MONITORING AND ANALYSIS OF DATA OBTAINED FROM MOISTURE TEMPERATURE RECORDING STATIONS

14589

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State Job No. 14589(0)

FINAL REPORT

Submitted to

The Ohio Department of Transportation

CWRU

Case Western Reserve University

Department of Civil Engineering

September, 2001

repared in Cooperation with the Ohio Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration

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FHWA REPORT No.	FHWA/OH-2001/09
Author:	Dr. J. Ludwig Figueroa
Performing Organization:	Case Western Reserve University
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Executive Summary

The performance of asphalt concrete pavements is in part affected by the seasonal variations of the resilient modulus of the AC layer and of the subgrade soil. To determine the variation of these parameters throughout Ohio, seven moisture-temperature-rainfall recording stations, previously installed during an Ohio Department of Transportation-funded project, and two additional ones installed during this project, were monitored for an additional period of 2-1/2 years. These stations, located to include various climatic zones and the four most common soil types within the state, recorded air, asphalt concrete and subgrade soil temperature, rainfall and moisture content (or degree of saturation) of the subgrade soil on a two-hour basis.

Recorded data led to the development of polynomial equations to calculate the average asphalt concrete pavement temperature from the air temperature and to the division of the state into three temperature zones: Northern, Central and Southern.

Recorded depths of frost penetration indicated average depths of 45 to 61 cm. within the southern zone and of 70 to 82 cm. within the northern zone. Similarly, the northern and the southern zones experience an average of 7 to 12 and 4 to 5 freeze-thaw cycles, respectively.

The degree of saturation calculated from moisture and temperature sensor readings varied form about 90% to 100% throughout the monitoring period. The late spring to early summer consistently led to a higher degree of saturation at all depths.

Finally, a method to back calculate the resilient modulus of subgrade soils (Eri) at the break point from measured FWD deflections was developed. Seasonal averages of this modulus were obtained at each of six station locations where FWD testing was conducted. Seasons were ranked in terms of expected higher resilient modulus. The designated "fall" testing period (early fall) showed the highest followed by "summer", "winter" and "spring" in decreasing order. Determined monthly and seasonal variation of material properties will find immediate application as inputs in mechanistic-empirical pavement design procedures.

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Abstract

The seasonal variations in the resilient modulus of asphalt concrete (AC) pavements and the corresponding resilient modulus variations of the subgrade soil are major factors in determining the performance of new AC pavements and overlays. Unfortunately, current design procedures do not directly consider these factors. It is expected however, that with the implementation of mechanistic pavement design procedures these variations will be included, leading to a more realistic design

Nine moisture-temperature-rainfall monitoring stations previously installed during project "Characterization of Ohio Subgrade Types" were monitored for an additional period of 2-1/2 years.. These stations record hourly, daily and seasonal variations in air temperature, rainfall, temperature within the asphalt concrete layer and moisture content (or degree of saturation) and temperature within the subgrade soil. Typically, temperature variations within the subgrade soil are minimal on a daily basis. Only the uppermost subgrade soil thermistor shows daily temperature variations although within a narrower range, following those of the bottom asphalt concrete thermistor.

The thermistors within the asphalt concrete layer exhibit large daily temperature fluctuations. Typically the AC layer exhibits a uniform temperature (no temperature gradient) twice a day, normally occurring between 8:00 and 10:00 AM and around 8:00 PM. Similarly, the maximum daytime temperature gradient within the pavement is observed between 2:00 and 4:00 PM at all seasons and the maximum overnight temperature gradient occurs around 6:00 AM. It is

to be noted that the temperature gradient is greater in the afternoon than in the early morning and that AC layer temperature variations closely follow air temperature changes.

The average AC pavement temperature was calculated in the middle of the layer at each location, and then monthly and seasonal averages were tabulated. The average pavement temperature difference between summer and winter is of the order of 30 to 35 deg. C at all sites. This range also indicates the wide variation in the elastic properties of the AC. As expected the northern sites exhibit slightly lower averages than the southern sites. Observations in temperature changes within the pavement and subgrade profiles indicate that the daytime and the nighttime averages for any sensors located at depths in excess of 30.48 cm. (1.0 ft.) from the surface (i.e. the subgrade soil sensors) are very similar. In addition, the asphalt concrete sensors show warmer temperatures than the soil sensors (on the average) during the spring and summer. However, this trend reverses during the fall and winter.

Polynomial equations were derived relating the average asphalt concrete pavement temperature to the air temperature for eight (excluding the Columbiana Co.) of the nine monitored stations. The coefficients included in these equations indicate that asphalt concrete temperature is higher in the southern part than in the northern part of the state. The regression coefficients also point to the fact that the state of Ohio may be subdivided into three general temperature zones: North, (from the North Shore to Mansfield – Mount Vernon) Central (from Mansfield – Mount Vernon to Lancaster) and South (from Lancaster to the southern state line).

As a result of temperature differences during the four seasons the resilient modulus of the asphalt concrete also changes in an inverse form to the temperature variation. It was determined that for a typical mid-season day the resilient modulus averages:

3791.7 MPa (550 ksi) in the spring (+/- 1034.1 MPa or +/- 150 ksi)
1723.5 MPa (250 ksi) in the summer (+/- 1034.1 MPa or +/- 150 ksi)
8272.8 MPa (1200 ksi) in the fall (+/- 1378.8 MPa or +/- 200 ksi)

15511.5 MPa (2250 ksi) in the winter (+/- 1551.1 MPa or +/- 225 ksi)

Recorded depths of frost penetration show, as expected, that they are greater in the northern than in the southern stations. On a normal season the average depth of frost penetration is about 45.7 to 61.0 cm. (1.5 to 2.0 ft) at the southern stations and from 70.1 to 82.3 cm. (2.3 to 2.7 ft) at the northern locations. It was also observed that when the frost penetration is high at the northern sites the number of freeze-thaw cycles is lower. This normally occurs during severe winters. The number of cycles appears to increase during milder winters. Normally, the northern sites experience an average 7 to 12 cycles as compared to between 4 and 5 in the southern sites.

A calibration equation previously developed was used to obtain monthly and seasonal averages of the degree of saturation from moisture and temperature sensor readings at each of four moisture sensor locations. The degree of saturation typically varied between about 90% and 100% throughout the monitoring period. The late spring to early summer period seems to consistently lead to slightly higher (nearing 100%) degree of saturation at all depths.

Finally a method to back calculate the resilient modulus of subgrade soils at the break point from measured FWD deflections was developed. Overall seasonal averages of the modulus were obtained at each of six station locations where FWD testing was conducted. Seasons were ranked in terms of expected higher resilient modulus. The designated “fall” testing period (early fall) showed the highest followed by “summer”, “winter” and “spring” in decreasing order. This ranking is expected since the fall testing period follows the generally drier summer season and the spring testing period happens at the spring thaw and normally wetter early spring. Generally, for the most part a higher back calculated resilient modulus followed lower amounts of rainfall. Similarly lower resilient modulus back calculations were generally preceded by higher rainfall. Attempts to correlate the amount of rainfall accumulated over either one month, two or three months preceding the date of FWD testing with the back calculated resilient modulus were unsuccessful.

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Chapter 1

INTRODUCTION

Flexible pavement response to traffic loading largely depends on the stiffness properties of the materials composing the pavement profile. Fundamental aspects which must be considered in the design of new asphalt concrete pavements and overlays include the seasonal variations of the resilient modulus of the asphalt concrete and the corresponding variations in the resilient modulus of the subgrade.

Among the factors affecting the resilient modulus of the asphalt concrete such as type of asphalt mix (including aggregates and admixtures), degree of compaction, and temperature, only temperature varies with time.

Similarly, among the factors affecting the resilient modulus of fine grained soils such as soil type (i.e. A-4, A-6, A-7, etc.), dry unit weight and moisture content (or degree of saturation), only the moisture content varies with time.

Environmental factors including temperature within the asphalt concrete and moisture within the subgrade soil are now easily monitored with field data acquisition systems developed over the past few years. A total of nine moisture-temperature-monitoring stations were installed during the ODOT-funded project "Characterization of Ohio Subgrade Types". Some of these stations have been collecting data since 1991 at intervals of 2 hours, providing a wealth of information as to the variation of environmental factors in typical climatic zones within the State of Ohio.

Similarly, the Ohio Department of Transportation has been collecting FWD readings periodically, on 152.4 m. (500 ft.)-long sections adjacent to some of the environmental monitoring stations. This information coupled with the environmental data obtained from the stations permits the back calculation of the resilient modulus of the subgrade soil, to obtain trends on the variation of this parameter throughout the years.

The eventual implementation of mechanistic flexible pavement design procedures in the State of Ohio requires the determination of changes in material properties for an accurate evaluation of pavement life and proper determination of required layer thicknesses.

This report includes the results of the research project "Monitoring and Analysis of Data Obtained from Moisture-Temperature Recording Stations," funded by the Ohio Department of Transportation (ODOT). In essence, this project is an extension of the previously ODOT-funded project "Characterization of Ohio Subgrade Types" since data has been collected for a substantially longer period of time.

The project under consideration in this report consisted of three major efforts:

The first part included the extension of the monitoring and analysis period for data obtained from the originally installed stations located throughout Ohio. At most of these stations, the temperature (to obtain the depth of frost penetration) and the degree of saturation of the subgrade soil, the temperature of the asphalt concrete surface layer, the air temperature and the amount of rainfall have been almost continuously monitored and recorded.

The second part consisted of the analysis of seasonal FWD deflection data obtained by ODOT, which coupled with the moisture and temperature readings would yield a more extensive measure of the variability in the resilient properties of both asphalt concrete surface layer and subgrade soil.

It is expected that with the analysis of data obtained in parts 1 and 2, more representative seasonal average resilient properties of both surface and subgrade layers in flexible pavements, as well as of climate-related parameters could be obtained.

The third part involved the development of guidelines regarding the use of these resilient properties in the eventual implementation of a mechanistic flexible pavement design procedure.

Following, a summary of the contents of subsequent chapters is presented.

Chapter two includes the review of pertinent background information including previously developed methods linking changes in the stiffness properties of pavement materials to also varying environmental factors. In addition, the criteria used for selecting the location of each of the monitoring stations as well as the pavement section characteristics and sensor location existing at each site are presented.

Chapter three analyzes the seasonal data collected and discusses the effects of these environment-related factors on properties of influence in the mechanistic design of asphalt concrete pavements, such as the modulus of the asphalt concrete. The influence of temperature, rainfall and frost is discussed in detail. Finally, graphs and charts showing the variation of the degree of saturation at the monitored test sites are presented.

Chapter four discusses results of back calculating the resilient modulus of subgrade soil from measured FWD deflections and the possible link of changing resilient modulus as a result of previous rainfall regimes.

Chapter five includes a summary of the overall findings and implementation recommendations, along with any conclusions drawn as a result of this research. All supporting information in the form of tables and graphs is included in the appendixes.

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Chapter 2

REVIEW OF PERTINENT BACKGROUND INFORMATION

The first section of this chapter summarizes pertinent information concerning the criteria used for site selection, pavement section characteristics and periods of available data. The second section reviews material property determination procedures used in the previous project and summarizes the procedure to backcalculate the resilient modulus of subgrade soils, based on measured subgrade deflections, also developed during the same project. Both of these methods will be used in subsequent chapters to analyze the additional data obtained, as well as to develop guidelines of eventual application in flexible pavement mechanistic design procedures.

2.1 Site Selection

A total of nine moisture-temperature-monitoring stations were installed during the ODOT-funded project "Characterization of Ohio Subgrade Types," between 1991 and 1994. At the end of the spring of 1997, five of these stations were in operation at the locations listed in Table 2.1a. However, later in the summer of 1997 the Athens Co. station was successfully restarted. The location selection criteria included the coverage of climatic zones within the state of Ohio: northwestern, northeastern, southwestern, southeastern and central; soil type A-3, A-4, A-6 and A-7; and a flexible pavement structure. Other factors considered in the selection criteria included a four-lane flexible pavement to facilitate the closure of one lane during installation as well as non-destructive testing; pavements in good condition, sites with good drainage and away from power lines to eliminate electrical noise. Other special considerations included the proximity to a Weight In Motion (WIM) station, such as the Licking Co. site.

Table 2.1a Monitoring Station Locations

COUNTY	CLIMATE ZONE	ROAD	MILE POST	LANE	SOIL TYPE
ADAMS	SW	SR-32	4.4	WB	A-4a(8)
ATHENS ***	SE	US-50	5.9	WB	A-6a(10)
COLUMBIANA *	NE	SR-11	18.2	NB	A-6a(1)
CRAWFORD	Central	US-30	5.1	EB	A-6a(8)
KNOX	Central	SR-13	16.3	NB	A-6a(10)
LICKING	Central	I-70	117@WIM	WB	A-4a(5)
LUCAS *	NW	I-475	10.9	NB	A-3a
WOOD 2.85 **	NW	SR-795	2.85	WB	A-7-6(15)
WOOD 8.1	NW	SR-795	8.1	WB	A-7-6(13)

Note: Numbers in parenthesis ( ) in SOIL TYPE column represent the Group Index

* Not operating at present

** Dismantled

*** Restarted, Summer '97

Table 2.1b Monitoring Station Soil Classification Parameters

SITE	% PASSING SIEVE #				LL	PL	GROUP
	200	40	10	4			
ADAMS	88.6	96.9	99.2	99.7	32.2	23.1	A-4a(8)
ATHENS	79.3	96.1	96.8	98.5	34.2	20.1	A-6a(10)
COLUMBIANA	42.0	57.6	68.2	76.3	30.0	11.0	A-6a(1)
CRAWFORD	65.6	90.0	97.5	99.0	33.2	18.3	A-6a(8)
KNOX	90.1	98.9	99.6	99.7	36.0	21.9	A-6a(10)
LICKING	60.2	77.5	87.8	92.7	25.1	17.7	A-4a(5)
LUCAS	15.5	96.1	100.0	100.0	----	----	A-3a
WOOD (2.85)	90.1	97.7	99.3	99.9	46.1	22.8	A-7-6(15)
WOOD (8.1)	92.5	98.4	99.8	100.0	44.2	22.6	A-7-6(13)

The WOOD 2.85 Co. station was dismantled in the summer of 1995 because of new urban development at the site and the lack of Non-Destructive (FWD) testing data. The COLUMBIANA Co. station was extensively damaged by a vehicle crash, shortly after its installation, even though it was located at least 9.2 m. (30 ft.) from the road shoulder. Replacement of the logger unit indicated that only a small number of sensors remained in operation. The scant usable data collected at this station was considered to be statistically insignificant to be able to develop meaningful relationships. The LUCAS Co. station was damaged by lightning discharges in their vicinity. Information about soil types existing at each site is given in Table 2.1b. More detail regarding the geological characteristics of these soils can be found in the report by Figueroa et al. (1994).

