22/97	203	19,679	135.69
9/17/97	259	28,732	198.11		9/17/97	259	26,978	186.01
10/13/97	286	34,802	239.96		10/13/97	286	30,113	207.63
12/10/97	344	***32,280***	***222.57***		12/10/97	344	***30,734***	***211.91***
2/25/98	421	***32,020***	***220.78***		2/26/98	422	***30,702***	***211.69***
3/12/98	436	***28,866***	***199.03***		3/12/98	436	***27,257***	***187.94***
3/27/98	451	34,105	235.15		3/27/98	451	32,816	226.27
4/30/98	485	32,337	222.96		4/30/98	485	30,084	207.43
5/7/98	492	32,991	227.47		5/7/98	492	28,569	196.98
6/16/98	532	30,462	210.04		6/16/98	532	24,836	171.24
7/23/98	569	29,138	200.91		7/23/98	569	23,833	164.33
9/3/98	611	30,250	208.57		9/3/98	611	28,796	198.55
Sumner County					McNairy County			
test date	day	(psi)	MPa		test date	day	(psi)	MPa
					10/10/97	283	25,640	176.79
12/11/97	345	***38,886***	***268.12***		12/11/97	345	***24,946***	***172.00***
2/9/98	405	***36,100***	***248.91***		2/6/98	402	***24,879***	***171.54***
3/13/98	437	***32,908***	***226.90***		3/11/98	435	***24,677***	***170.15***
3/24/98	448	38,053	262.38		3/26/98	450	26,300	181.34
4/20/98	475	37,724	260.11		4/23/98	478	24,194	166.82
5/27/98	512	33,645	231.98		5/21/98	506	22,342	154.05
6/24/98	540	31,011	213.82		6/18/98	534	22,086	152.28
7/28/98	574	33,374	230.11		7/21/98	567	23,009	158.65
9/10/98	618	33,747	232.69		9/17/98	625	28,650	197.54



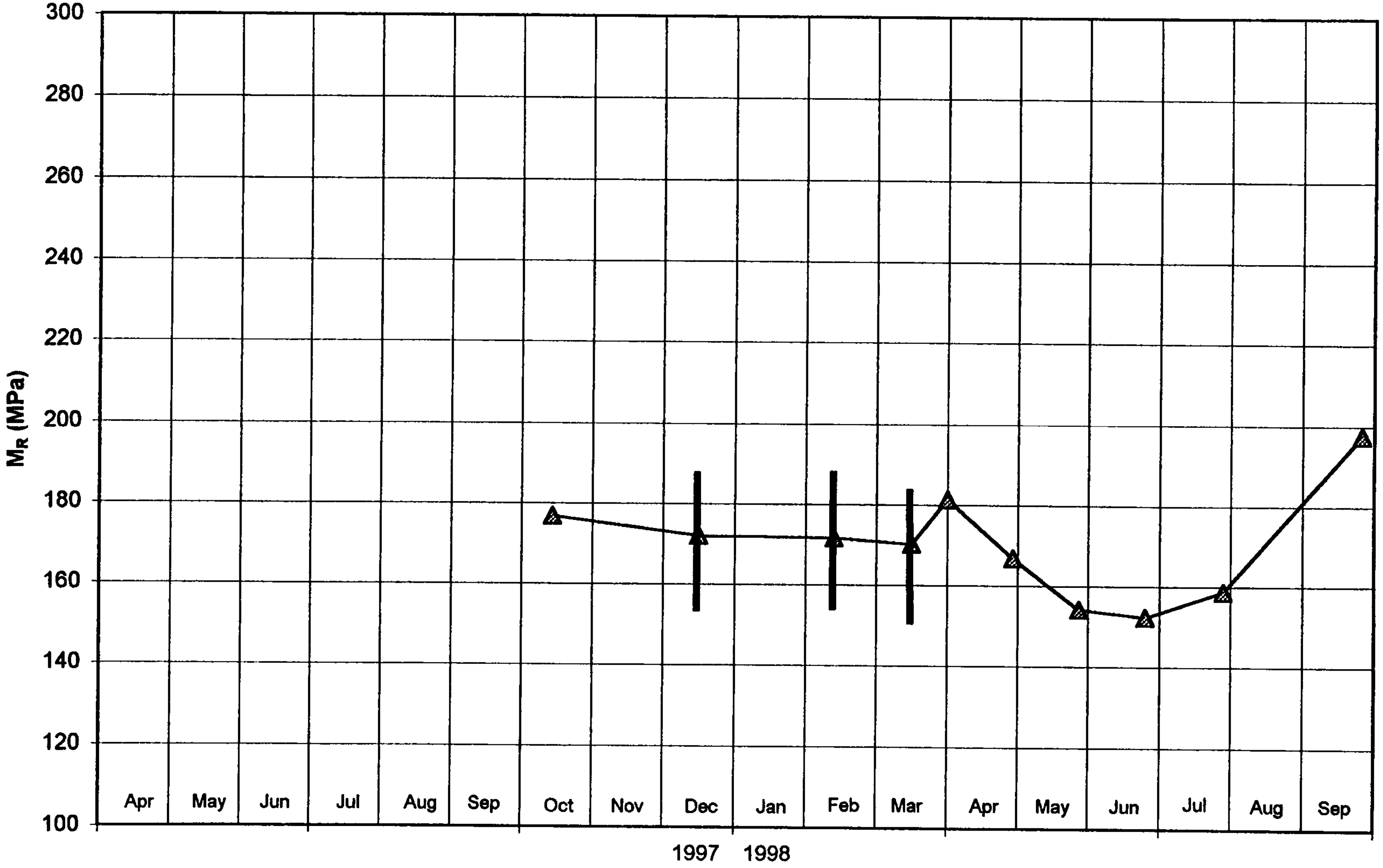
D.31 - Blount County FWD Backcalculated Subgrade Modulus



D.32 - Overton County FWD Backcalculated Subgrade Modulus



D.33 - Sumner County FWD Backcalculated Subgrade Modulus



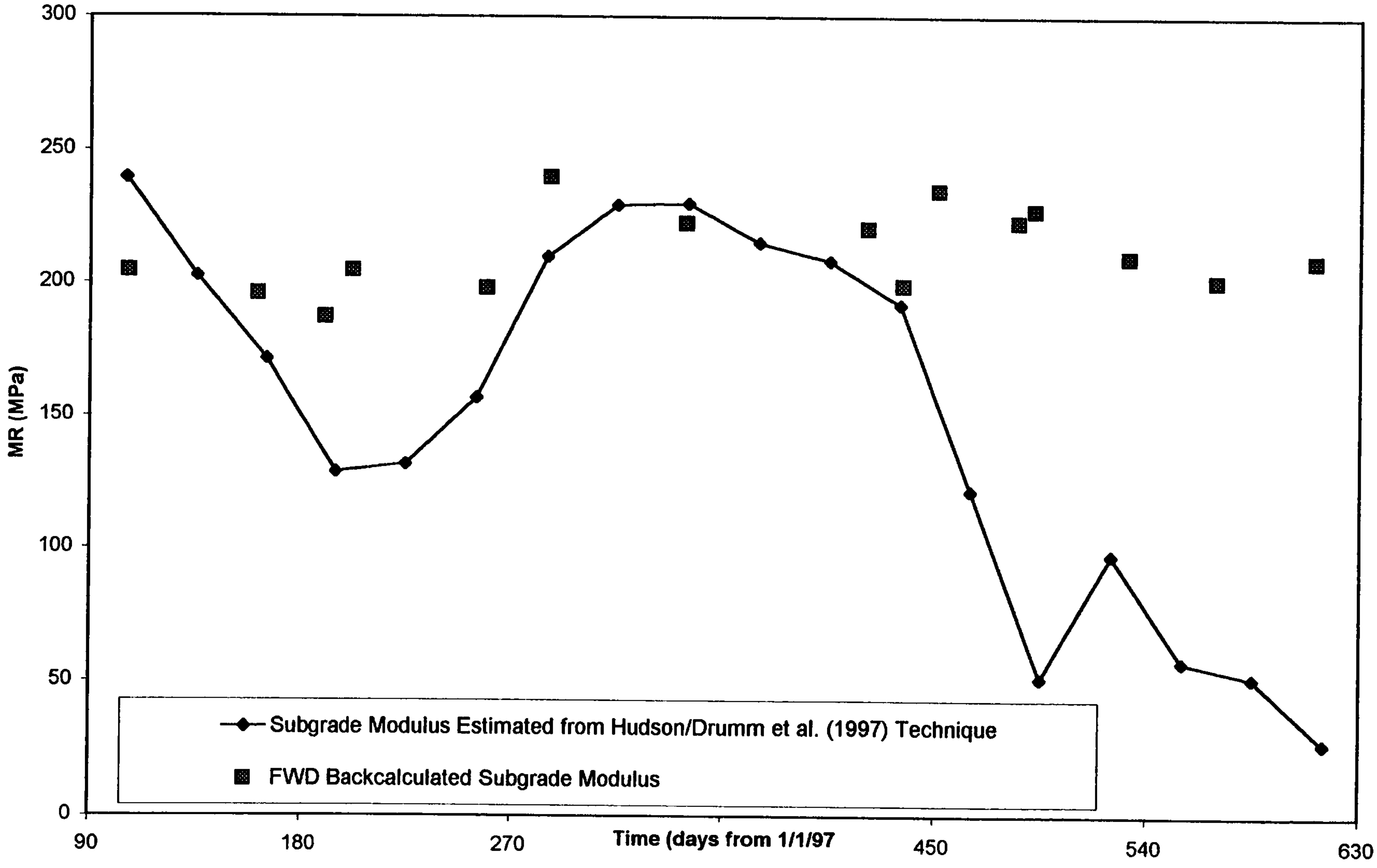
D.34 - McNairy County FWD Backcalculated Subgrade Modulus

APPENDIX E
ESTIMATED FLUCTUATIONS IN M_R

Blount County Estimated M_R (Hudson/Drumm et al.)

Matching Soil Type	Optimum					
Wilson Co.Sta.28						
27	Grav.Moist.(%)	23				
1.57	Density(Mg/m^3)	1.59	90%Opt.Density=	1.43		
2.84	Sp.Gravity	2.68	In-Situ Density=	1.37	86.48	
94.79	%Saturation	89.92	$\Delta M_R/\Delta S$ Slope=	-1900		
			Optimum M_R=	200		

Month	Day	Volumetric Moisture Content		%Saturation	ΔS	M_R
April	105	0.4277		87.83	-2.09	239.69
May	135	0.4372		89.78	-0.14	202.61
June	165	0.4452		91.42	1.51	171.34
July	195	0.4562		93.68	3.76	128.47
August	225	0.4554		93.52	3.61	131.50
September	255	0.4489		92.19	2.28	156.74
October	285	0.4353		89.39	-0.53	210.04
November	315	0.4303		88.36	-1.55	229.54
December	345	0.4301		88.33	-1.59	230.13
January	375	0.4339		89.11	-0.81	215.30
February	405	0.4357		89.47	-0.44	208.37
March	435	0.4400		90.35	0.43	191.74
April	465	0.4579		94.04	4.13	121.57
May	495	0.4760		97.75	7.83	51.19
June	525	0.4641		95.31	5.40	97.42
July	555	0.4744		97.42	7.51	57.40
August	585	0.4759		97.74	7.82	51.40
September	615	0.4821		99.00	9.08	27.40

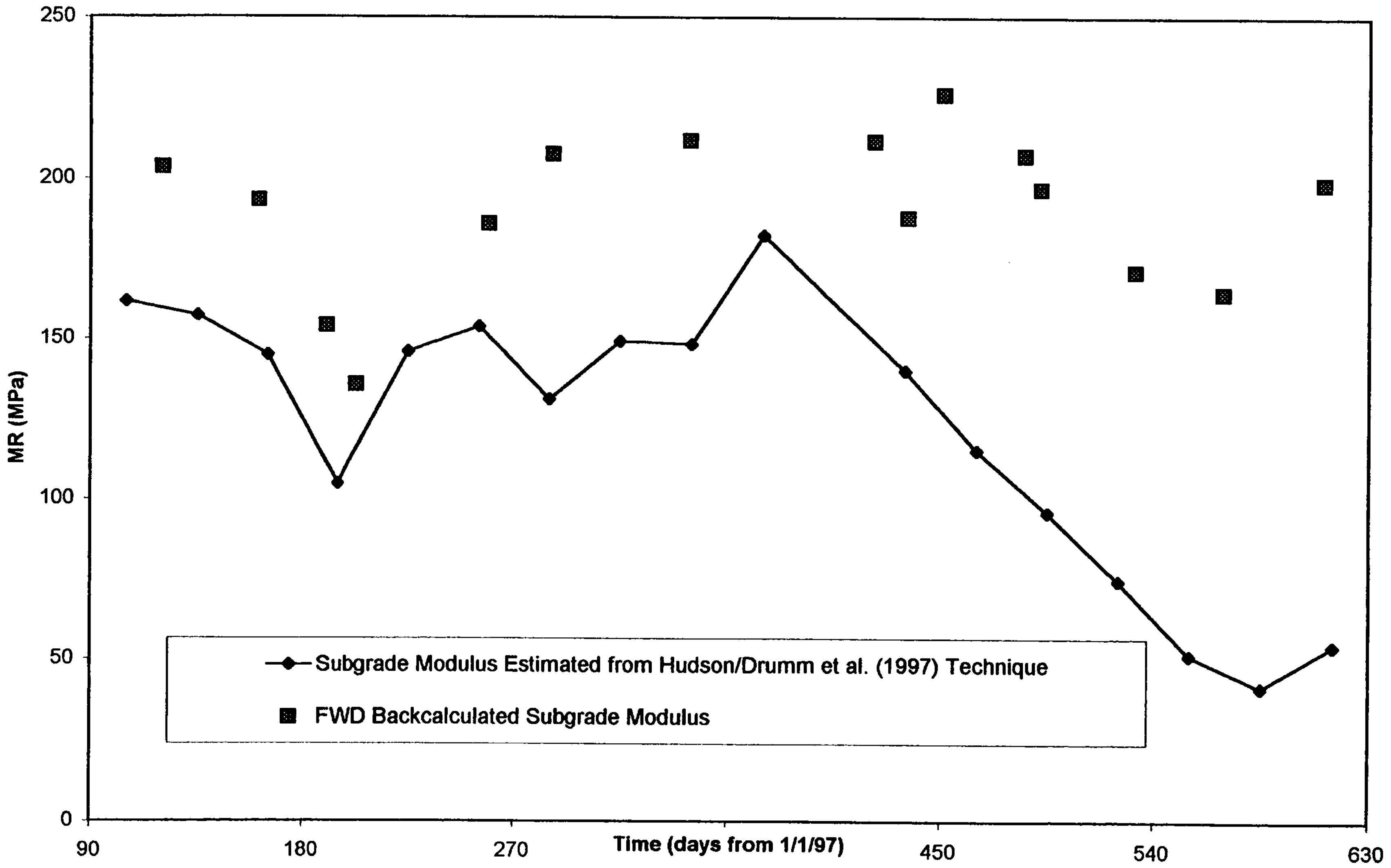


E.1 - Blount County Estimated Subgrade Modulus

Overton County Estimated M_R (Hudson/Drumm et al.)

Matching Soil Type	Optimum				
Knox Co.Sta.500					
19.2	Grav.Moist.(%)	20			
1.70	Density(Mg/m^3)	1.67	90%Opt.Density=	1.50	
2.70	Sp.Gravity	2.68	In-Situ Density=	1.56	93.59
88.13	%Saturation	**88.63**	$\Delta M_R/\Delta S$ Slope=	-1900	
			Optimum M_R=	180	

Month	Day	Volumetric Moisture Content		%Saturation	ΔS	M_R
April	105	0.3734		89.59	0.96	161.76
May	135	0.3743		89.82	1.19	157.36
June	165	0.3771		90.47	1.85	144.94
July	195	0.3859		92.59	3.96	104.74
August	225	0.3768		90.41	1.79	146.01
September	255	0.3751		90.00	1.38	153.87
October	285	0.3801		91.20	2.57	131.15
November	315	0.3761		90.25	1.62	149.20
December	345	0.3763		90.29	1.67	148.33
January	375	0.3689		88.50	-0.13	182.39
March	435	0.3781		90.72	2.10	140.17
April	465	0.3836		92.03	3.40	115.31
May	495	0.3878		93.05	4.43	95.90
June	525	0.3925		94.18	5.55	74.54
July	555	0.3976		95.40	6.78	51.26
August	585	0.3998		95.92	7.29	41.41
September	615	0.3970		95.25	6.62	54.13