Table 2.2a is a summary of the pavement profile geometric characteristics along with the subgrade soil type existing at each monitoring site. Similarly Table 2.2b lists wire denomination numbers and sensor types (moisture and temperature) at each of the monitoring stations, along with the depth of every sensor measured from the pavement surface. A rain gage (tipping bucket type) is also installed next to the data logger at each site.

Table 2.2a Pavement Profile and Subgrade Type Existing at Each Location

Site	**Thickness (cm)**		
	AC Layer	**Gravel Layer**	**Subgrade Type**
Adams	39.6 (15.6")	12.7 (5.0")	A-4a(8)
Athens	29.2 (11.5")	15.2 (6.0")	A-6a(10)
Columbiana	29.5 (11.6")	15.0 (5.9")	A-6a(1)
Crawford	29.5 (11.6")	24.1 (9.5")	A-6a(8)
Knox	33.3 (13.1")	20.3 (8.0")	A-6a(10)
Licking	34.8 (13.7")	10.2 (4.0")*	A-4a(5)
Lucas	28.7 (11.3")	55.9 (22.0")	A-3a
Wood (2.85)	26.7 (10.5")	15.2 (6.0")	A-7-6(15)
Wood (8.1)	30.5 (12.0")	15.2 (6.0")	A-7-6(13)

* Plus 45.7 cm (18") of lime stabilized soil

Available asphalt concrete pavement, soil temperature and weather-related data to be analyzed in this report include data from the monitoring stations for the periods listed in Table 2.3.

2.2 Material Property Determination Procedures

Following is a summary of relationships and procedures developed during the project "Characterization of Ohio Subgrade Types" of fundamental importance in determining the variation of flexible pavement material properties throughout the year.

Table 2.2b Sensor Depth and Nomenclature

Adams			Athens			Columbiana		
Wire#	Depth (cm)	Type	Wire#	Depth (cm)	Type	Wire#	Depth (cm)	Type
15	AIR	T	15	AIR	T	15	AIR	T
14	6.4 (0'-2.5")	T*	14	5.1 (0'-2")	T*	14	5.1 (0'-2")	T*
13	12.7 (0'-5")	T*	13	10.2 (0'-4")	T*	13	10.2 (0'-4")	T*
12	19.0 (0'-7.5")	T*	12	15.2 (0'-6")	T*X	12	15.2 (0'-6")	T*
11	25.4 (0'-10")	T*X	11	20.3 (0'-8")	T*X	11	20.3 (0'-8")	T*
10	31.7 (1'-0.5")	T*	10	25.4 (0'-10")	T*	10	25.4 (0'-10")	T*
4	45.7 (1'-6")	M	4	45.7 (1'-6")	M	4	45.7 (1'-6")	M
9	60.9 (2'-0")	TX	9	60.9 (2'-0")	T	9	60.9 (2'-0")	T
3	76.2 (2'-6")	M	3	76.2 (2'-6")	M	3	76.2 (2'-6")	M
8	91.4 (3'-0")	T	8	91.4 (3'-0")	T	8	91.4 (3'-0")	T
2	106.7 (3'-6")	MX	2	106.7 (3'-6")	M	2	106.7 (3'-6")	M
7	121.9 (4'-0")	T	7	121.9 (4'-0")	T	7	121.9 (4'-0")	T
1	137.1 (4'-6")	M	1	137.1 (4'-6")	M	1	137.1 (4'-6")	M
6	152.4 (5')	T	6	152.4 (5')	T	6	152.4 (5')	T

Crawford			Knox			Licking		
Wire#	Depth (cm)	Type	Wire#	Depth (cm)	Type	Wire#	Depth (cm)	Type
15	AIR	T	14	AIR	T	14	AIR	T
14	5.1 (0'-2")	T*	13	5.1 (0'-2")	T*	13	5.1 (0'-2")	T*X
13	10.2 (0'-4")	T*	12	10.2 (0'-4")	T*	12	10.2 (0'-4")	T*
12	15.2 (0'-6")	T*	11	20.3 (0'-8")	T*	11	20.3 (0'-8")	T*
11	20.3 (0'-8")	T*	10	29.2 (0'-11.5")	T*X	10	25.4 (0'-10")	T*
10	25.4 (0'-10")	T*X	9	45.7 (1'-6")	T	9	30.5 (1'-0")	T
4	45.7 (1'-6")	M	4	60.9 (2'-0")	M	4	45.7 (1'-6")	M
9	60.9 (2'-0")	T	8	76.2 (2'-6")	T	8	60.9 (2'-0")	TX
3	76.2 (2'-6")	M	3	91.4 (3'-0")	M	3	76.2 (2'-6")	M
8	91.4 (3'-0")	T	7	106.7 (3'-6")	T	7	91.4 (3'-0")	T
2	106.7 (3'-6")	M	2	121.9 (4'-0")	M	2	106.7 (3'-6")	M
7	121.9 (4'-0")	T	6	137.1 (4'-6")	T	6	121.9 (4'-0")	T
1	137.1 (4'-6")	M	1	152.4 (5')	M	1	137.1 (4'-6")	M
6	152.4 (5')	T					152.4 (5')	

Table 2.2b Sensor Depth and Nomenclature (cont.)

Lucas			Wood(2.85)			Wood(8.1)		
Wire#	Depth (cm)	Type	Wire#	Depth (cm)	Type	Wire#	Depth (cm)	Type
15	AIR	T	14	AIR	T	15	AIR	T
14	5.1 (0'-2")	T*X	13	5.1 (0'-2")	T*	14	5.1 (0'-2")	T*X
13	10.2 (0'-4")	T*	12	10.2 (0'-4")	T*	13	10.2 (0'-4")	T*
12	15.2 (0'-6")	T*X	11	15.2 (0'-6")	T*	12	15.2 (0'-6")	T*X
11	20.3 (0'-8")	T*	10	20.3 (0'-8")	T*	11	20.3 (0'-8")	T*
10	25.4 (0'-10")	T*	4	45.7 (1'-6")	M	10	25.4 (0'-10")	T*
4	45.7 (1'-6")	M	9	60.9 (2'-0")	T	4	45.7 (1'-6")	M
9	60.9 (2'-0")	T	3	76.2 (2'-6")	M	9	60.9 (2'-0")	T
3	76.2 (2'-6")	MX	8	91.4 (3'-0")	T	3	76.2 (2'-6")	M
8	91.4 (3'-0")	T	2	106.7 (3'-6")	M	8	91.4 (3'-0")	T
2	106.7 (3'-6")	M	7	121.9 (4'-0")	T	2	106.7 (3'-6")	M
7	121.9 (4'-0")	T	1	137.1 (4'-6")	M	7	121.9 (4'-0")	T
1	137.1 (4'-6")	M	6	152.4 (5')	T	1	137.1 (4'-6")	M
6	152.4 (5')	T				6	152.4 (5')	T

Sensor Types
"T" = Temperature Probe
"*" = Sensor in Asphalt Concrete
"M" = Moisture Sensor
"X" = Damaged Sensor (disconnected)

Table 2.3 Available Moisture-Temperature-Weather Data

Site	From	To	From	To	From	To	From	To
Adams	3/1/94	7/6/94	6/14/95	5/4/96	10/10/96	Present		
Athens	12/21/91	1/12/94	5/12/94	7/4/96	12/21/96	2/22/97	restarted	
Columbiana	11/3/94	6/20/95	7/7/95	3/14/96				
Crawford	6/3/92	8/20/96	10/10/96	Present				
Knox	12/20/91	6/4/92	6/10/92	8/15/95	3/21/96	Present		
Licking	12/5/91	6/13/97	Present					
Lucas	6/2/92	8/11/92	8/15/92	10/16/92	12/29/92	12/18/96		
Wood(2.85)	6/2/92	6/13/95						
Wood(8.1)	6/2/92	8/18/92	8/20/92	10/21/92	12/29/92	1/11/94	5/12/94	Present

2.2.1 Relationships Between Resilient Modulus of the Asphalt Concrete and Temperature

The resilient modulus of the asphalt concrete is one of the parameters required in the determination of the resilient modulus of subgrade soils by the backcalculation procedure explained in the following section. The asphalt concrete modulus is known to be independent of the applied stresses (as opposed to that of subgrade soils) but dependent upon the asphalt concrete temperature. Figueroa et al., 1994 conducted a complete testing program to develop a relationship between the resilient modulus of the asphalt concrete and its temperature. The Indirect Tension for Resilient Modulus for Bituminous Mixtures test method (ASTM D 4123-82) was followed in testing 4" diameter asphalt concrete cores, obtained from the center of the truck lane during the installation of each monitoring station listed in Tables 2.1 and 2.2. A parabolic equation yields the best fit to the test data for typical Ohio mixtures. Equation 2.1 defines the curves of best fit with the coefficients listed in Table 2.4 for each type of asphalt concrete (ODOT items 404 and 402) found at the monitored sections, in conjunction with the curve-fit regression coefficient, R. Figure 2.1 is a graphical representation of the regression equation trend lines for both types of mixes.

$$E_r = a_0 + a_1 P + a_2 P^2 \qquad (2.1)$$

where:

E_T = Resilient modulus MPa in SI units or (psi x 10^6in English units)
a_0, a_1, a_2 = Regression constants listed in Table 2.4:
Columns 2 & 3 for SI units
Columns 4 & 5 for English units
P = Asphalt concrete temperature: Deg. C in SI units or (Deg F in English units)

Table 2.4 Equation 2.1 Regression Coefficients

1	2	3	4	5
Coefficient	SI Units		English Units	
	AC Type		AC Type	
	404	402	404	402
a_0	12659	12118	3.5405	3.1164
a_1	-562.10	-473.59	-0.0611	-0.0487
a_2	5.8344	3.9292	2.57×10^{-4}	1.73×10^{-4}
R^2	0.8548	0.6403	0.8547	0.6403

The test is conducted using a repeated indirect tensile test set-up under controlled temperature and controlled loading conditions with a typical load application time of 0.1 seconds and a rest period of 1.9 seconds, with an applied load nearing 444.8 N (100 lbs.). The load is applied to the 4" disks along the diameter through a narrow curved loading strip, while the load, the vertical and horizontal deformations are recorded to calculate the Poisson's ratio and the resilient modulus by the following equations.

$$\upsilon = \frac{3.59 \Delta H}{\Delta V} \qquad (2.2)$$

$$E_r = \frac{P(\upsilon + 0.27)}{t \, \Delta H} \qquad (2.3)$$

Where:

E_r = Resilient modulus of elasticity (psi)
P = Applied repeated load (lb)
υ = Resilient Poisson's ratio
t = Specimen thickness (in)
ΔH = Total recoverable horizontal deformation (in)
ΔV = Recoverable vertical deformation (in)

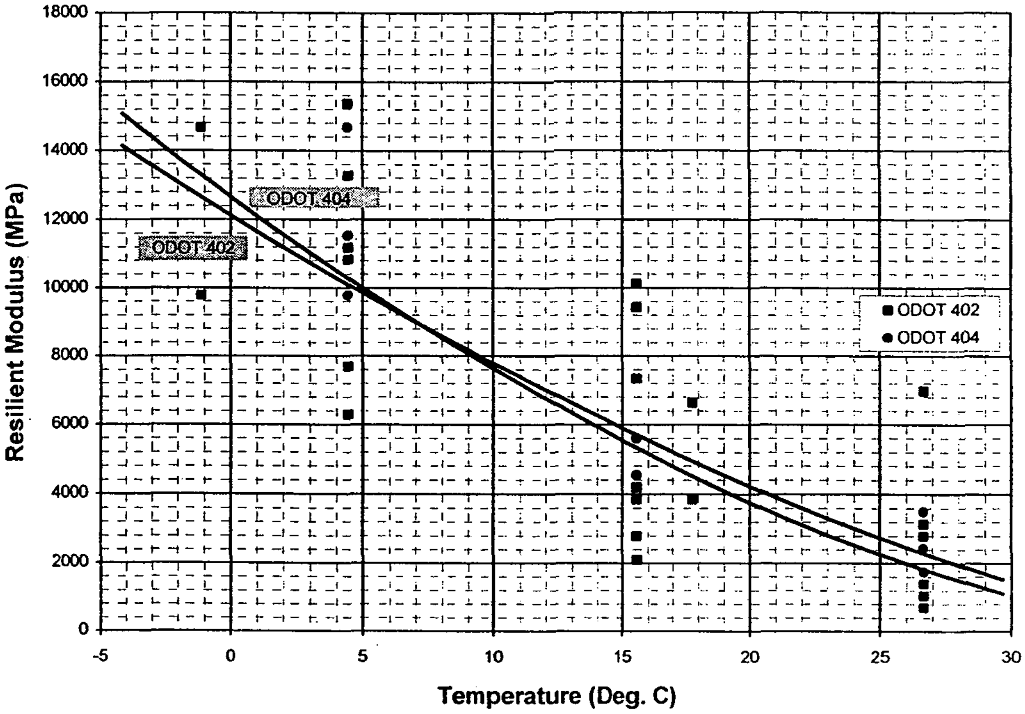

Figure 2.1 AC Modulus vs. Temperature

To consider the influence of temperature on the resilient modulus, each asphalt concrete disk was tested at temperatures of: 4.5, 15.5, and 26.5 degrees Celsius (40, 60, and 80 degrees Fahrenheit). A few additional tests were conducted at temperatures of (-1.1 and 17.8° C (30 and 64 deg. F). The samples, as well as the testing machine, were kept in a controlled-temperature room and brought to the specified test temperature. The temperature was maintained constant until all of the specimens reached the necessary equilibrium temperature and the tests were completed.

In turn, the average asphalt concrete temperature can be related to the air temperature by developing relationships of the form given in Equation 2.4, from data obtained at each monitoring location, as will be shown in the following chapters. Thus, it is feasible to assess the resilient modulus of the AC from air temperature data, which is normally obtained during FWD testing.

$$P = C1 + C2\ A + C3\ A^2 \tag{2.4}$$

where

C1, C2, and C3 =	Regression constants updated in the following chapters for each station location.
P =	Average AC temperature (Deg C).
A =	Air temperature (Deg C).