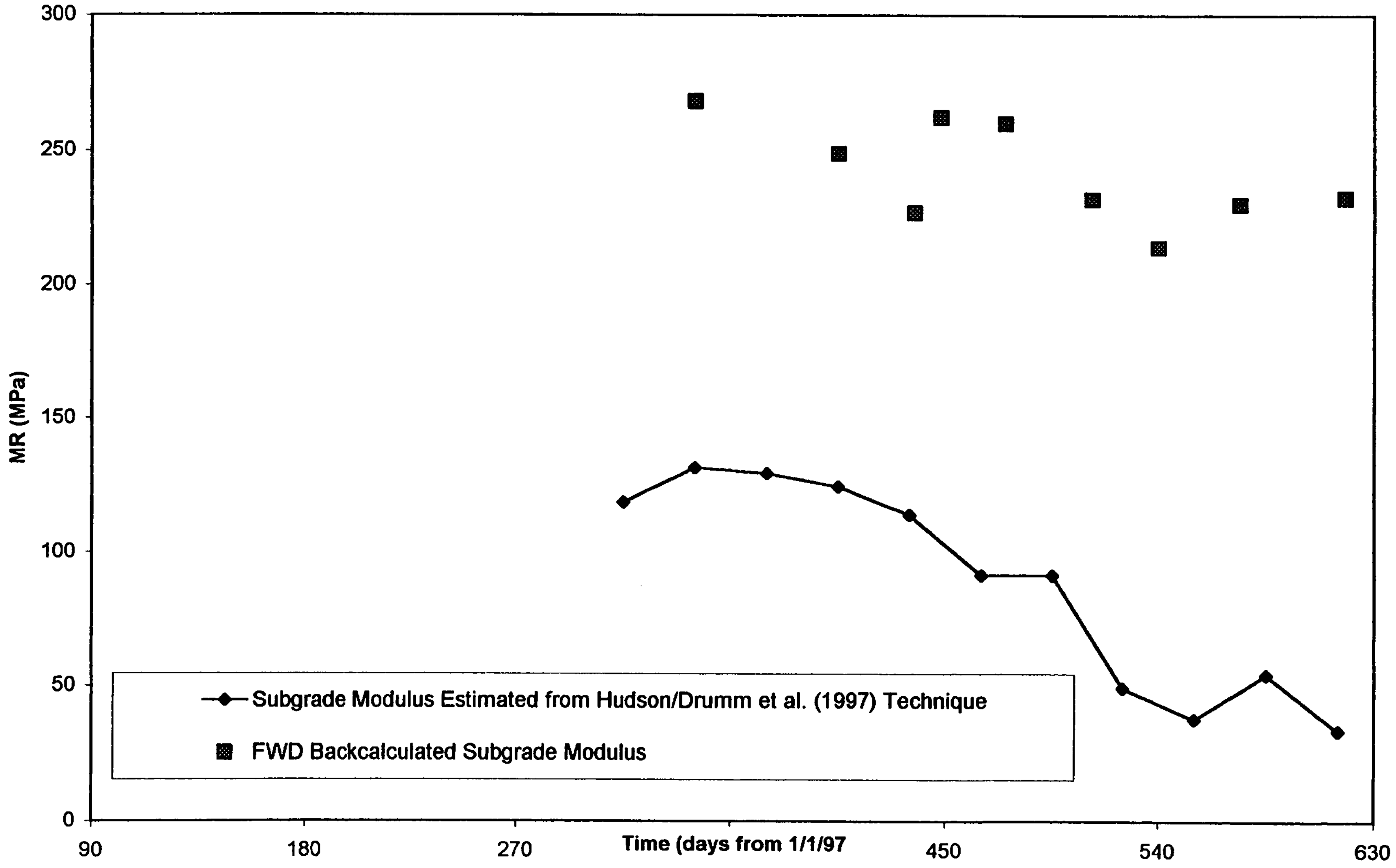


E.2 - Overton County Estimated Subgrade Modulus

Sumner County Estimated M_R (Hudson/Drumm et al.)

Matching Soil Type	Optimum				
Giles Co.Sta.270					
23.7	Grav.Moist.(%)	25			
1.54	Density(Mg/m^3)	1.5	90%Opt.Density=	1.35	
2.64	Sp.Gravity	2.62	In-Situ Density=	1.12	74.49
87.60	%Saturation	**87.72**	$\Delta M_R/\Delta S$ Slope=	-810	
			Optimum M_R=	125	

Month	Day	Volumetric Moisture Content		%Saturation	ΔS	M_R
April	105					
May	135					
June	165					
July	195					
August	225					
September	255					
October	285					
November	315	0.5077		88.53	0.80	118.49
December	345	0.4986		86.93	-0.79	131.43
January	375	0.5001		87.19	-0.54	129.36
February	405	0.5035		87.79	0.07	124.44
March	435	0.5110		89.09	1.37	113.90
April	465	0.5269		91.87	4.14	91.45
May	495	0.5269		91.87	4.14	91.45
June	525	0.5567		97.07	9.35	49.29
July	555	0.5649		98.50	10.78	37.72
August	585	0.5533		96.47	8.74	54.17
September	615	0.5678		99.00	11.28	33.66

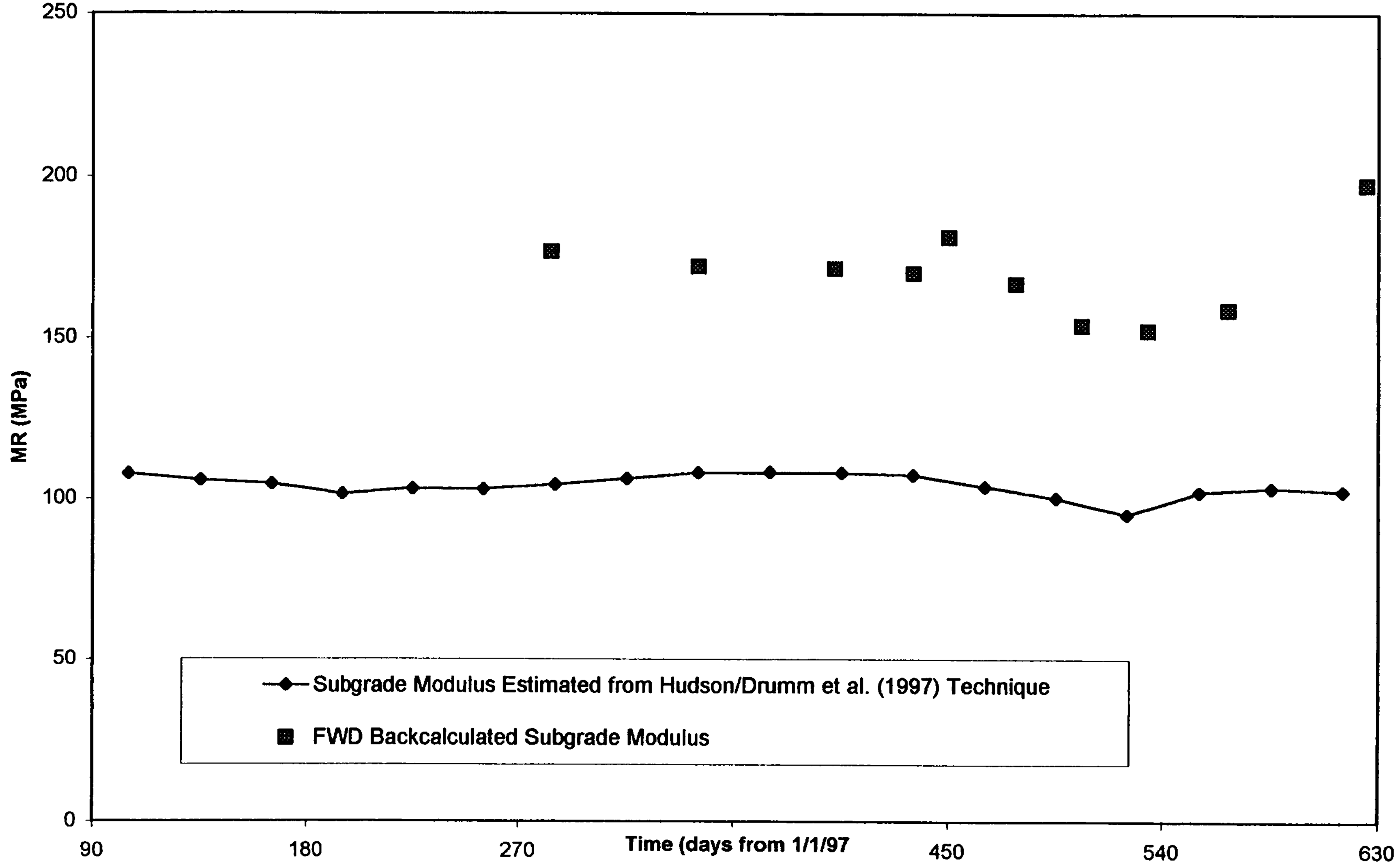


E.3 - Sumner County Estimated Subgrade Modulus

McNairy County Estimated M_R (Hudson/Drumm et al.)