2.2.2 Backcalculation of the Resilient Modulus of Subgrade Soils Based on Measured FWD Deflections

It is well known that pavement performance is affected among other factors by the characteristics of the subgrade. The seasonal variation of the resilient modulus of the subgrade soil is one of the major factors in determining design parameters for new asphalt concrete pavements and overlays. The flexible pavement analysis program (ILLIPAVE) was validated during the "Characterization of Ohio Subgrade Types" project (Figueroa et al., 1994) as an effective tool to calculate deflections. This program was also used to develop nomographs to back calculate the resilient modulus of the subgrade based on measured Falling Weight Deflectometer (FWD) deflections for a given soil type. Figure 2.2 depicts the fundamentals of this developed method and can be explained as follows:

The air temperature is measured during FWD tests. This temperature is entered into Equation 2.4 and the corresponding average asphalt concrete pavement temperature is obtained. The AC pavement temperature is then entered into Equation 2.1 (with coefficients defined in Table 2.4) or Figure 2.1 in order to obtain the AC modulus. The AC modulus is entered into a nomograph (developed for a given soil type) along with the AC thickness, the gravel base thickness, and the maximum FWD deflection to obtain the resilient modulus of the subgrade soil at the break point E_{ri}. The slopes of the lines before and after the break point on a plot representing the variation of the resilient modulus vs. the deviator stress were found to be approximately constant and independent of the degree of saturation by Figueroa et al., 1994

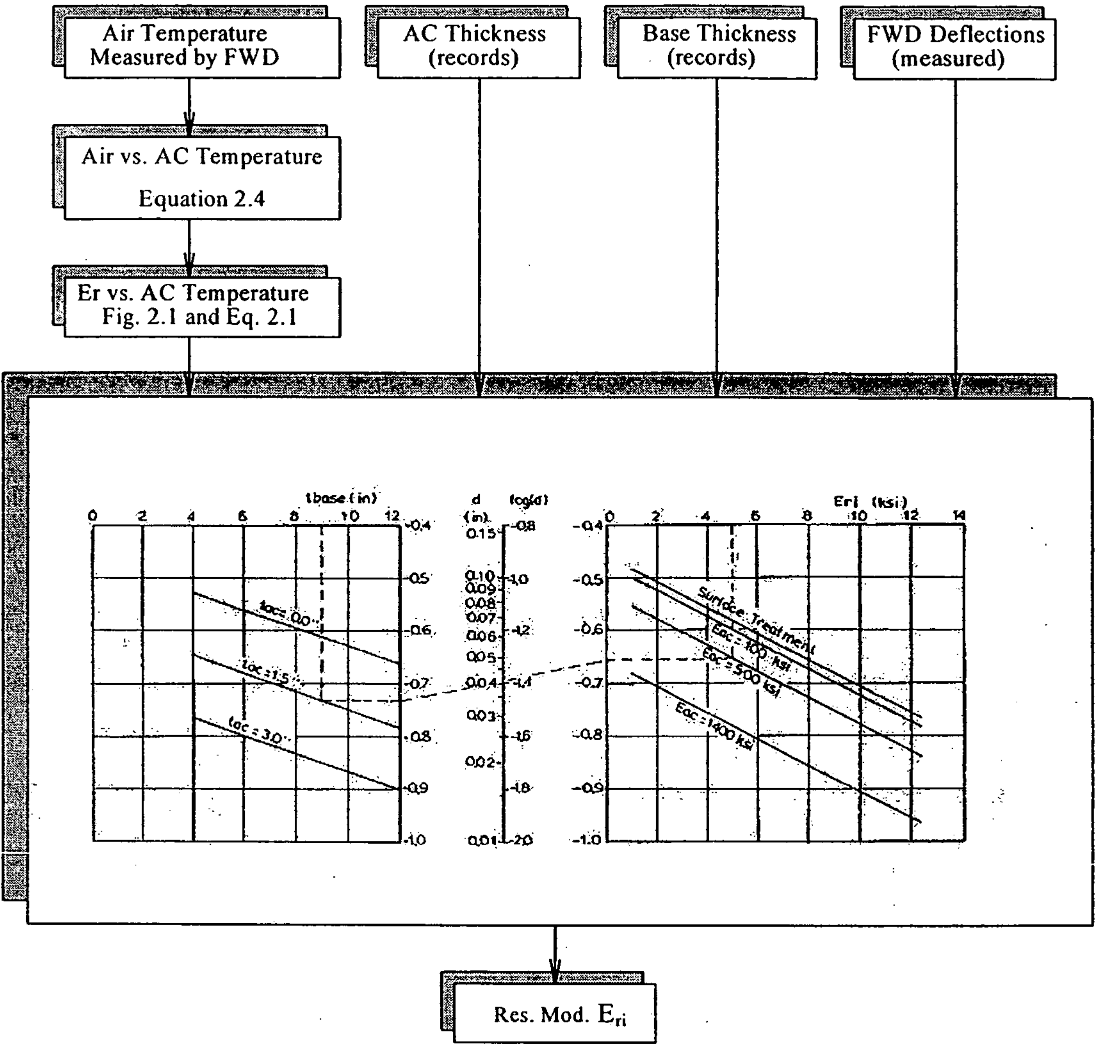

Figure 2.2 Back Calculation Procedure to Obtain E_{ri}

Alternatively, regression equations (presented below) were developed relating all of the previously mentioned parameters to measured maximum FWD pavement surface deflections. The basis of the nomographs as well as the regression equations can be explained as follows:

Typical flexible pavement structures are composed of a top asphalt concrete layer, a granular base course and a bottom subgrade layer. The development of nomographs to back calculate the resilient modulus of the subgrade for a given soil type, included the consideration of the influence of the applied load, the asphalt concrete thickness, the thickness of the gravel base course, the asphalt concrete resilient modulus and the resilient modulus of the subgrade soil.

Observing the deflections measured by FWD testing, the applied loads are typically around 40.03, 53.38 and 66.72 kN (9000, 12000 and 15000 lbs). Thus, these magnitudes were selected to calculate the contact pressure for a given type of soil. Thickness values of 10.2, 20.3 and 30.5 cm. (4, 8, and 12 in.) were chosen for both the asphalt concrete layer and the gravel base course, representing typical layer thickness ranges found in Ohio pavements. Data recorded by the moisture-temperature-rainfall monitoring stations shows that the seasonal air temperature usually varies between –1.11 and 26.7°C (30 and 80^{o}F). Thus, temperatures of –1.11, 10.0 and 26.7 °C (30, 50 and 80^{o}F) were adopted as representative of average temperatures in the winter, spring/fall, and summer respectively. These values are then entered into Equation 2.4 to obtain the corresponding asphalt concrete pavement temperature. Finally, the calculated pavement temperature is used as input to Equation 2.1 or Figure 2.1 to obtain the average asphalt concrete resilient modulus during the corresponding season.

Generalized relationships were obtained by conducting a regression analysis between the deflection as the dependent variable and the thickness of the asphalt concrete, the gravel base thickness, the resilient modulus of the asphalt concrete and the resilient modulus of the subgrade soil. Based on the higher Coefficient of Determination R^2, the logarithmic relationship provides the best fit, expressed by:

$$\log(d) = a_0 + a_1\, t_{ac} + a_2\, t_{base} + a_3\, E_{ac} + a_4\, E_{ri} \qquad (2.5)$$

Where:

d = Deflection at the center of load application (in)
t_{ac} = Thickness of the asphalt concrete (in)
t_{base} = Gravel base thickness (in)
E_{ac} = Resilient modulus of the asphalt concrete (ksi)
E_{ri} = Resilient modulus of the subgrade soil at the break point (ksi)
a_0, a_1, a_2, a_3, a_4 = Regression constants

Thus the resilient modulus of the subgrade soil is back calculated by:

$$E_{ri} = [\log(d) - a_0 - a_1 t_{ac} - a_2 t_{base} - a_3 E_{ac}] / a_4 \qquad (2.6)$$

Tables 2.5a and 2.5b summarize the coefficients (in SI and English units, respectively) for the three types of soil A-4, A-6 and A-7, along with the corresponding Coefficient of Determination R^2, to be used in conjunction with Equation 2.6 to back calculate the resilient modulus of the subgrade soil at the break point.

In summary, knowing both the thickness of the asphalt concrete layer and the gravel base course, the resilient modulus of the asphalt concrete from air temperature records in combination with Equations 2.4 and 2.1 and maximum measured surface deflections by the Falling Weight Deflectometer, the resilient modulus of the subgrade soil can be backcalculated following the procedure shown in Figure 2.2.

At a certain location, the thicknesses of both the asphalt concrete layer and the gravel base course are known from construction records. Thus, the total deflection is dependent upon the variations of the resilient modulus of the subgrade soil E_{ri} and the asphalt concrete modulus E_{ac}. Comparing the influence of E_{ac} with respect to E_{ri} in affecting the total deflection, it is found that the total deflection is very sensitive to the variation of E_{ri}. This influence is evident in the relative values of the coefficients a_4 and a_3, whereby a_4 is approximately two orders of magnitude higher than a_3, although E_{ac} and E_{ri} do not differ by as much as two orders of magnitude at a given time during the year. As a result of this observation, it can be concluded that the subgrade soil significantly contributes to the total deflection of typical flexible pavements.

Table 2.5a. Coefficients used in Equation 2.6 (SI units)

Soil Type	P (N)	a_0	a_1	a_2	a_3	a_4	R^2
A-4	40032	-0.67328	-0.01775	-3.99543E-04	-4.62929E-05	-2.90883E-03	0.92032
	53376	-0.55789	-0.01746	-4.97508E-04	-4.58201E-05	-2.92112E-03	0.91975
	66720	-0.46776	-0.01726	-5.77815E-04	-4.54227E-05	-2.92710E-03	0.91896
A-6	40032	-0.67834	-0.01761	-5.62748E-04	-4.55944E-05	-3.23827E-03	0.91943
	53376	-0.56192	-0.01731	-6.61429E-04	-4.50786E-05	-3.28619E-03	0.91859
	66720	-0.47122	-0.01711	-7.38004E-04	-4.47405E-05	-3.29810E-03	0.91778
A-7	40032	-0.61095	-0.01719	-9.14484E-04	-4.39790E-05	-4.48548E-03	0.92234
	53376	-0.49853	-0.01674	-1.15048E-03	-4.38220E-05	-4.40564E-03	0.92347
	66720	-0.40663	-0.01670	-1.08492E-03	-4.30709E-05	-4.48473E-03	0.92195

$$\log(\mathbf{d}) = a_0 + a_1 \mathbf{t}_{ac} + a_2 \mathbf{t}_{base} + a_3 \mathbf{E}_{ac} + a_4 \mathbf{E}_{ri}$$

$\mathbf{t}_{ac}$ and $\mathbf{t}_{base}$ = given in cm.

$\mathbf{E}_{ac}$ and $\mathbf{E}_{ri}$ = given in MPa

R^2 = Coefficient of Determination

Table 2.5b. Coefficients used in Equation 2.6 (English units)

Soil Type	P (lb)	a_0	a_1	a_2	a_3	a_4	R^2
A-4	9000	-1.07811	-0.04509	-1.01484 E-3	-3.19143 E-4	-2.00535 E-2	0.92032
	12000	-0.96273	-0.04434	-1.26367 E-3	-3.15884 E-4	-2.01382 E-2	0.91975
	15000	-0.87260	-0.04384	-1.46765 E-3	-3.13144 E-4	-2.01794 E-2	0.91896
A-6	9000	-1.08317	-0.04474	-1.42938 E-3	-3.14328 E-4	-2.23246 E-2	0.91943
	12000	-0.96675	-0.04396	-1.68003 E-3	-3.10772 E-4	-2.26550 E-2	0.91859
	15000	-0.87606	-0.04346	-1.87453 E-3	-3.08441 E-4	-2.27371 E-2	0.91778
A-7	9000	-1.01578	-0.04365	-2.32279 E-3	-3.03191 E-4	-3.09229 E-2	0.92234
	12000	-0.90336	-0.04251	-2.92221 E-3	-3.02109 E-4	-3.03725 E-2	0.92347
	15000	-0.81146	-0.04242	-2.75569 E-3	-2.96931 E-4	-3.09177 E-2	0.92195

$$\log(\mathbf{d}) = a_0 + a_1 \mathbf{t}_{ac} + a_2 \mathbf{t}_{base} + a_3 \mathbf{E}_{ac} + a_4 \mathbf{E}_{ri}$$

$\mathbf{t}_{ac}$ and $\mathbf{t}_{base}$ = given in inches

$\mathbf{E}_{ac}$ and $\mathbf{E}_{ri}$ = given in ksi

R^2 = Coefficient of Determination

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Chapter 3

SEASONAL FACTORS AFFECTING ASPHALT CONCRETE PAVEMENTS

This chapter presents the seasonal data collected at the moisture-temperature monitoring stations with emphasis on the effects of seasonal factors on the engineering properties of materials included in a flexible pavement profile. Of particular interest is the discussion of temperature variations (daily, monthly and seasonal) within the asphalt concrete and the development of relationships linking the average AC temperature (and consequently the modulus) to the measured air temperature. Summary tables and graphs are included in this chapter showing the amount of rainfall, depth of frost penetration, number of freeze-thaw cycles and the variation of the degree of saturation with depth at the different monitoring stations.

3.1 Temperature Data

Temperature is one of the most important parameters affecting the performance of asphalt concrete pavements and in particular during the warmer months. As previously shown in Figure 2.1, the modulus of the asphalt concrete decreases with an increase in temperature. However it is only when the AC temperature rises beyond 10-15.6°C (50-60°F) that there is a substantial decrease in the surface layer stiffness. Any applied traffic loads during this period will significantly affect the stress on the subgrade soil, increasing the likelihood of distress development.

Asphalt concrete pavement, soil and air temperature data to be analyzed in the following sections includes data from eight of the nine monitoring stations for the periods listed in Table 2.3. As previously indicated, scant data was only collected at the Columbiana Co. station since initially this unit was damaged by lightning and soon after it was repaired, a vehicle crash damaged it beyond repair. Thus, development of meaningful relationships was not possible at this site.

3.1.1. Daily Asphalt Concrete Pavement and Subgrade Temperature Variations

Typically, temperature variations within the subgrade soil are minimal on a daily basis. Only the uppermost subgrade soil thermistor shows daily temperature variations, although within a narrower range, following those of the lowest asphalt concrete thermistor.

The thermistors within the asphalt concrete layer do exhibit large daily temperature fluctuations. Figures 3.1 to 3.4 show typical surface layer temperature variations for a typical three-day period at mid-spring, mid-summer, mid-fall and mid-winter. Wood Co. 2.85 station surface layer thermistor and air temperature readings obtained in 1993-1994 are shown in these figures. Sensors W13, W12, W11 and W10 are located at 5.08, 10.16, 15.24 and 20.32 cm. (2, 4, 6 and 8 in.) below the surface of the 26.7 cm. (10.5 in)-thick AC surface layer.