Matching Soil Type	Optimum				
Roan Co.Sta.85					
13.2	Grav.Moist.(%)	13			
1.86	Density(Mg/m^3)	1.85	90%Opt.Density=	1.67	
2.6	Sp.Gravity	2.72	In-Situ Density=	1.64	88.69
86.26	%Saturation	**75.19**	$\Delta M_R/\Delta S$ Slope=	-300	
			Optimum M_R=	110	

Month	Day	Volumetric Moisture Content		%Saturation	ΔS	M_R
April	105	0.3015		76.00	0.81	107.57
May	135	0.3041		76.64	1.45	105.64
June	165	0.3055		77.01	1.82	104.54
July	195	0.3098		78.07	2.88	101.36
August	225	0.3076		77.53	2.34	102.99
September	255	0.3078		77.57	2.38	102.85
October	285	0.3058		77.07	1.88	104.37
November	315	0.3034		76.48	1.29	106.14
December	345	0.3011		75.89	0.70	107.91
January	375	0.3009		75.85	0.66	108.02
February	405	0.3011		75.88	0.69	107.92
March	435	0.3020		76.13	0.94	107.19
April	465	0.3067		77.29	2.10	103.69
May	495	0.3111		78.41	3.22	100.33
June	525	0.3181		80.18	4.99	95.03
July	555	0.3088		77.84	2.65	102.05
August	585	0.3071		77.42	2.23	103.32
September	615	0.3083		77.71	2.52	102.43

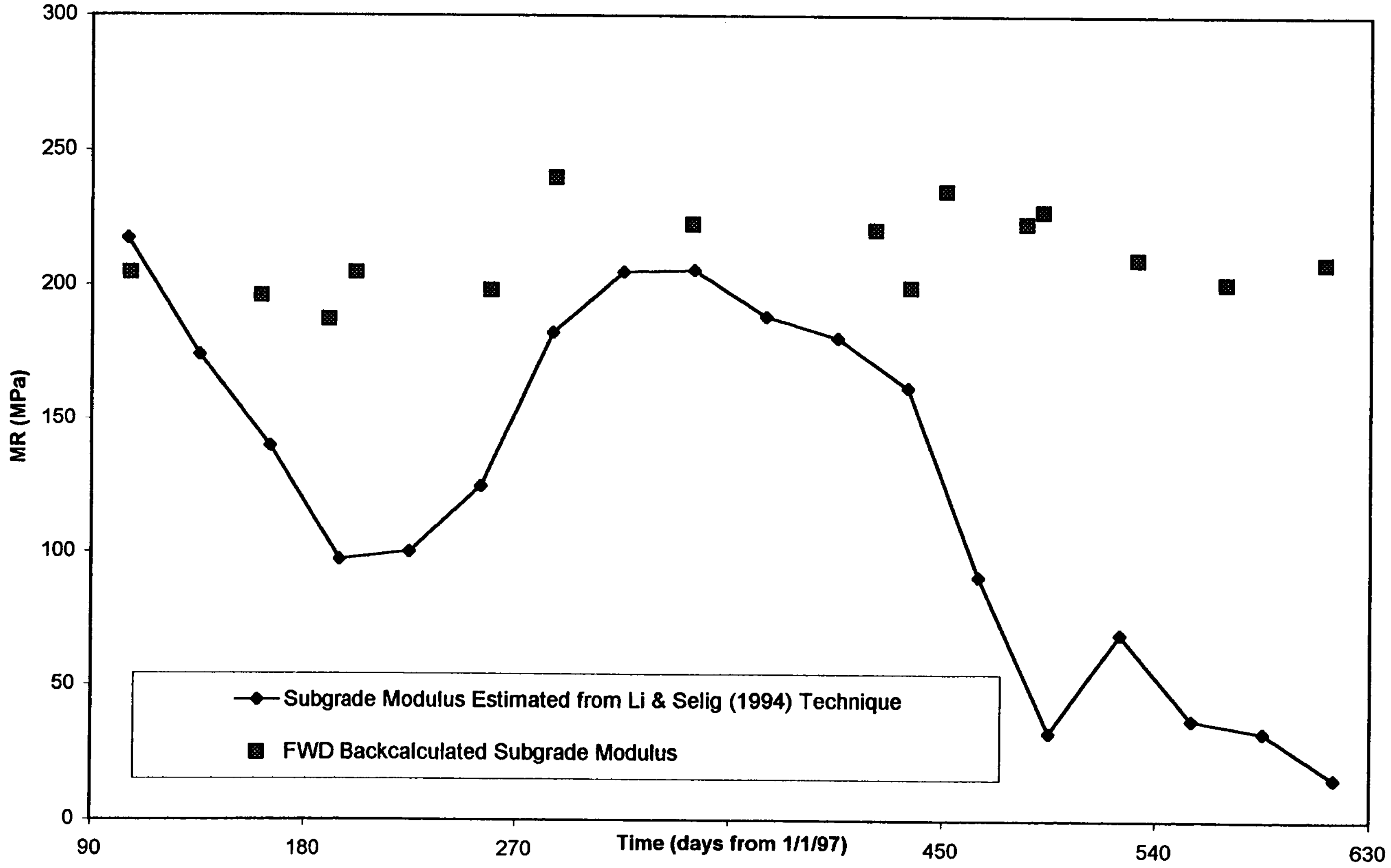


E.4 - McNairy County Estimated Subgrade Modulus

Blount County Estimated M_R (Li & Selig)

Parameters	Optimum			
k=354.8	Grav.Moist.(%)	23	Opt. Vol. Moisture	41.5
n= -0.1900	Density(Mg/m^3)	1.59	90%Opt.Density=	1.43
σ_d = 27.6 Kpa	Sp.Gravity	2.68	In-Situ Density=	1.58
	%Saturation	**89.92**		
			Optimum M_R=	292.56

Month	Day	Volumetric Moisture Content		$w - w_{opt}$	R_{m2}	M_R
April	105	0.4277		1.27	0.74	217.31
May	135	0.4372		2.22	0.59	173.74
June	165	0.4452		3.02	0.48	139.77
July	195	0.4562		4.12	0.33	97.28
August	225	0.4554		4.04	0.34	100.13
September	255	0.4489		3.39	0.43	124.77
October	285	0.4353		2.03	0.62	182.19
November	315	0.4303		1.53	0.70	205.02
December	345	0.4301		1.51	0.70	205.73
January	375	0.4339		1.89	0.64	188.25
February	405	0.4357		2.07	0.62	180.29
March	435	0.4400		2.50	0.55	161.65
April	465	0.4579		4.29	0.31	90.88
May	495	0.4760		6.10	0.11	32.63
June	525	0.4641		4.91	0.24	69.45
July	555	0.4744		5.94	0.13	37.26
August	585	0.4759		6.09	0.11	32.79
September	615	0.4821		6.71	0.05	15.83