Figure 3.1 WOOD 2.85 Sta. SPRING 1993 AC TEMPERATURE REVERSAL

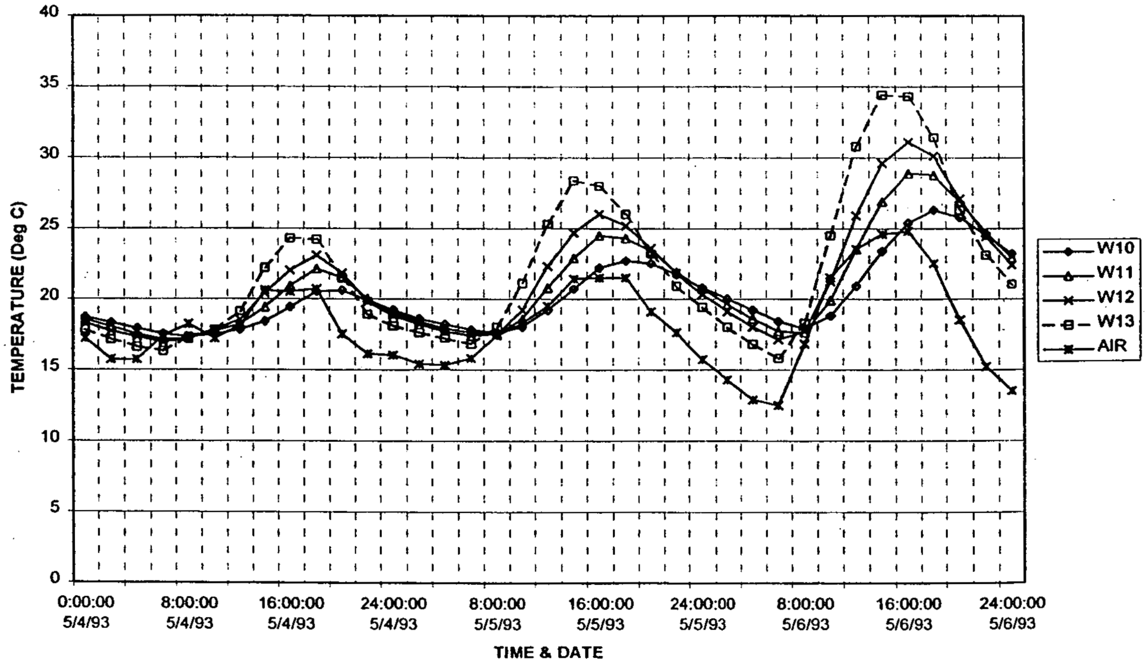


Figure 3.2 WOOD 2.85 Sta. SUMMER 1993 AC TEMPERATURE REVERSAL

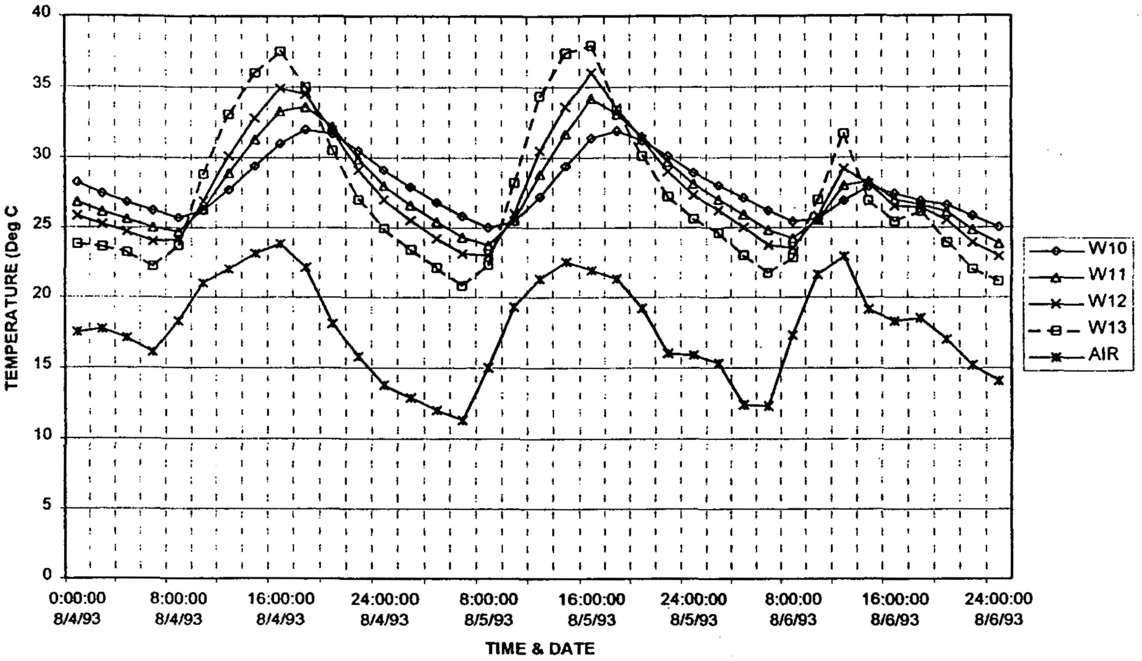


Figure 3.3 WOOD 2.85 Sta. FALL 1993 AC TEMPERATURE REVERSAL

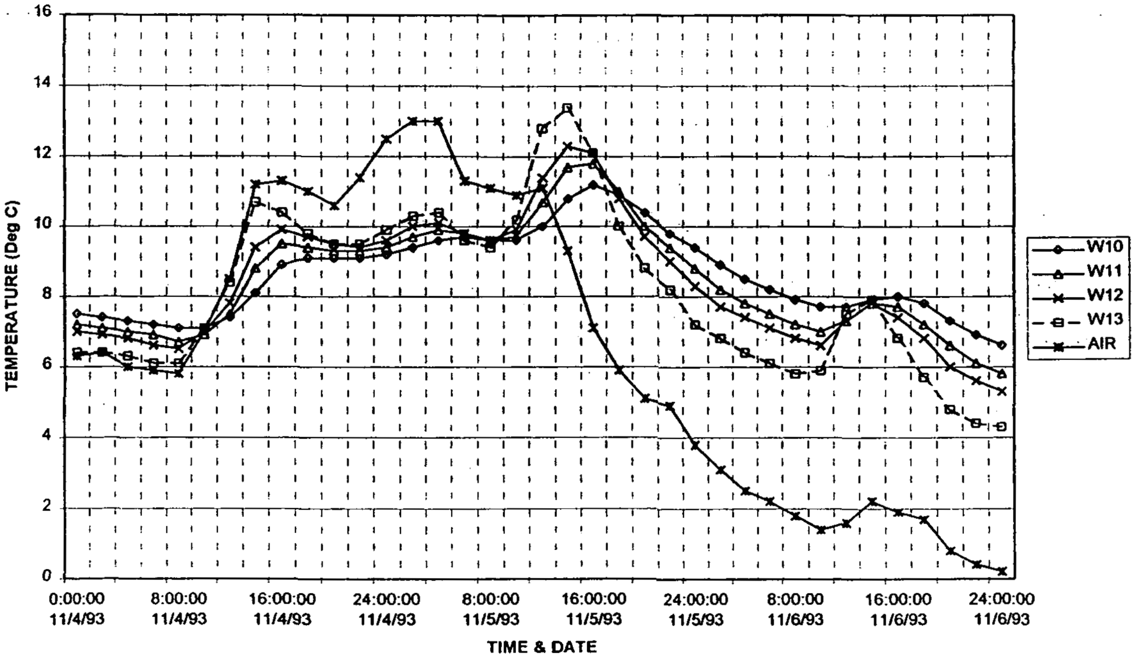
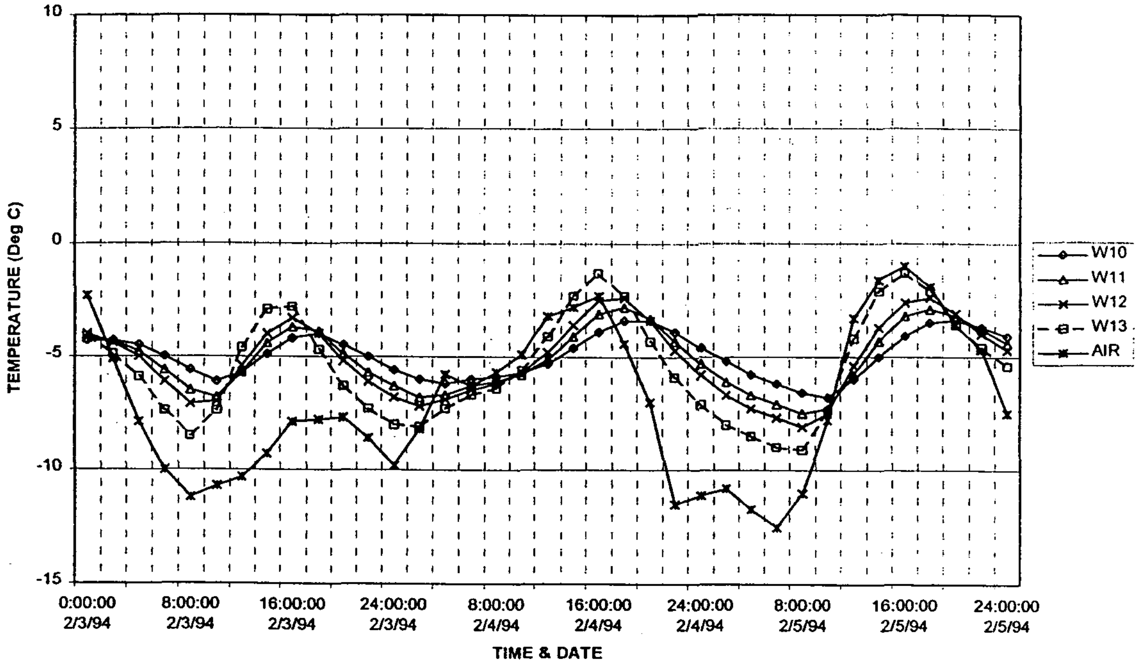


Figure 3.4 WOOD 2.85 Sta. WINTER 1993-1994 AC TEMPERATURE REVERSAL



Normally and depending on the air temperature variations and weather fronts, as seen in these figures the AC layer experiences a uniform temperature (no temperature gradient) twice a day, primarily during the days that solar radiation influences the asphalt concrete temperature. These points occur between 8:00 and 10:00 AM and around 8:00 PM. After the morning period of no temperature gradient, thermistors closer to the surface show faster warming as compared to those near the bottom of the surface layer. An opposite trend occurs after the evening period of no temperature gradient. This information is important in selecting the optimal times for FWD testing (between 8:00-10:00 AM) since the surface layer exhibits a uniform stiffness throughout its thickness. Similarly, the maximum daytime temperature gradient within the pavement is observed between 2:00 and 4:00 PM at all seasons and the maximum overnight temperature gradient occurs around 6:00 AM. It is to be noted that the temperature gradient is greater in the afternoon than in the early morning and that AC layer temperature variations closely follow air temperature changes.

3.1.2. Monthly and Seasonal Asphalt Concrete Pavement Temperature Variations

The daytime and nighttime seasonal temperature averages were computed from the temperature sensor readings. This information is presented in two different formats.

Temperature data from the Logger data files was separated into daytime and nighttime values. All data points lying between 7:00 AM and 7:00 PM were defined as daytime temperatures. The remaining points were considered nighttime temperatures. For each of the station locations the average AC pavement temperature was calculated in the middle of the layer and both the monthly and seasonal averages of these temperatures were calculated. Tables 3.1 and 3.2 contain the daytime, nighttime and combined (total: day and night) monthly and seasonal AC pavement temperatures.

Graphs of the monthly and seasonal average AC pavement temperatures are shown in Figures 3.5 and 3.6. It is to be noted that the average pavement temperature difference between summer and winter is on the order of 30 to 35 deg. C at all sites. This temperature range

Figure 3.5 Average AC Monthly Temperature

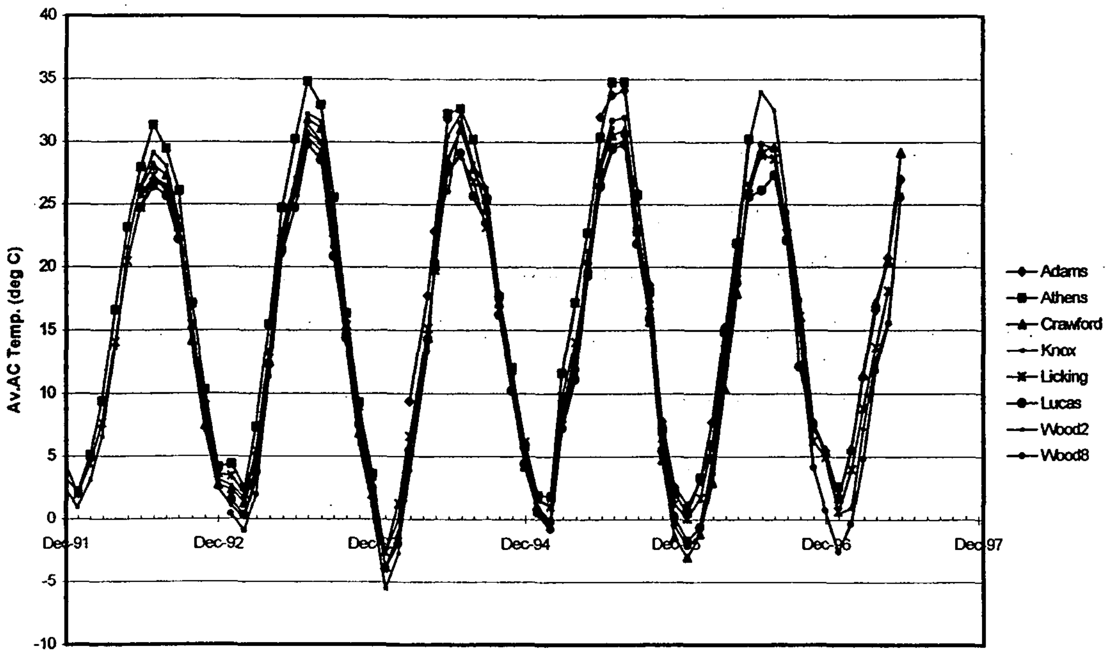
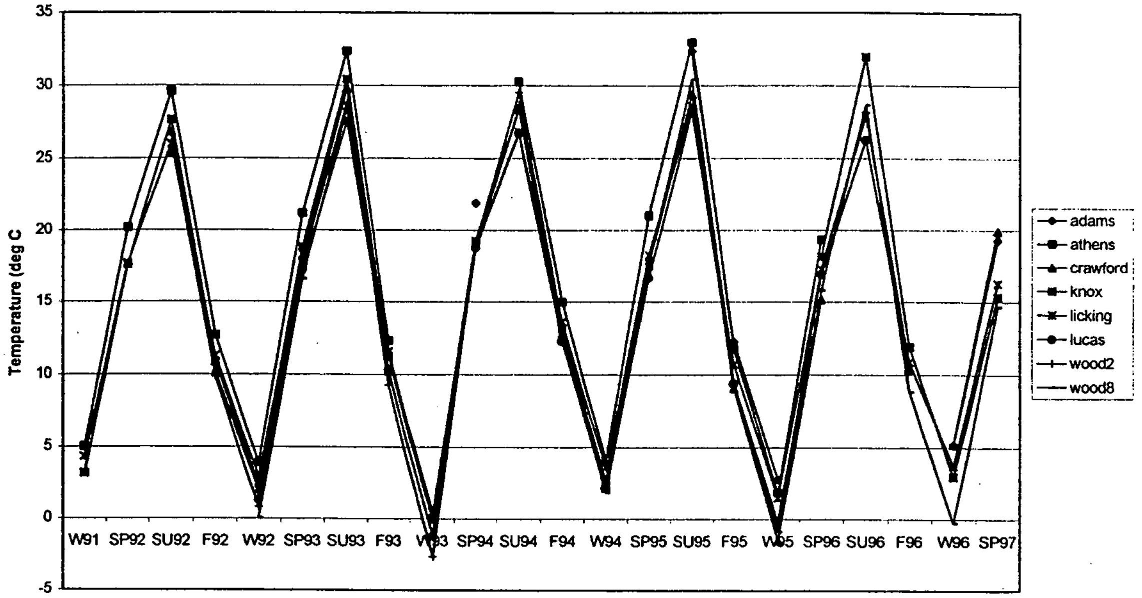


Figure 3.6 Average Seasonal AC Temperature



obviously indicate the wide variation in the elastic properties of the AC as it will be shown later in this chapter. As expected the northern sites exhibit slightly lower averages than the southern sites. These average temperatures are later used to calculate the corresponding AC modulus average values.

Seasonal and monthly averages of the AC temperature are tabulated in Appendix A including all collected data, at all sections. The seasonal averages are contained in Tables A1 to A9, whereas the monthly averages are listed in Tables A10 to A18. All data points collected have been examined for accuracy, deleting values from damaged sensors to obtain these averages.

Figueroa et al. (1994) indicated from observations in temperature changes within the pavement and subgrade profiles that the daytime and the nighttime averages for any sensors located at depths in excess of 30.5 cm. (1.0 ft.) (i.e. the soil sensors) are virtually identical. In addition, the asphalt concrete sensors are warmer than the soil sensors (on the average) during the spring and summer seasons. Furthermore, in the fall and winter seasons the soil sensors are warmer than the asphalt concrete sensors.

Table 3.1 AVERAGE MONTHLY ASPHALT CONCRETE TEMPERATURE (deg C)

COUNTY	TIME	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
	day	1.54	4.53	9.85	17.05	23.38	32.48	34.24	34.57	26.24	18.93	7.96	4.17
ADAMS	night	1.43	4.09	9.12	16.00	22.30	31.35	33.26	33.70	25.54	18.23	7.56	3.90
	total	1.48	4.31	9.49	16.52	22.84	31.91	33.75	34.13	25.89	18.58	7.76	4.03
	day	2.53	3.35	9.22	17.02	24.18	31.42	34.48	32.83	26.51	18.00	10.14	4.03
ATHENS	night	2.12	2.53	7.92	15.05	21.94	29.01	32.33	30.89	24.81	16.57	9.24	3.48
	total	2.32	2.94	8.57	16.04	23.13	30.22	33.40	31.86	25.69	17.29	9.69	3.76
	day	-0.36	0.99	6.93	14.06	21.08	27.79	31.00	30.09	23.97	16.08	7.61	2.72
CRAWFORD	night	-0.50	0.62	5.91	12.63	19.26	26.18	29.30	28.65	22.77	15.14	7.09	2.43
	total	-0.43	0.81	6.42	13.34	20.17	26.99	30.15	29.37	23.37	15.61	7.35	2.57
	day	0.49	1.58	7.02	13.86	21.44	28.22	31.67	30.26	24.20	16.46	8.85	3.80
KNOX	night	0.46	1.41	6.60	13.28	20.50	27.70	31.30	30.03	23.97	16.17	8.66	3.61
	total	0.48	1.49	6.81	13.57	20.96	27.96	31.49	30.14	24.09	16.31	8.75	3.70
	day	0.83	2.45	7.60	14.31	20.80	26.68	29.31	28.42	23.12	16.33	8.60	3.99
LICKING	night	0.87	2.34	7.19	13.62	19.83	25.96	28.70	27.95	22.76	16.08	8.43	3.87
	total	0.85	2.39	7.40	13.97	20.32	26.31	29.01	28.18	22.94	16.20	8.51	3.93
	day	-0.74	-0.31	5.46	12.65	20.13	26.15	28.56	27.74	22.31	14.75	7.79	2.45
LUCAS	night	-0.97	-0.59	5.00	12.35	19.72	25.53	27.82	27.13	21.86	14.58	7.59	2.30
	total	-0.86	-0.45	5.31	12.49	19.92	25.83	28.19	27.41	22.09	14.66	7.69	2.37
	day	-1.31	-0.85	5.38	13.27	22.28	27.46	30.53	28.52	23.69	15.45	7.97	2.61
WOOD2	night	-1.32	-1.01	4.71	12.21	20.77	26.75	29.94	27.94	23.30	15.09	7.76	2.55
	total	-1.31	-0.93	5.04	12.74	21.52	27.10	30.24	28.23	23.50	15.27	7.87	2.58
	day	-0.95	-0.82	4.65	11.83	20.22	26.47	30.33	29.24	23.35	15.96	6.63	1.60
WOOD8	night	-0.95	-0.91	4.31	11.23	19.36	26.07	29.91	28.90	23.16	15.76	6.52	1.52
	total	-0.95	-0.86	4.48	11.53	19.79	26.27	30.12	29.07	23.26	15.86	6.57	1.56

Table 3.2 AVERAGE SEASONAL ASPHALT CONCRETE TEMPERATURE (deg C)

LOCATION		SPRING	SUMMER	FALL	WINTER
ADAMS	day	21.14	32.78	12.53	4.15
	night	20.03	31.93	11.97	3.81
	total	20.58	32.35	12.25	3.98
ATHENS	day	21.56	32.27	13.24	4.10
	night	19.43	30.29	12.17	3.36
	total	20.49	31.28	12.93	3.72
CRAWFORD	day	18.79	29.30	10.91	1.55
	night	17.10	27.89	10.23	1.15
	total	17.94	28.59	10.57	1.35
KNOX	day	18.18	29.75	11.90	2.32
	night	17.47	29.50	11.69	2.16
	total	17.83	29.62	11.80	2.24
LICKING	day	18.17	27.84	11.70	2.81
	night	17.38	27.33	11.52	2.70
	total	17.78	27.58	11.61	2.76
LUCAS	day	17.43	27.12	10.66	0.63
	night	17.07	26.46	10.49	0.41
	total	17.25	26.79	10.57	0.52
WOOD 2	day	18.68	28.42	10.93	0.20
	night	17.49	27.88	10.69	0.03
	total	18.09	28.15	10.81	0.11
WOOD 8	day	16.58	28.60	10.40	0.21
	night	15.93	28.26	10.26	0.12
	Total	16.26	28.43	10.33	0.16

3.1.3. Relationships Between Air Temperature and Average Asphalt Concrete Pavement Temperature

Equations were derived relating the average asphalt concrete pavement temperature to the air temperature for eight (excluding the Columbiana Co.) of the nine monitored stations. These station sites were selected among other considerations, in order to show the change in asphalt concrete temperature corresponding to a change in latitude for a given air temperature.

Figure A1 to A9 show the average AC temperature as a function of air temperature for all stations. These figures include all of the available field data (both the daytime and the nighttime values). Statistical regression analyses were conducted on the combined daytime and nighttime values to develop regression equations between the average AC temperature and the air temperature. Such equations would be useful in inferring the average AC modulus based on air temperature readings, as it will be shown later. After viewing the graphs of asphalt concrete temperature vs. air temperature, a polynomial relationship following the general form of Equation 2.4, reproduced below, yielded the best fit for the field data.

$$P = C1 + C2\ A + C3\ A^2 \tag{2.4}$$

where

C1, C2, and C3 = Regression constants updated in the following chapters for each station location.
P = Average AC temperature (Deg C).
A = Air temperature (Deg C).

The values of C1, C2, and C3 for the combined daytime and nightime data are included in Table 3.3 for the eight analyzed station locations. In addition, the coefficient of determination, R^2, indicating the highly significant relationship (R^2>0.82 in all cases) between the two parameters in every instance is included for each equation.

The monitoring station locations in order of increasing latitude are Adams, Athens, Licking, Knox, Crawford and Wood (8.1), Lucas and Wood(2.85) Co. sites. It is instructive to note that the coefficient C1 (intercept at zero air temperature) for the most part, tends to decrease with increasing latitude. This indicates that asphalt concrete temperature will be higher in the southern part than in the northern part of the state. Similarly, the coefficient C3 tends to be higher in the southern part than in the northern part of the state. This can be related to the declination of the sun during the colder seasons leading to more direct sunlight in the southern than in the northern counties of the state.

Table 3.3 Average AC Temp. vs. Air Temp. Coefficients

Site	No. of Points	C1	C2	C3	R^2
Adams	8441	5.7167	0.7879	0.0087	0.8248
Athens	24087	5.0064	0.8954	0.0080	0.8608
Columbiana*					
Crawford	24459	4.9474	0.8945	0.0065	0.8688
Knox	26271	5.3628	0.8824	0.0074	0.8383
Licking	29285	5.2109	0.8465	0.0039	0.8638
Lucas	21408	5.1270	0.9145	0.0014	0.8832
Wood(2.85)	16502	4.0461	0.9483	0.0051	0.8793
Wood(8.1)	22209	4.3623	0.9469	0.0034	0.8664

* Not enough data to develop

Examination of the regression equation coefficients shown in Table 3.3 indicates that the state of Ohio may be subdivided into three general temperature zones: North, (from the North Shore to Mansfield – Mount Vernon) Central (from Mansfield – Mount Vernon to Lancaster) and South (from Lancaster to the southern state line). This division will be useful in assessing the average AC modulus on a seasonal or monthly basis for any future implementation of mechanistic pavement design procedures.

3.1.4. Monthly and Seasonal Asphalt Concrete Resilient ModulusVariation

As a result of temperature differences during the four seasons the resilient modulus of the asphalt concrete is also expected to vary, in view of the direct dependency of the elastic modulus of the AC on temperature. To examine the temperature susceptibility (modulus variation) of the asphalt concrete, the same 3-day sequence used to illustrate the daily variation of temperature during a given season was selected in this section. Referring back to Figures 3.1 to 3.4 where typical surface layer temperature variations for a three-day period at mid-spring, mid-summer, mid-fall and mid-winter at the Wood Co. 2.85 station, the elastic modulus was calculated from the values of temperature measured at thermistors W12, W11 and W10, with the aid of Equation 2.1 along with the coefficients for mixture 404 contained in Table 2.4. As expected, the elastic modulus also displays the typical sinusoidal day-night variation also observed in the temperature changes within the pavement surface layer (when weather fronts do not come through during the three day sequence).

Figures 3.7 to 3.10 depict the resilient modulus variation for the three-day sequence during the spring, summer, fall and winter. The times of the day of equal stiffness are also evident as indicated in the temperature-related discussion. These figures have been plotted with the same vertical scale to facilitate the comparison of relative modulus values with respect to the season. For a typical mid-season day the resilient modulus averages:

3791.7 MPa (550 ksi) in the spring (+/- 1034.1 MPa or +/- 150 ksi)
1723.5 MPa (250 ksi) in the summer (+/- 1034.1 MPa or +/- 150 ksi)
8272.8 MPa (1200 ksi) in the fall (+/- 1378.8 MPa or +/- 200 ksi)
15511.5 MPa (2250 ksi) in the winter (+/- 1551.1 MPa or +/- 225 ksi)

The larger modulus range in the colder seasons can be explained as a result of the steeper variation of the resilient modulus at colder than at warmer temperatures as indicated in Figure 2.1. These typical modulus values also indicate that the contribution of the subgrade soil in supporting traffic loads is more important during the warmer months because of the lower stiffness of the surface layer during this time of the year. Unfortunately, this fact is also coupled with the lower stiffness of the subgrade soil itself during and after the rainy spring and early summer as is typical in Ohio. Consequently the two combined effects make the spring-summer the critical time of the year considering environmental effects.

It should be mentioned that a desirable asphalt concrete mixture must have a narrower modulus range such that it is not too brittle in the winter (low temperature cracking) and not too soft in the summer (rutting). Additives to asphalt cement may minimize this range and consequently improve the performance of the asphalt concrete.

Tables 3.4 and 3.5 include monthly and seasonal daytime, nightime and total averages of the resilent modulus of the asphalt concrete for eight of the nine monitored stations. Once again these averages were determined from corresponding average AC temperatures as summarized in Tables 3.1 and 3.2, in combination with Equation 2.1. It is evident, that the three temperature zones proposed in the previous section are reaffirmed in regards to the relative values of the modulus of the AC. Specifically, the southern zone is represented by the Adams and Athens Co. stations; the central zone by the Licking, Knox and Crawford Co. stations and the northern zone by the Lucas and two Wood Co. stations. Expected ranges of the resilient modulus are easily selected from this table. A graphical representation of the monthly and seasonal averages of the resilient modulus of the asphalt concrete is included in Figures 3.11 and 3.12 respectively.