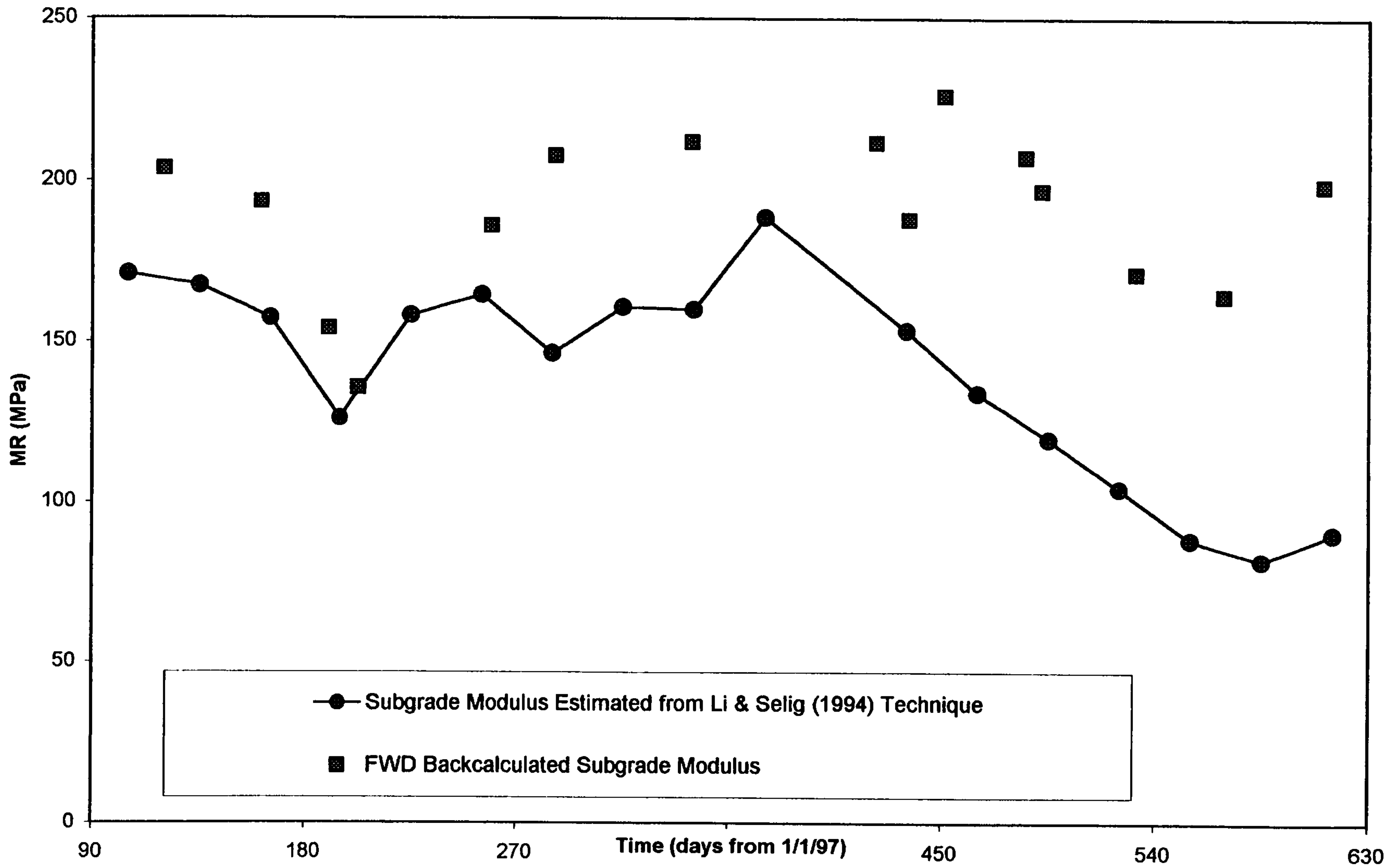


E.5 - Blount County Subgrade Modulus Calculated from Model

Overton County Estimated M_R (Li & Selig)

Parameters	Optimum			
k = 374.1	Grav.Moist.(%)	20	Opt. Vol. Moisture	36
n = -0.4620	Density(Mg/m^3)	1.67	90%Opt.Density=	1.50
σ_d = 27.6 Kpa	Sp.Gravity	2.68	In-Situ Density=	1.56
	%Saturation	**88.63**		
			Optimum M_R=	234.04

Month	Day	Volumetric Moisture Content		$w - w_{opt}$	R_{m2}	M_R
April	105	0.3734		1.34	0.73	171.11
May	135	0.3743		1.43	0.72	167.47
June	165	0.3771		1.71	0.67	157.33
July	195	0.3859		2.59	0.54	126.12
August	225	0.3768		1.68	0.68	158.20
September	255	0.3751		1.51	0.70	164.59
October	285	0.3801		2.01	0.63	146.35
November	315	0.3761		1.61	0.69	160.78
December	345	0.3763		1.63	0.68	160.07
January	375	0.3689		0.89	0.81	188.60
March	435	0.3781		1.81	0.66	153.50
April	465	0.3836		2.36	0.57	134.09
May	495	0.3878		2.78	0.51	119.59
June	525	0.3925		3.25	0.45	104.28
July	555	0.3976		3.76	0.38	88.39
August	585	0.3998		3.98	0.35	81.91
September	615	0.3970		3.70	0.39	90.30

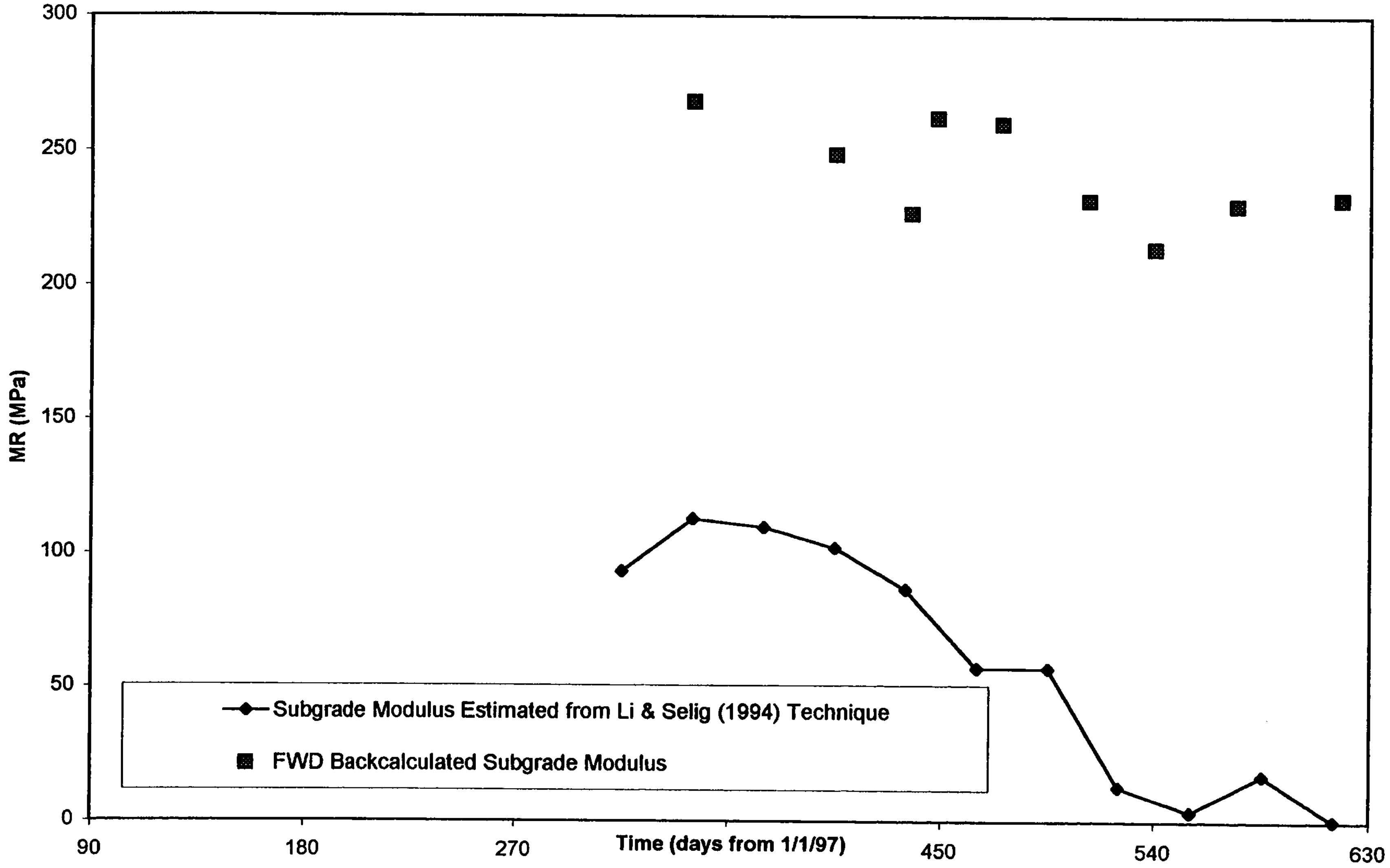


E.6 - Overton County Subgrade Modulus Calculated from Model

Sumner County Estimated M_R (Li & Selig)

Parameters	Optimum			
k= 185	Grav.Moist.(%)	25	Opt. Vol. Moisture	49.5
n= -0.3786	Density(Mg/m^3)	1.5	90%Opt.Density=	1.35
σ_d = 27.6 Kpa	Sp.Gravity	2.62	In-Situ Density=	1.56
	%Saturation	**87.72**		
			Optimum M_R=	125.96

Month	Day	Volumetric Moisture Content		$w - w_{opt}$	R_{m2}	M_R
April	105					
May	135					
June	165					
July	195					
August	225					
September	255					
October	285					
November	315	0.5077		1.27	0.74	93.40
December	345	0.4986		0.36	0.90	112.90
January	375	0.5001		0.51	0.87	109.69
February	405	0.5035		0.85	0.81	102.20
March	435	0.5110		1.60	0.69	86.81
April	465	0.5269		3.19	0.45	57.20
May	495	0.5269		3.19	0.45	57.20
June	525	0.5567		6.17	0.10	13.10
July	555	0.5649		6.99	0.03	3.63
August	585	0.5533		5.83	0.14	17.43
September	615	0.5678		7.28	0.00	0.57