Figure 3.7 HOURLY VARIATION OF AC MODULUS - WOOD 2.85 STATION (SPRING)

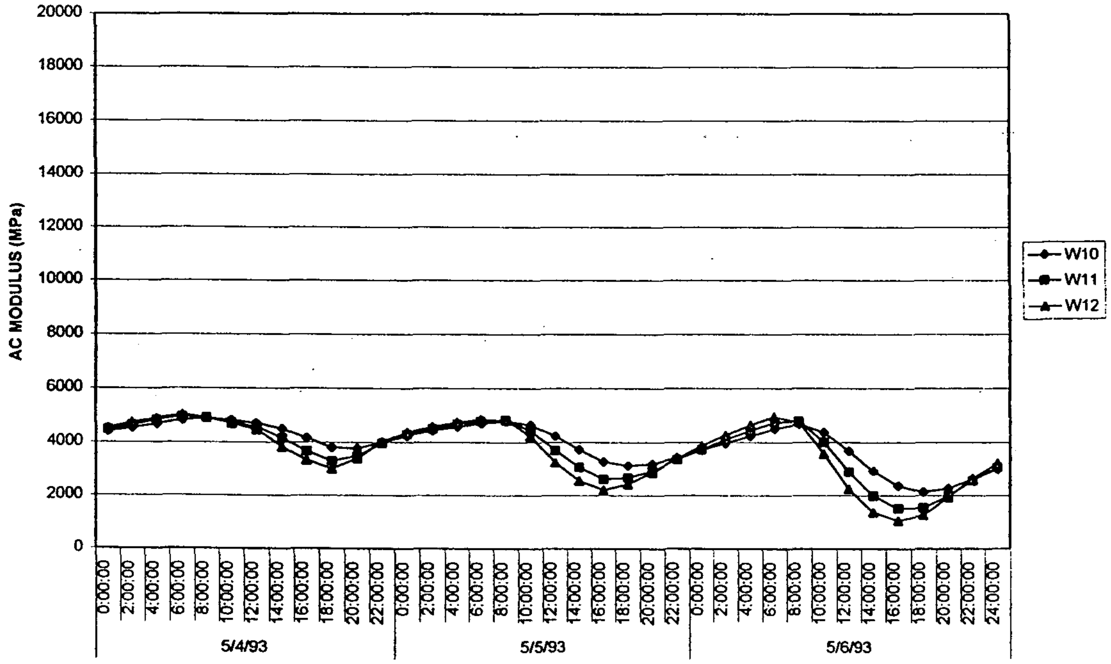


Figure 3.8 HOURLY VARIATION OF AC MODULUS - WOOD 2.85 STATION (SUMMER)

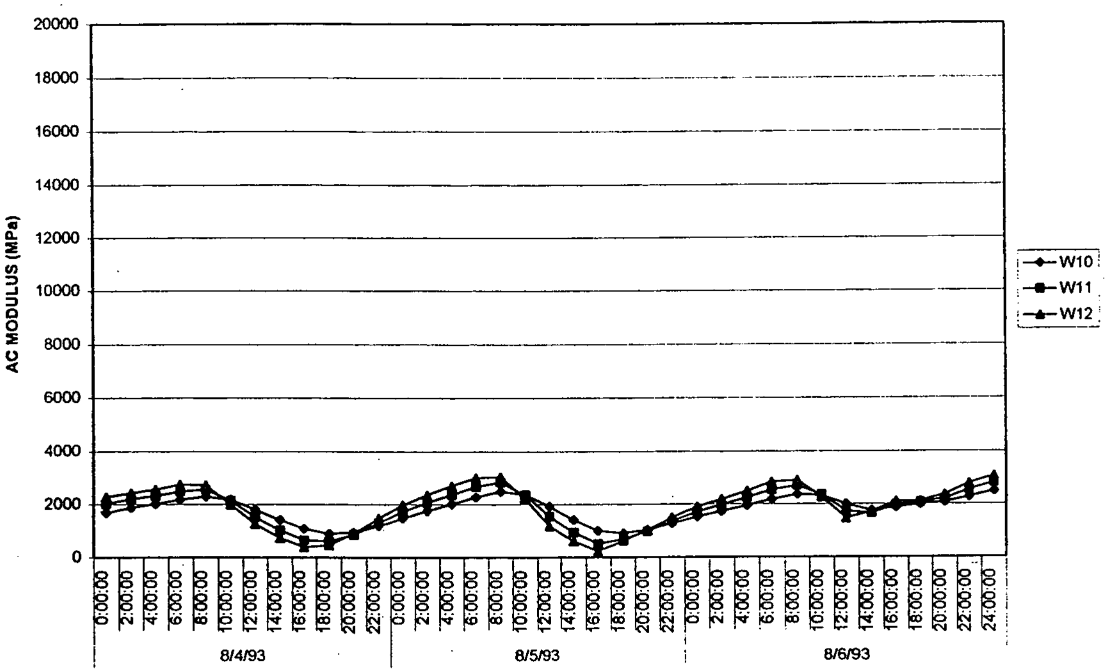


Figure 3.9 HOURLY VARIATION OF AC MODULUS - WOOD 2.85 STATION (FALL)

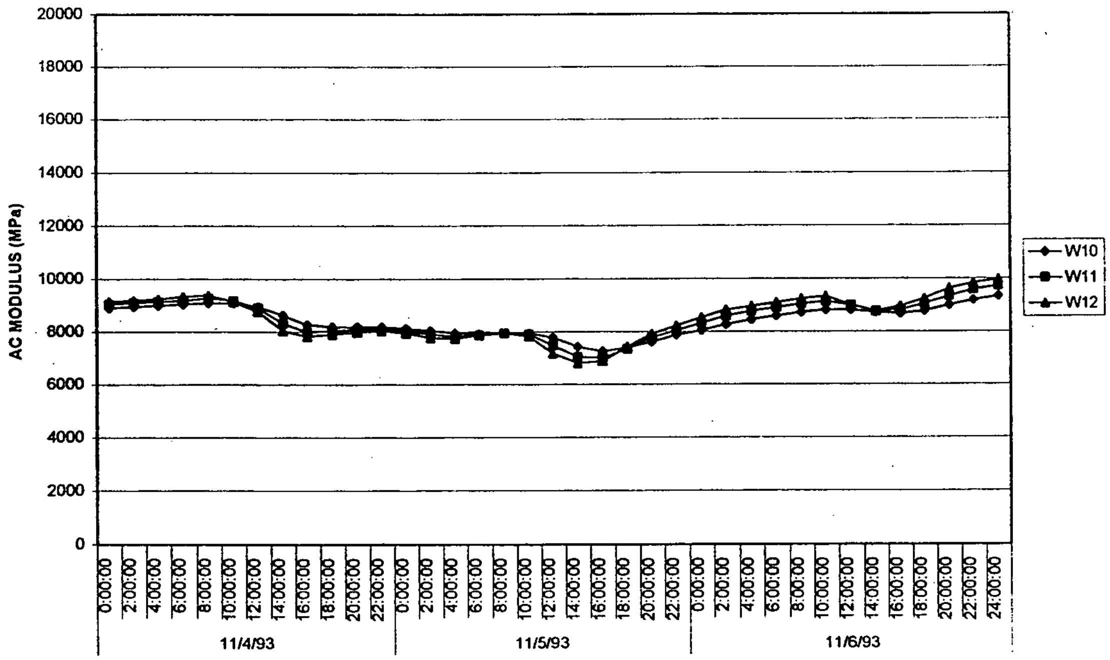


Figure 3.10 HOURLY VARIATION OF AC MODULUS - WOOD 2.85 STATION (WINTER)

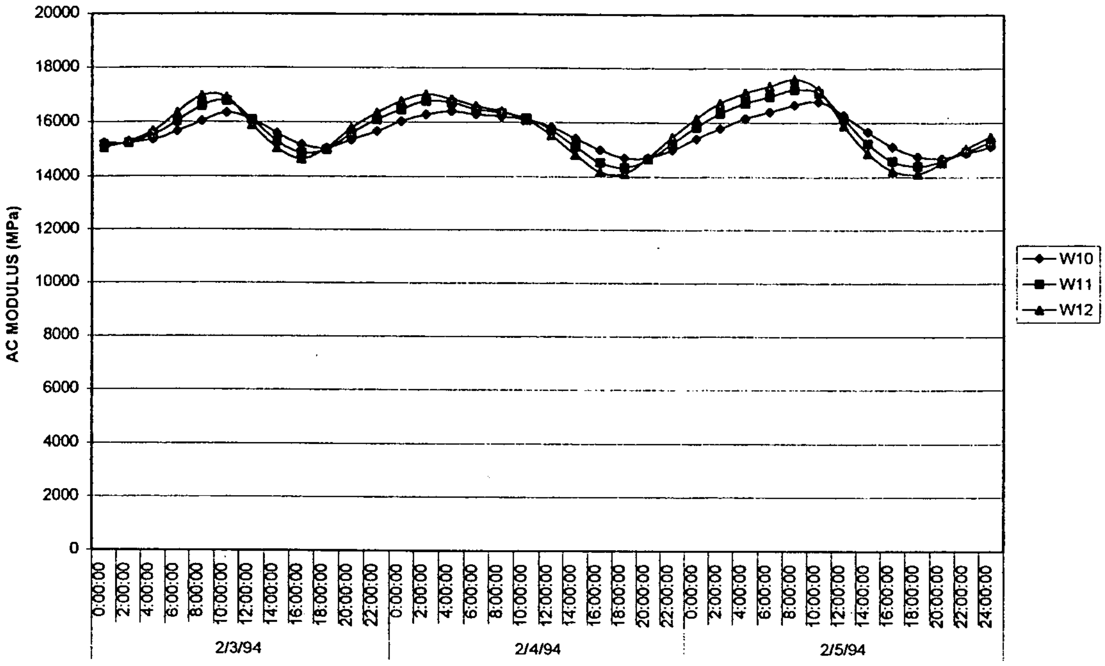


Table 3.4 AVERAGE MONTHLY AC MODULUS (MPa)

COUNTY	TIME	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
ADAMS	day	11905.9	10354.8	7838.5	4963.7	2923.1	799.7	503.3	448.1	2157.8	4308.8	8693.3	10534.0
	night	11968.0	10575.4	8162.5	5349.7	3240.2	1013.4	661.8	586.0	2337.1	4550.0	8879.5	10671.9
	total	11933.5	10465.1	8003.9	5156.7	3081.6	903.1	579.1	517.1	2247.4	4432.8	8789.9	10603.0
ATHENS	day	11375.1	10954.6	8121.1	4977.5	2702.4	999.6	461.9	737.7	2088.9	4632.8	7714.4	10603.0
	night	11595.7	11382.0	8714.0	5701.3	3350.5	1496.0	827.3	1103.0	2530.1	5136.0	8114.2	10885.6
	total	11485.4	11168.3	8417.6	5336.0	2998.9	1240.9	641.1	916.9	2295.7	4881.0	7914.3	10740.9
CRAWFORD	day	12940.0	12202.4	9175.9	6087.4	3612.5	1778.7	1082.4	1268.5	2757.6	5315.3	8858.8	11278.6
	night	13022.8	12402.3	9672.3	6659.6	4198.4	2171.6	1434.0	1578.7	3102.3	5666.9	9107.0	11430.3
	total	12981.4	12298.9	9424.1	6370.1	3902.0	1971.7	1254.7	1420.2	2930.0	5494.5	8982.9	11354.4
KNOX	day	12471.2	11885.3	9134.6	6163.2	3502.2	1675.2	951.4	1234.0	2695.6	5177.4	8293.5	10720.2
	night	12491.9	11974.9	9334.5	6397.6	3798.6	1799.3	1020.3	1282.3	2757.6	5287.7	8376.2	10816.7
	total	12478.1	11926.6	9238.0	6280.4	3646.9	1737.3	985.8	1254.7	2730.0	5232.5	8334.8	10768.4
LICKING	day	12285.1	11423.4	8865.7	5990.9	3702.1	2047.5	1434.0	1633.9	2998.9	5225.7	8403.8	10623.7
	night	12271.3	11478.5	9051.8	6259.8	4012.3	2226.8	1571.8	1737.3	3109.2	5315.3	8479.6	10685.7
	total	12278.2	11450.9	8962.2	6121.9	3853.7	2137.1	1502.9	1689.0	3054.0	5273.9	8445.2	10651.2
LUCAS	day	13160.6	12912.5	9892.9	6652.7	3915.8	2178.5	1599.4	1785.5	3240.2	5818.5	8776.1	11416.5
	night	13284.7	13071.0	10113.5	6776.8	4046.8	2337.1	1771.8	1937.2	3371.2	5887.5	8872.6	11499.2
	total	13222.7	12995.2	9961.8	6721.7	3984.7	2261.2	1682.1	1868.3	3302.2	5853.0	8824.3	11457.8
WOOD2	day	13477.8	13215.8	9927.4	6397.6	3247.1	1854.5	1178.9	1606.3	2833.4	5549.7	8693.3	11333.7
	night	13484.7	13312.3	10258.3	6832.0	3709.0	2026.8	1296.1	1744.2	2950.6	5687.6	8789.9	11368.2
	total	13484.7	13264.1	10092.8	6618.2	3474.6	1944.1	1234.0	1675.2	2895.5	5618.6	8741.6	11354.4
WOOD8	day	13271.0	13202.0	10292.7	6990.5	3888.2	2095.8	1220.2	1447.7	2930.0	5363.5	9320.7	11871.5
	night	13277.8	13250.3	10465.1	7245.6	4170.9	2199.2	1303.0	1523.6	2992.0	5432.5	9375.8	11912.8
	total	13271.0	13222.7	10375.5	7121.5	4026.1	2150.9	1261.6	1482.2	2957.5	5398.0	9348.3	11892.2

Figure 3.11 MONTHLY VARIATION OF AC MODULUS

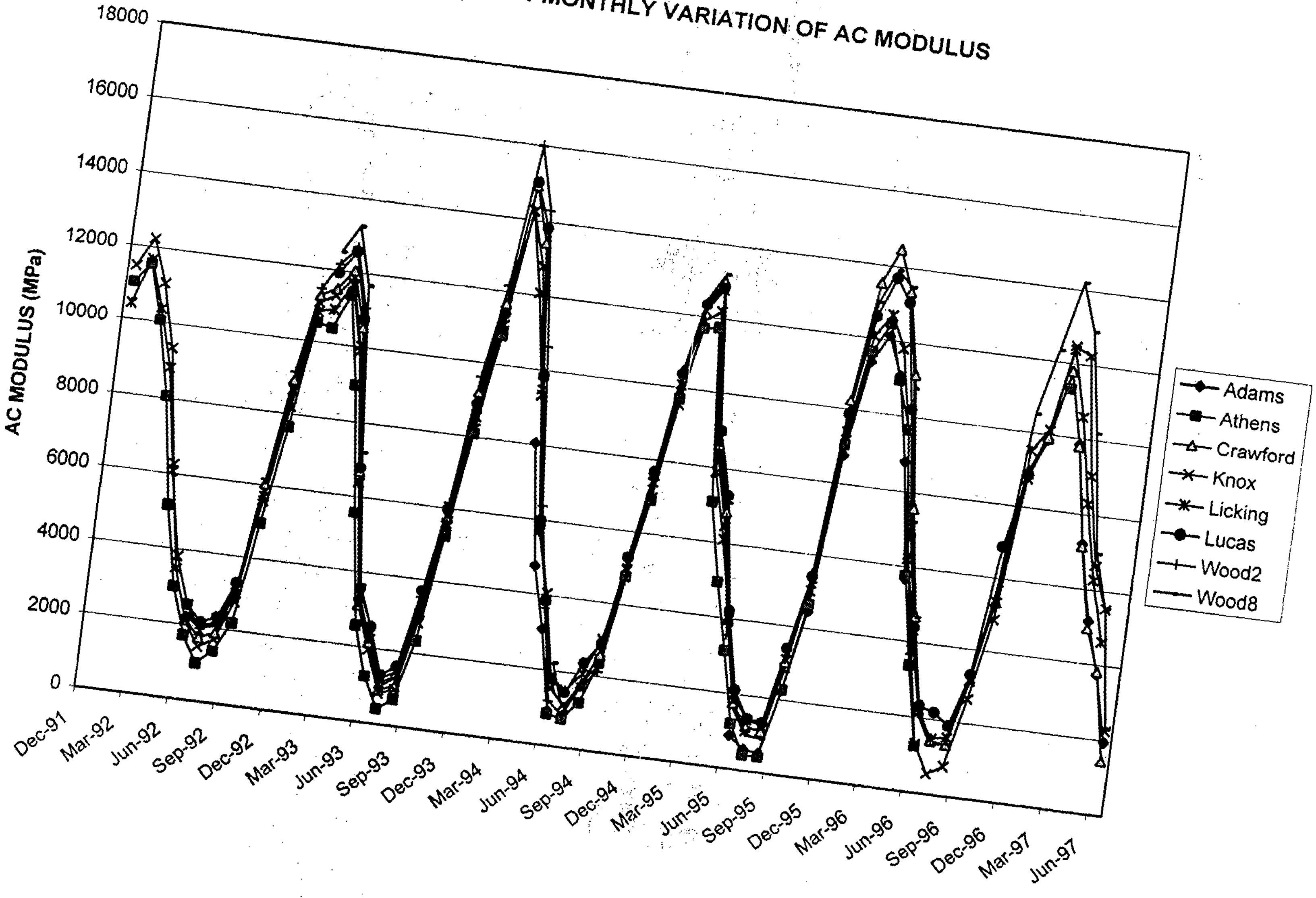


Figure 3.12 SEASONAL AC MODULUS

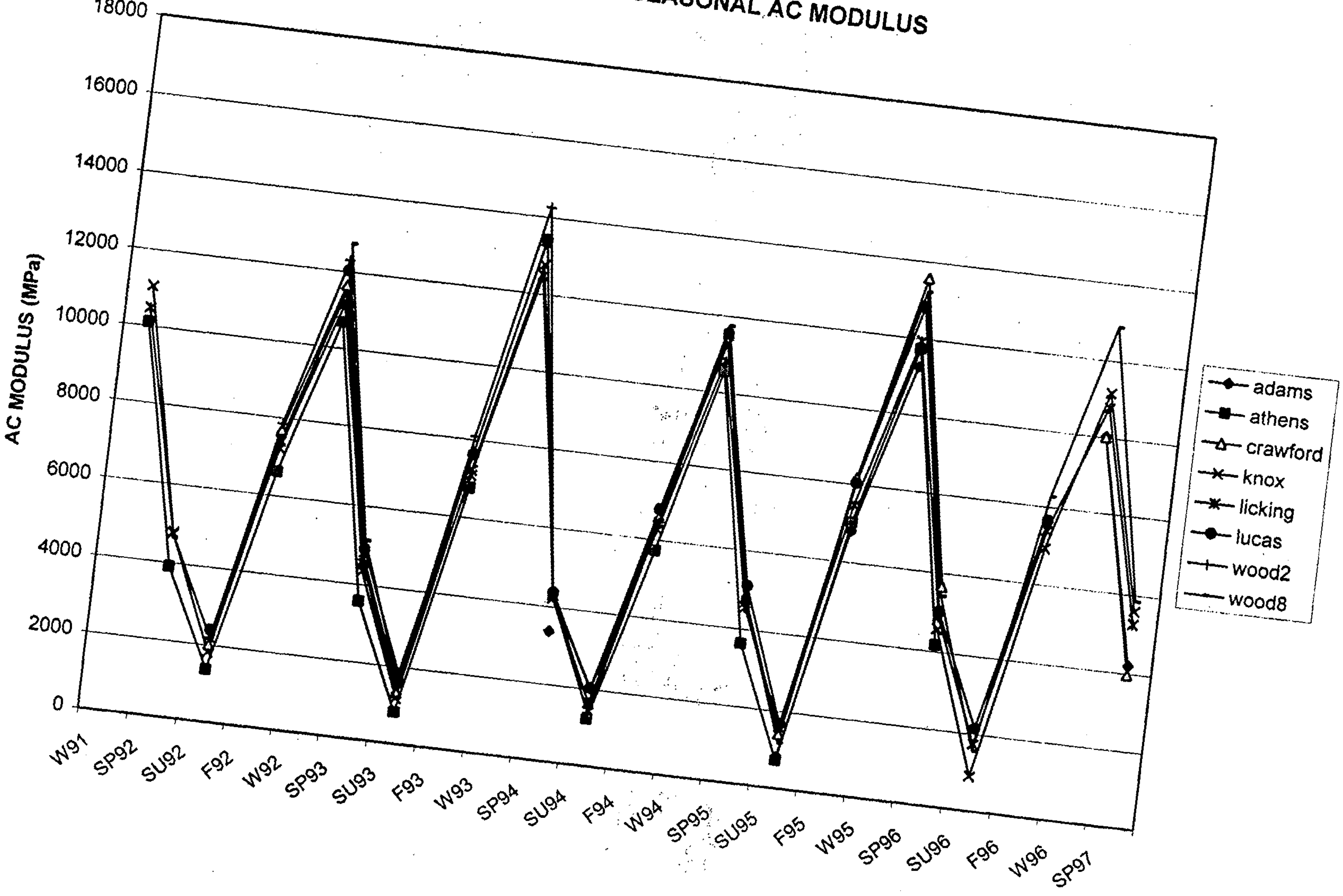


Table 3.5 AVERAGE SEASONAL ASPHALT CONCRETE ELASTIC MODULUS (MPa)

LOCATION		SPRING	SUMMER	FALL	WINTER
ADAMS	day	3598.7	744.6	6701.0	10540.9
	night	3950.3	903.1	6935.4	10713.3
	total	3771.0	827.3	6797.5	10630.5
ATHENS	day	3467.7	841.1	6411.4	10568.5
	night	4143.3	1227.1	6852.6	10947.7
	total	3798.6	1027.2	6535.5	10761.5
CRAWFORD	day	4357.0	1434.0	7383.5	11899.0
	night	4943.0	1758.0	7673.0	12112.8
	total	4646.6	1592.5	7528.2	12002.5
KNOX	day	4563.8	1337.4	6962.9	11485.4
	night	4812.0	1392.6	7052.6	11575.0
	total	4687.9	1365.0	7004.3	11533.7
LICKING	day	4570.7	1764.9	7045.7	11230.3
	night	4846.5	1889.0	7121.5	11285.5
	total	4708.6	1826.9	7087.0	11257.9
LUCAS	day	4825.8	1937.2	7486.9	12402.3
	night	4956.8	2102.7	7562.7	12512.6
	total	4894.7	2019.9	7528.2	12457.5
WOOD 2	day	4391.5	1633.9	7376.6	12636.7
	Night	4812.0	1758.0	7480.0	12726.3
	total	4598.3	1695.9	7424.8	12678.1
WOOD 8	day	5129.1	1592.5	7597.2	12629.8
	night	5370.4	1668.3	7666.1	12678.1
	Total	5253.2	1627.0	7631.7	12650.5

3.1.5 Seasonal Subgrade Temperature Variations

The most important information obtained from the seasonal variation of subgrade temperature refers to the depth of frost penetration. This information is helpful when determining roadside drainage ditch depths as well as granular base thickness for asphalt concrete pavements when the subgrade soil is frost susceptible.

Two computer programs were written to scan the collected data files containing the temperature at a given time of the day measured by the active temperature sensors to determine the maximum depth of frost penetration and the number of freeze-thaw cycles. In the first program, for a given reporting time, the temperature values are examined in order of decreasing sensor depth. Once the first sub-freezing temperature value is found, the depth of frost penetration is obtained by linearly interpolating between the depth of this temperature sensor, its corresponding temperature, the depth of the temperature sensor immediately below the first frozen temperature sensor, and its temperature. This program then generates a file containing the time of the year in decimals of months and the depth of frost penetration in feet. The second program takes the data file generated by the first scanning program and determines the number of freeze-thaw cycles and the depth of frost penetration. A frost cycle is defined as a period when the frost line drops below the bottom of the asphalt concrete pavement and then recedes back into the pavement surface layer.

Figure 3.13 MAX. DEPTH OF FROST PENETRATION

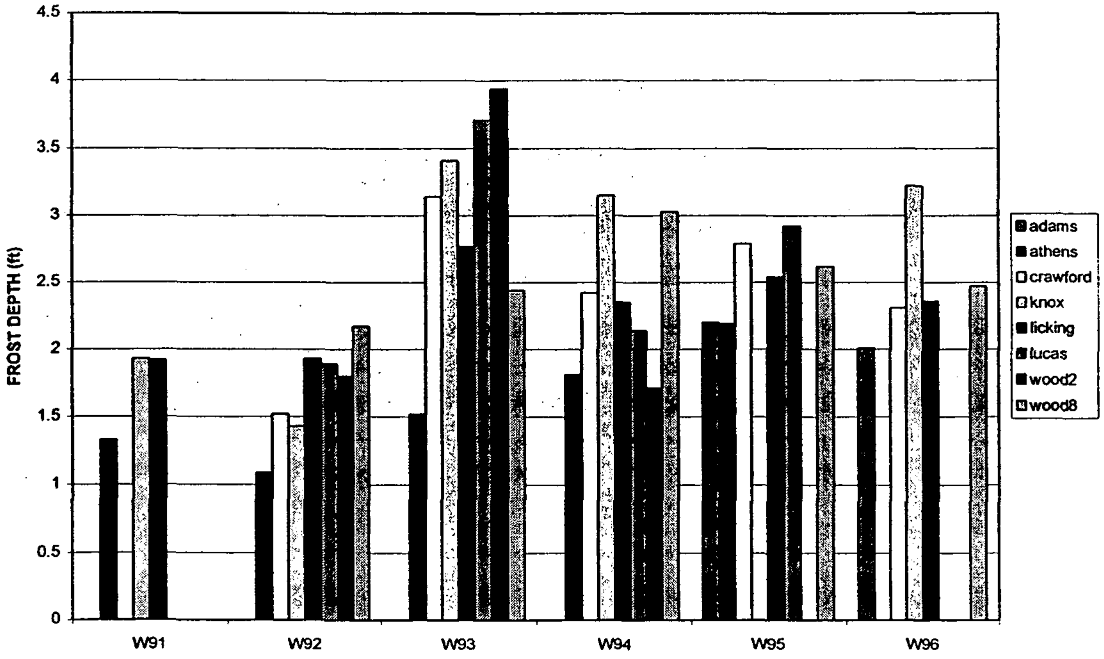
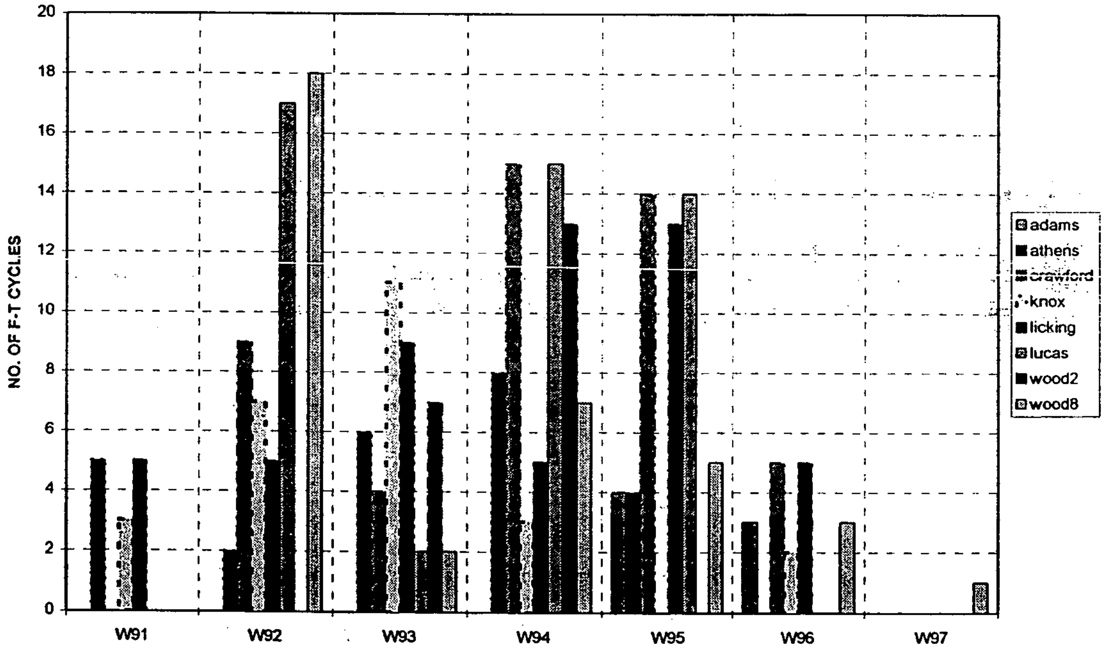


Figure 3.13 depicts the maximum depth of frost penetration, while Figure 3.14 shows the number of freeze-thaw cycles. A combined presentation of the number of freeze-thaw cycles and depth of frost penetration for the winters between 1991-1992 to 1996-1997 is included in Figure 3.15 for the available data at eight of the nine monitoring stations. It is to be noted from this figure that when the frost penetration is high at the northern sites the number of freeze-thaw cycles is lower. This normally occurs during harsh winters. The number of cycles appears to increase during milder winters. Normally, the northern sites experience an average 7 to 12 cycles as compared to between 4 and 5 in the southern sites.

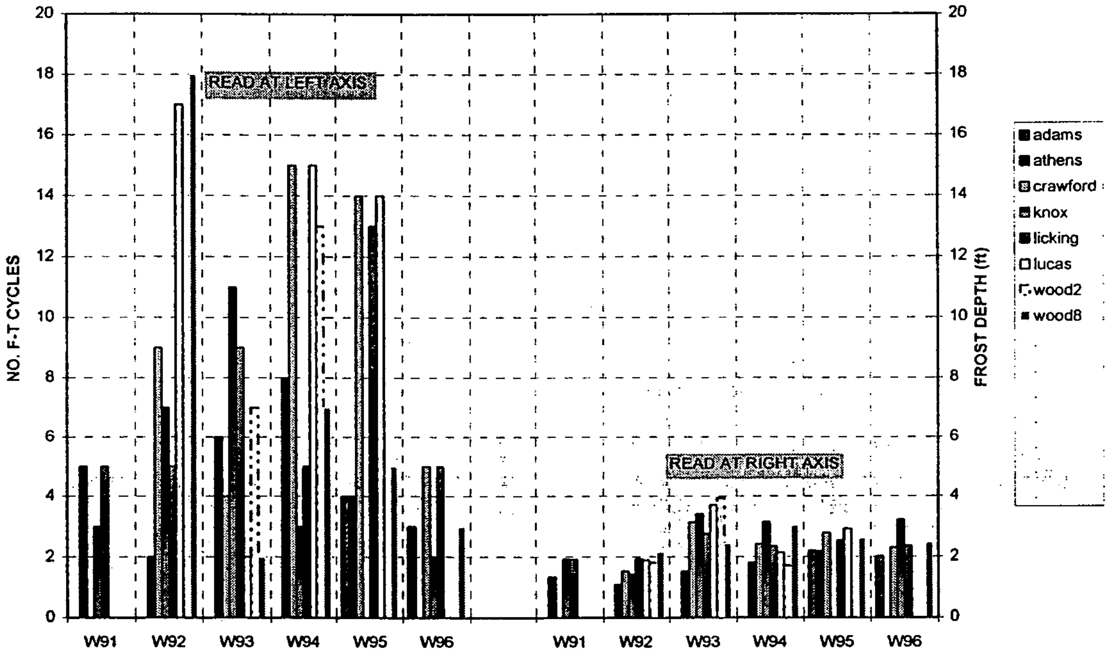
Figure 3.14 NUMBER OF FREEZE-THAW CYCLES



As expected the depth of frost penetration is greater in the northern than in the southern stations. The maximum depth of frost penetration measured to date approached 121.9 cm. (4.0 ft.) at the Wood 2 station during the 1993-1994 winter, which happened to be a severe winter. On a normal season the average depth of frost penetration is about 45.7 to 61.0 cm. (1.5 to 2.0') at the southern stations and from 70.1 to 82.3 cm. (2.3 to 2.7') at the northern locations.