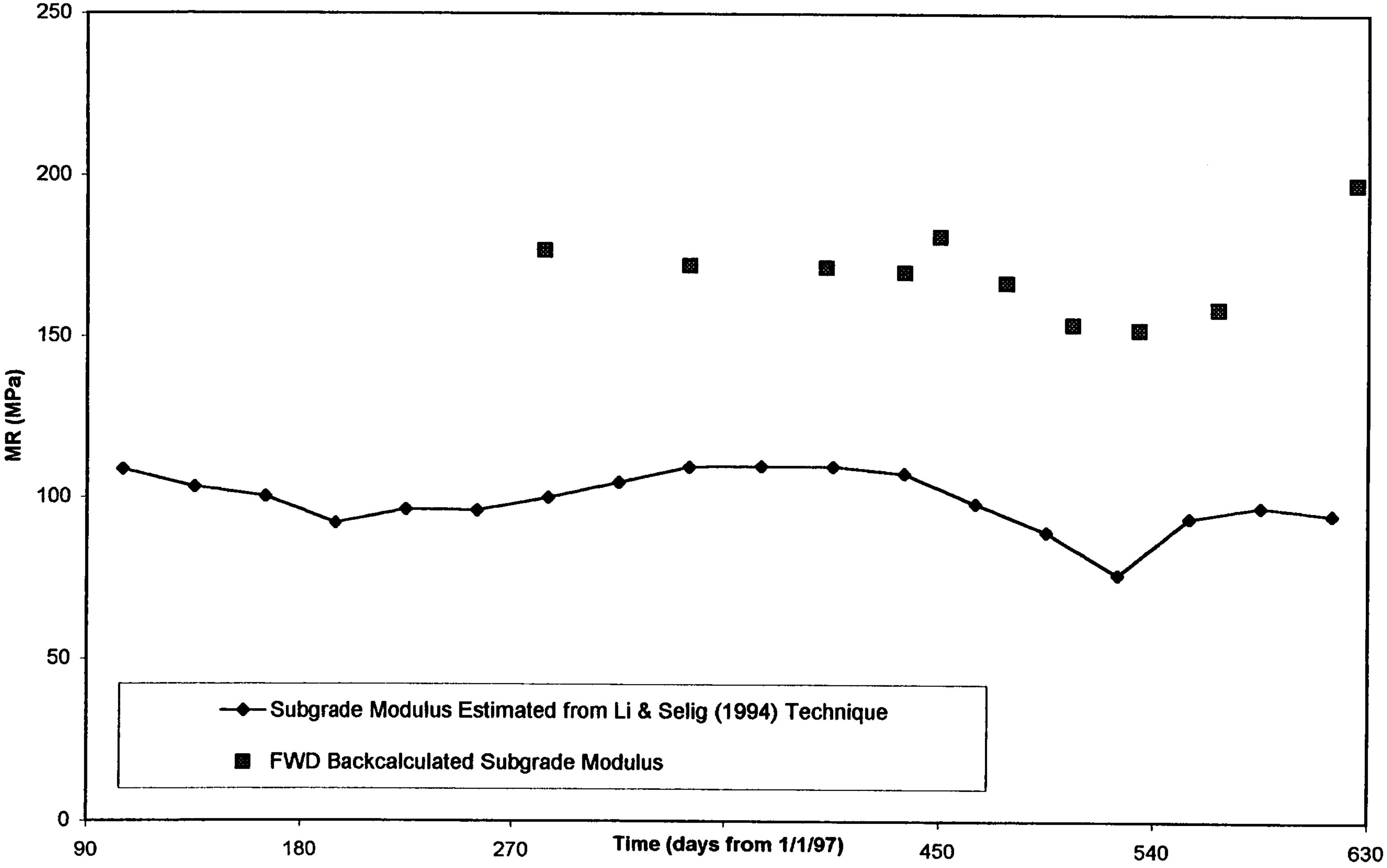


E.7 - Sumner County Subgrade Modulus Calculated from Model

McNairy County Estimated M_R (Li & Selig)

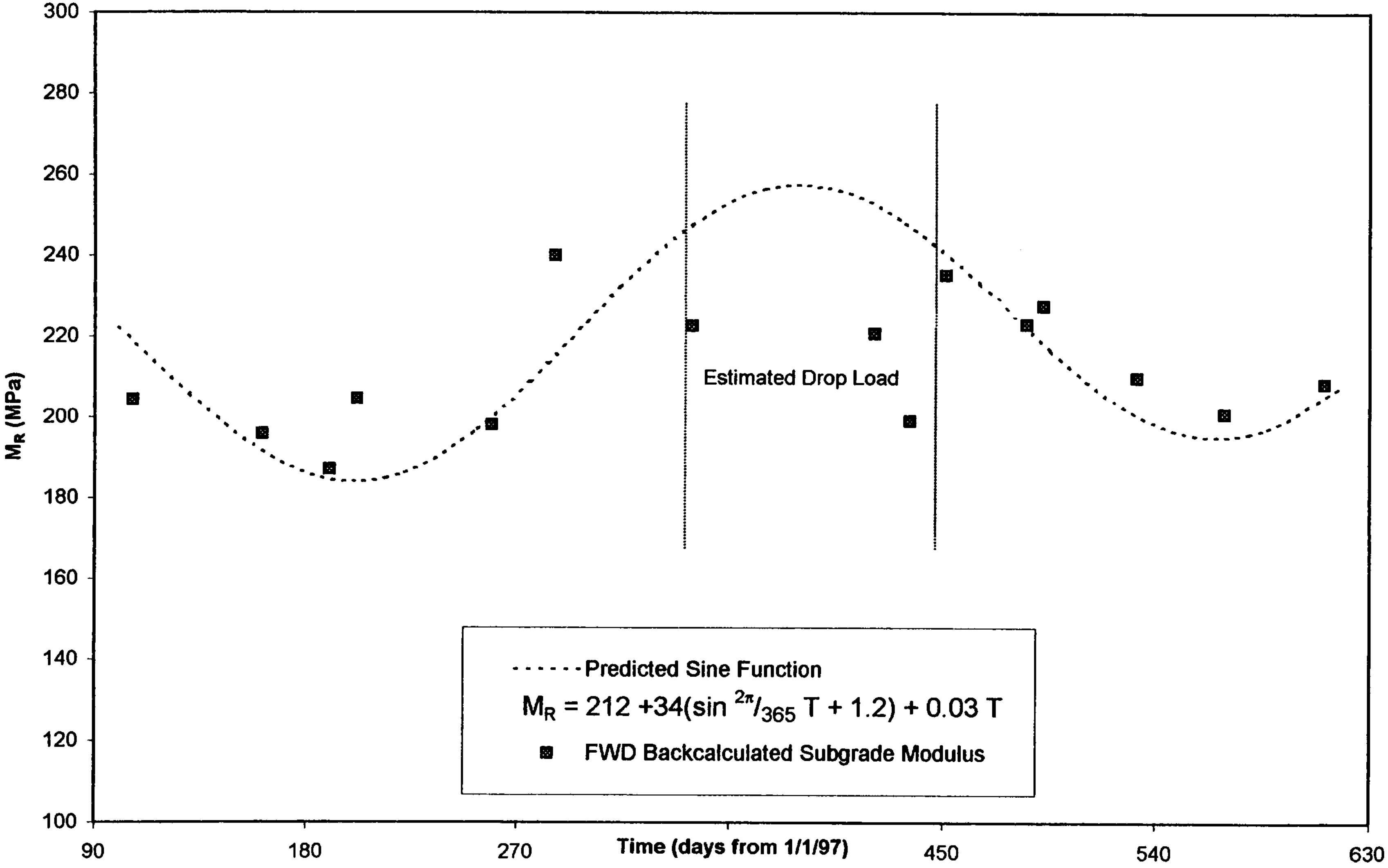
Parameters	Optimum			
k = 157.6	Grav.Moist.(%)	13	Opt. Vol. Moisture	30
n = -0.2990	Density(Mg/m^3)	1.85	90%Opt.Density=	1.67
σ_d = 27.6 Kpa	Sp.Gravity	2.72	In-Situ Density=	1.56
	%Saturation	75.19		
			Optimum M_R=	116.34

Month	Day	Volumetric Moisture Content		$w - w_{opt}$	R_{m2}	M_R
April	105	0.3015		0.15	0.93	108.50
May	135	0.3041		0.41	0.89	103.26
June	165	0.3055		0.55	0.86	100.32
July	195	0.3098		0.98	0.79	92.01
August	225	0.3076		0.76	0.83	96.24
September	255	0.3078		0.78	0.82	95.87
October	285	0.3058		0.58	0.86	99.88
November	315	0.3034		0.34	0.90	104.60
December	345	0.3011		0.11	0.94	109.44
January	375	0.3009		0.09	0.94	109.72
February	405	0.3011		0.11	0.94	109.46
March	435	0.3020		0.20	0.92	107.45
April	465	0.3067		0.67	0.84	98.09
May	495	0.3111		1.11	0.77	89.40
June	525	0.3181		1.81	0.66	76.30
July	555	0.3088		0.88	0.81	93.80
August	585	0.3071		0.71	0.83	97.12
September	615	0.3083		0.83	0.81	94.78



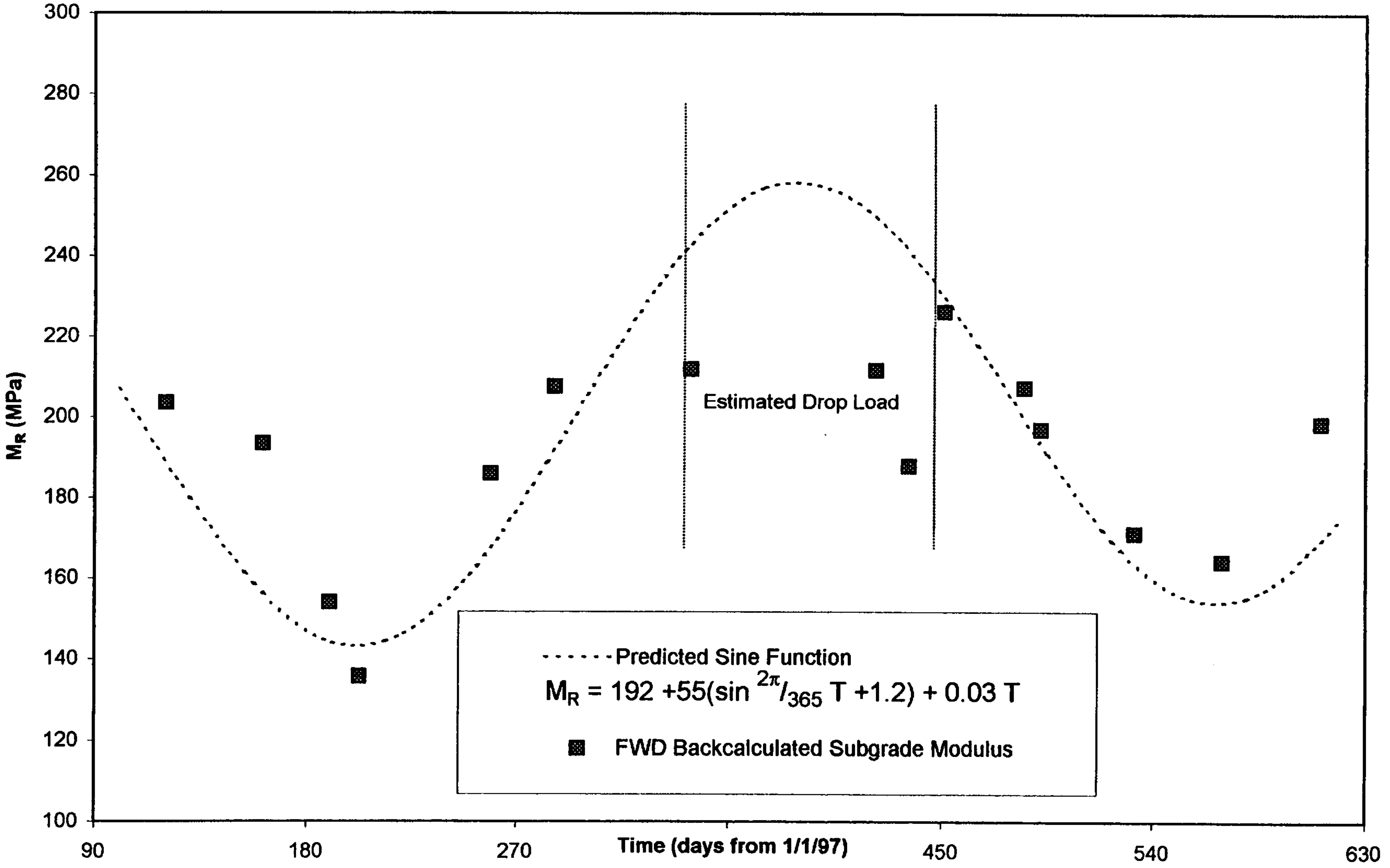
E.8 - McNairy County Subgrade Modulus Calculated from Model

	Blount County Sine Function						
	FWD Modulus				Sine Function		
Test Date	Day	MPa			Month	day	MPa
4/16/97	106	204.41			1	10	245.63
6/10/97	161	195.85			2	41	245.34
7/9/97	190	187.17			3	69	237.34
7/21/97	202	204.71			*4*	100	222.43
9/17/97	259	198.11			5	130	205.97
10/13/97	286	239.96			*6*	161	191.74
12/10/97	344	222.57			7	191	184.58
2/25/98	421	220.78			8	222	186.27
3/12/98	436	199.03			*9*	253	196.97
3/27/98	451	235.15			10	283	213.35
4/30/98	485	222.96			*11*	314	232.18
5/7/98	492	227.47			12	344	247.60
6/16/98	532	210.04			1	375	256.58
7/23/98	569	200.91			2	406	256.29
9/3/98	611	208.57			3	434	248.29
					4	465	233.38
	Average =	211.85			5	495	216.92
	Minimum=	187.17			6	526	202.69
	Maximum=	239.96			7	556	195.53
	B=	28.11			8	587	197.22
	(or)	24.67			9	618	207.92
		26.39					



E.9 - Blount County Predicted Sine Function

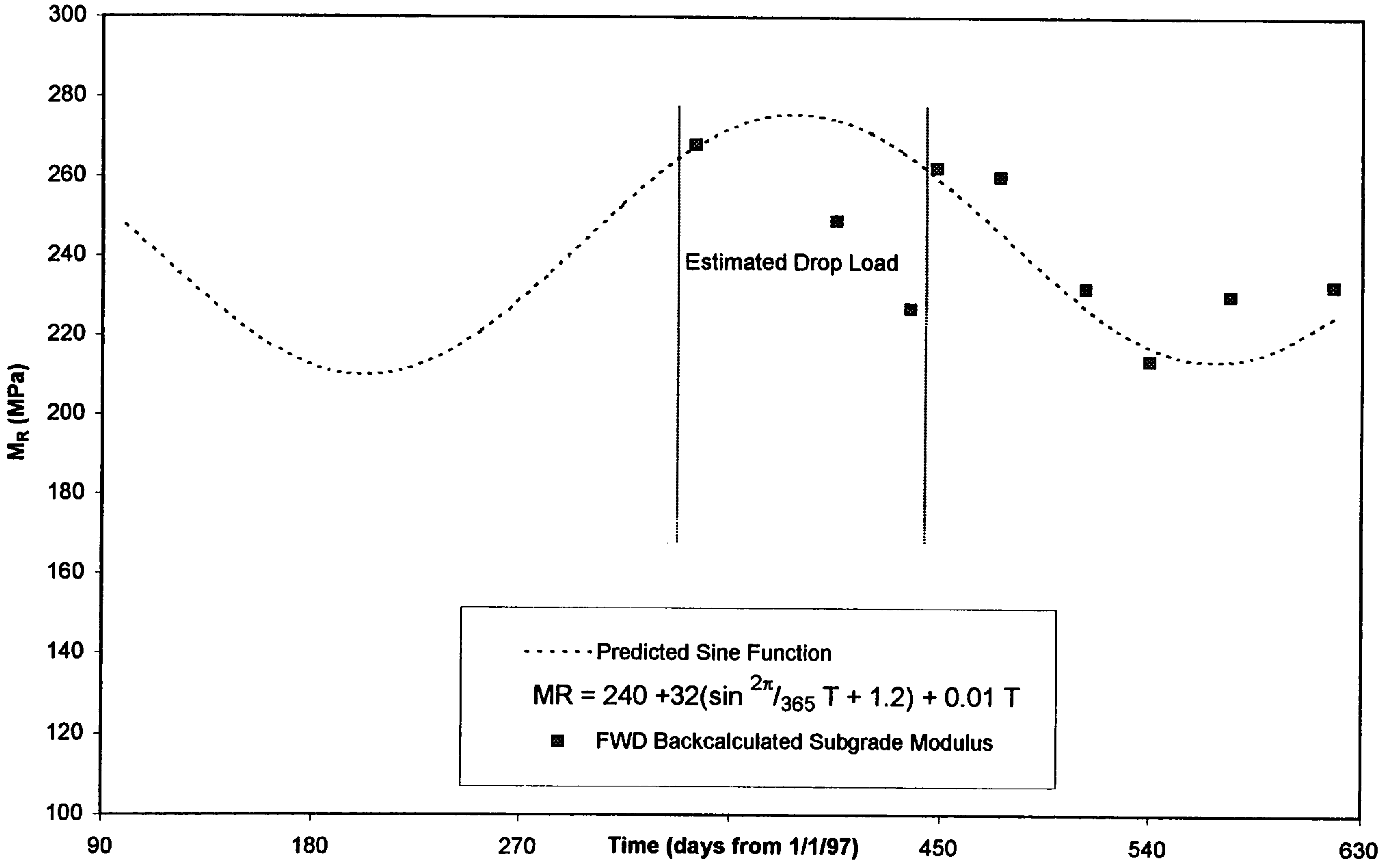
	Overton County Sine Function						
			Modulus		Sine Function		
	Test Date	Day	Mpa		Month	day	MPa
	4/30/97	120	203.54		1	10	246.22
	6/10/97	161	193.38		2	41	245.17
	7/9/97	190	154.08		3	69	231.71
	7/22/97	203	135.69		***4***	100	207.01
	9/17/97	259	186.01		5	130	179.84
	10/13/97	286	207.63		***6***	161	156.25
	12/10/97	344	211.91		7	191	144.11
	2/26/98	422	211.69		8	222	146.27
	3/12/98	436	187.94		***9***	253	162.99
	3/27/98	451	226.27		10	283	188.94
	4/30/98	485	207.43		***11***	314	218.83
	5/7/98	492	196.98		12	344	243.22
	6/16/98	532	171.24		1	375	257.17
	7/23/98	569	164.33		2	406	256.12
	9/3/98	611	198.55		3	434	242.66
					4	465	217.96
		Average=	190.44		5	495	190.79
		Minimum=	135.69		6	526	167.20
		Maximum=	226.27		7	556	155.06
		B=	35.82		8	587	157.22
		(or)	54.76		9	618	173.94
			45.29				



E.10 - Overton County Predicted Sine Function

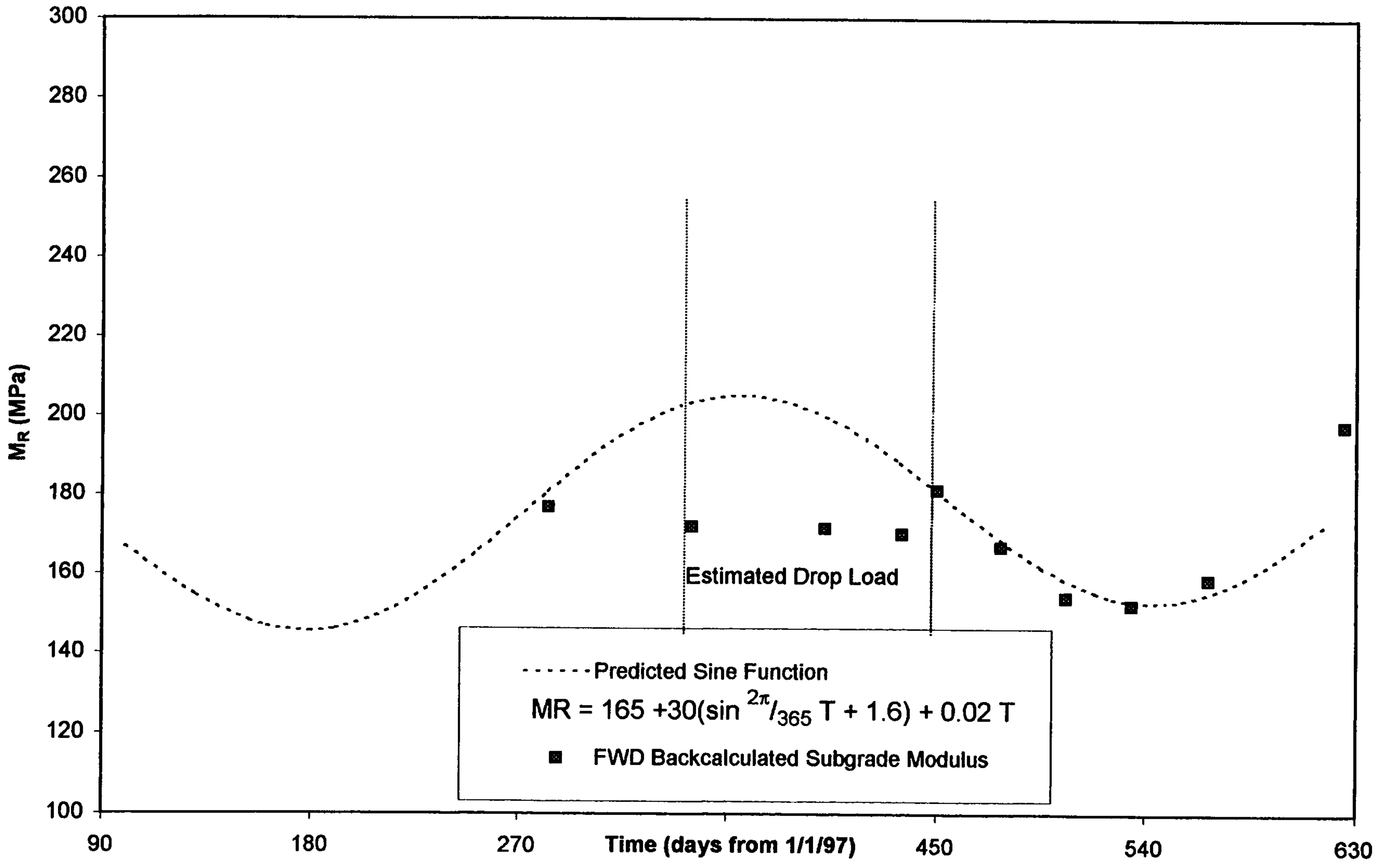
Sumner County Sine Function

			Modulus		Sine Function		
	Test Date	Day	Mpa		Month	day	MPa
					1	10	271.47
					2	41	270.63
					3	69	262.59
					4	100	247.99
					5	130	231.96
					6	161	218.00
	12/11/97	345	268.12		7	191	210.71
	2/9/98	405	248.91		8	222	211.74
	3/13/98	437	226.90		9	253	221.24
	3/24/98	448	262.38		10	283	236.11
	4/20/98	475	260.11		11	314	253.27
	5/27/98	512	231.98		12	344	267.24
	6/24/98	540	213.82		1	375	275.12
	7/28/98	574	230.11		2	406	274.28
	9/10/98	618	232.69		3	434	266.24
					4	465	251.64
		Average=	241.67		5	495	235.61
		Minimum=	213.82		6	526	221.65
		Maximum=	268.12		7	556	214.36
		***B*=**	26.45		8	587	215.39
		(or)	27.85		9	618	224.89



E.11 - Sumner County Predicted Sine Function

	McNairy County Sine Function						
			Modulus		Sine Function		
	Test Date	Day	Mpa		Month	day	MPa
					1	10	197.63
					2	41	191.59
					3	69	181.08
					4	100	166.99
					5	130	154.64
	10/10/97	283	176.79		*6*	161	146.83
	12/11/97	345	172.00		7	191	146.25
	2/6/98	402	171.54		8	222	153.19
	3/11/98	435	170.15		*9*	253	166.04
	3/26/98	450	181.34		10	283	180.91
	4/23/98	478	166.82		*11*	314	194.79
	5/21/98	506	154.05		12	344	203.35
	6/18/98	534	152.28		1	375	204.93
	7/21/98	567	158.65		2	406	198.89
	9/17/98	625	197.54		3	434	188.38
					4	465	174.29
		Average=	170.12		5	495	161.94
		Minimum=	152.28		6	526	154.13
		Maximum=	197.54		7	556	153.55
		B=	27.43		8	587	160.49
		(or)	17.83		9	618	173.34



E.12 - McNairy County Predicted Sine Function

VITA

James W. Andrew was born in Bend, Oregon on July 5, 1950, and graduated from Bend Senior High School in June 1968. After two years of attending the University of Oregon Honors College majoring in English and Psychology, and a seven-year career in the logging and reforestation industry of the Pacific Northwest, James moved to Tennessee to learn carpentry and cabinetry. James returned to academia to complete his higher education in 1992 when he began attending Pellissippi State Technical Community College Evening School. He graduated Summa cum Laude in June 1994 with an Associate of Science degree and an Award of Merit in Science. In August 1994, James began attending the University of Tennessee at Knoxville where he was awarded membership in the Honor Society of Phi Kappa Phi, the Engineering Honor Society of Tau Beta Pi, and the Civil Engineering Honor Society of Chi Epsilon. James was also presented the John Callaway Academic Achievement Award in 1996, a Civil and Environmental Engineering Department "Bridge to the Future" Alumni Scholarship in 1995 and was elected to the National Dean's List in 1995. James graduated from the University of Tennessee Summa cum Laude with a Bachelor of Science degree in Civil and Environmental Engineering in December 1997, and was recognized as Top Graduate from the College of Engineering.

James Andrew has been married to Marybeth Moscinski since 1983, and they share the joy of two sons; Alex, born in 1984, and Galen, born in 1986. James is currently working as a Graduate Research Assistant for the Civil and Environmental Engineering Department at the University of Tennessee where he will receive the Master of Science degree in December 1998.