Summary tables and average values are included in Appendix B (Tables B1 to B8) showing the depth of frost penetration and the number of freeze-thaw cycles during each monitored winter for each of the seven monitoring stations. This data is complete including the monitoring periods listed in Table 2.3.

Figure 3.15 No. OF F-T CYCLES & FROST DEPTH

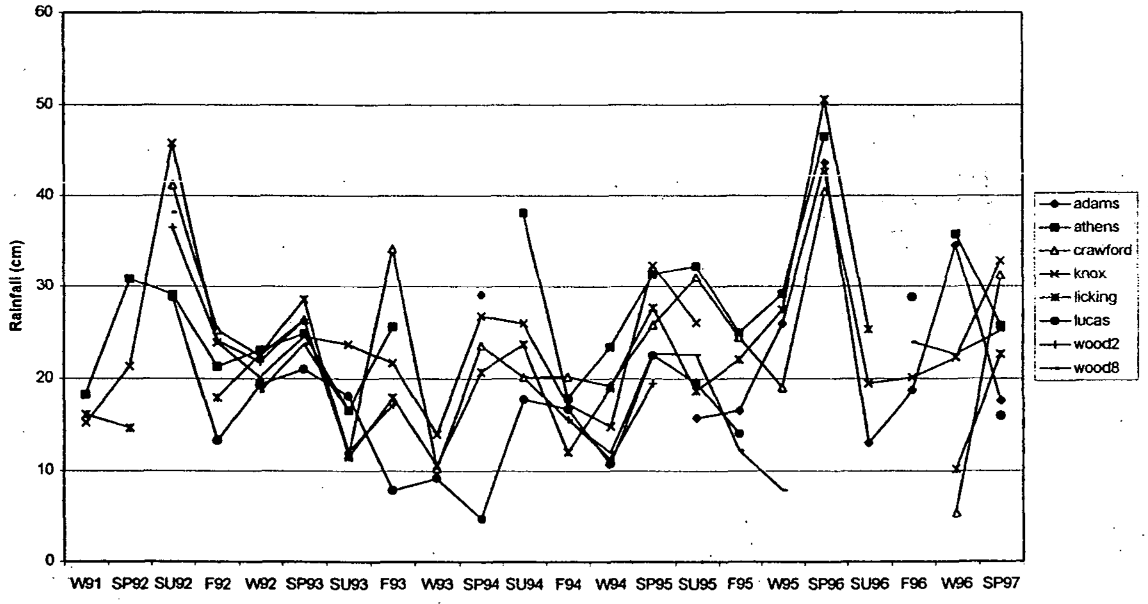


The most critical condition occurs when frost penetrates the entire surface layer and enters the gravel base and the subgrade soil. It is to be indicated that the definition of a frost cycle, previously given, does not take into consideration its "severity". For example, the long, deep cycle beginning in the middle of February at the Wood(8.1) Co. site should cause more damage than the short, shallow cycle occurring near the end of December at the Licking Co. site. It is well known that both repeated freeze-thaw cycles and a severe frost cycle are damaging to frost susceptible soils.

3.2 Rainfall Data

Precipitation summaries are included in Appendix C for all nine sites when data is available. Figure 3.16 and Tables C1 to C9 include the seasonal precipitation measured during the monitoring period. Similarly, Tables C10 to C18 contain detailed monthly precipitation recorded at each location. Rainfall data will later be used to determine if a correlation exists between the amount of precipitation and the value of the back calculated resilient modulus from Falling Weight Deflectometer-measured deflections. Data for the "cold" months (i.e. Jan., Feb., Mar., etc.) may be somewhat misleading because the snow must melt by itself in order to trigger the tipping switch within the rain gage, in view of the absence of automatic heaters in the gage.

Figure 3.16 SEASONAL RAINFALL



3.3 Degree of Saturation

In order to determine the degree of saturation from the voltage readings generated by the gypsum block-type moisture sensors the calibration developed by Figueroa et al .(1994) during the project "Characterization of Ohio Subgrade Types" was adopted as explained below.

3.3.1 Moisture Sensor Calibration Factors

Typically the gypsum block sensors provide a voltage output of approximately 0.0 volts when completely dry and of 4.0 volts when saturated (submerged). Incidentally, output voltages in excess of 4.0 have been observed (up to about 4.3 V) in the data retrieved at one of the Logger sites. It is possible that the moisture sensors are picking up localized spurious electrical currents. Another explanation involves the temperature sensors. Each moisture sensor has a temperature probe located six inches above it and six inches below. These temperature probes operate on a 5VDC current. The moisture sensors, on the other hand, use a 4VAC power source. In extremely wet soil there might be some current leakage ("cross talk") from the temperature probes to the moisture sensors.

Since the output voltages of the moisture sensors are being recorded at all sites, the calibration equation suggested by Armstrong, et al. (1985) had to be modified (see Figueroa et al. 1994, for more details). The sensor resistance contained in this equation was replaced by sensor output voltage and soil moisture tension was replaced by the degree of soil saturation. In addition, the degree of saturation is approximately inversely proportional to the soil moisture tension, as shown by Walsh et al. (1993) The developed combined equation are presented next.

Using the nomenclature

C, D, E, F, G, and H = Regression constants

V = Sensor output voltage (V)

T = Sensor temperature (Deg C)

Sr = Degree of saturation of the soil (%)

During the sensor calibration, it was observed that for a given degree of saturation, its output voltage varied linearly with temperature. Thus the equation:

$$V = A + BT \tag{3.1}$$

Could be followed to link voltage output to temperature. The slope and vertical intercept of the straight line represented by this equation was found to be a function of the degree of saturation of the soil. Coefficients A and B best related to the degree of saturation using a second order polynomial fit as shown below.

$$A = C + DSr + ESr^2 \tag{3.2}$$

$$B = F + GSr + HSr^2 \tag{3.3}$$

Since the sensor output voltage and the sensor temperature are known, Equation 3.1 needed to be solved in conjunction with Equations. 3.2 and 3.3 for the degree of saturation (S). As a result, Equation 3.4 was obtained.

$$(E+HT)Sr^2 + (D+GT)Sr + (C+FT-V) = 0 \tag{3.4}$$

The positive root of this simple quadratic equation is then solved for S, leading to Equation 3.5

$$Sr = \frac{-(D+GT)+\sqrt{(D+GT)^2-4(E+HT)(C+FT-V)}}{2(E+HT)} \tag{3.5}$$

with regression constants:

$C = 2.14103$
$D = -0.04139$
$E = 5.973315\text{x}10^{-4}$
$F = -0.03814$
$G = 2.312154\text{x}10^{-3}$
$H = -1.92560\text{ x}10^{-5}$

and Coefficient of Determination R^2=.94

This equation is valid for fine-grained soils with temperatures between 0 and 30 degrees Celsius and corresponding moisture sensor output voltages between 1.5 and 4.0 volts. In practice, the temperature at the moisture sensor depth is determined by interpolation of the temperature measured by the thermistors located above and below the moisture sensor, since the thermistors and moisture sensors are normally offset every six inches.

3.3.2 Degree of Saturation Results

Whenever possible, the degree of saturation was determined at each location at four sensor depths designated by sensors W1, W2, W3 and W4, , which measure voltages corresponding to Sr. The location of each sensor is specified in Table 2.2b with W1 being the deepest and in sequential order W2, W3 and finally W4 being the closest to the surface. The degree of saturation corresponding to these sensors has been labeled Sr1, Sr2, Sr3 and Sr4 respectively.

Monthly averages of the degree of saturation are included in Figures 3.17 to 3.24 for eight of the nine stations, with the numerical detail contained in Tables C19 to C26. Each figure and table shows the values for each of the working sensors identified above. Seasonal values have been included in Figures 3.25 to 3.32 and in Tables C27 to C34, where the "*" following the specific season indicates incomplete data.

Examination of these figures and tables indicates that the degree of saturation varies between about 90% and 100% throughout the monitoring period. It is also observed that the degree of saturation "appears" to consistently decrease in the winter months. This may not actually be an actual decrease in Sr but a peculiarity of the sensor, in particular when the frost line reaches the sensor depth. Minor variations in Sr (between 96 and 100%) are observed throughout the year which may be associated to previous rainfall regime affecting this zone. The late spring to early summer period seems to consistently lead to slightly higher (nearing 100%) degree of saturation at all depths. The delay in the increase with respect to the higher rainfall may be attributed to the low permeability of the subgrade soil and the time it takes for moisture to migrate from the shoulder to the center of the lane. In late summer and fall the flow will be reversed from the center of the lane to the shoulder, also leading to somewhat lower degree of saturation prior to the beginning of the winter.

Fig 3.17 Variation of Degree of Saturation ADAMS Co.

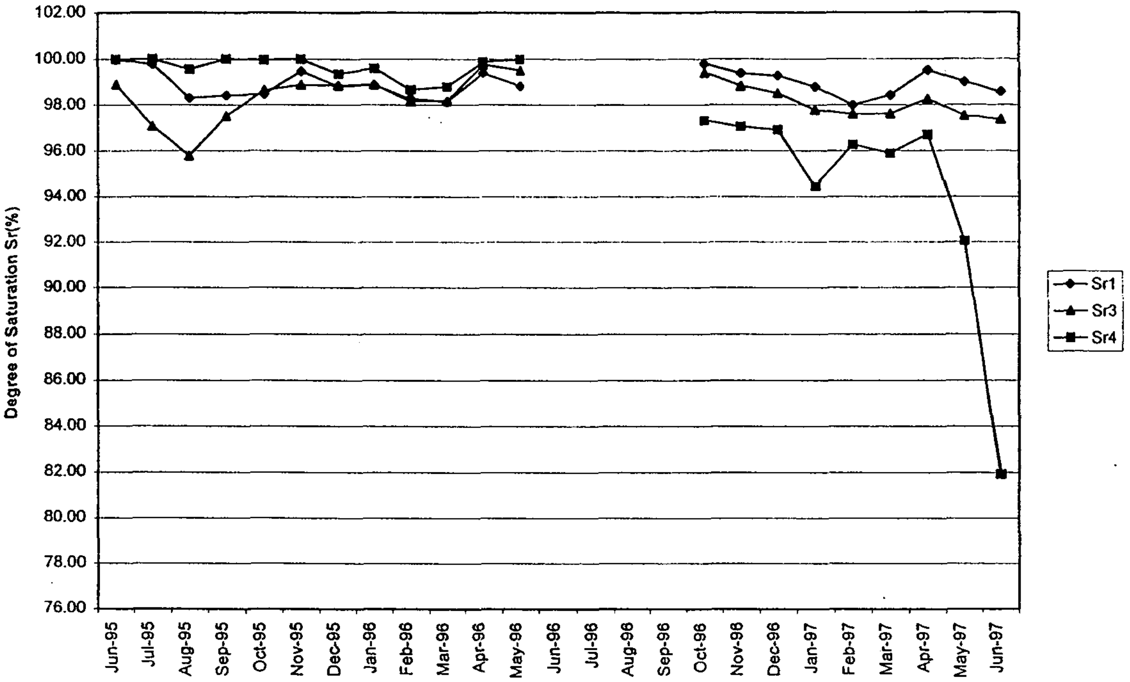


Figure 3.18 Variation of Degree of Saturation ATHENS Co.

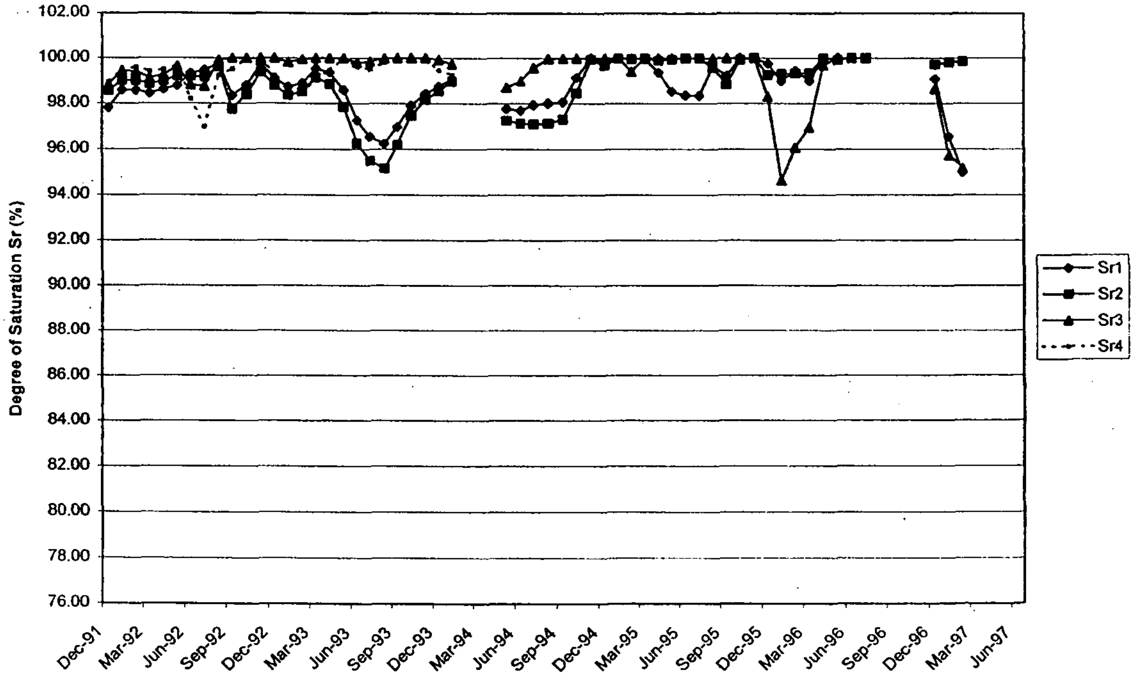


Figure 3.19 Variation of Degree of Saturation COLUMBIANA Co.

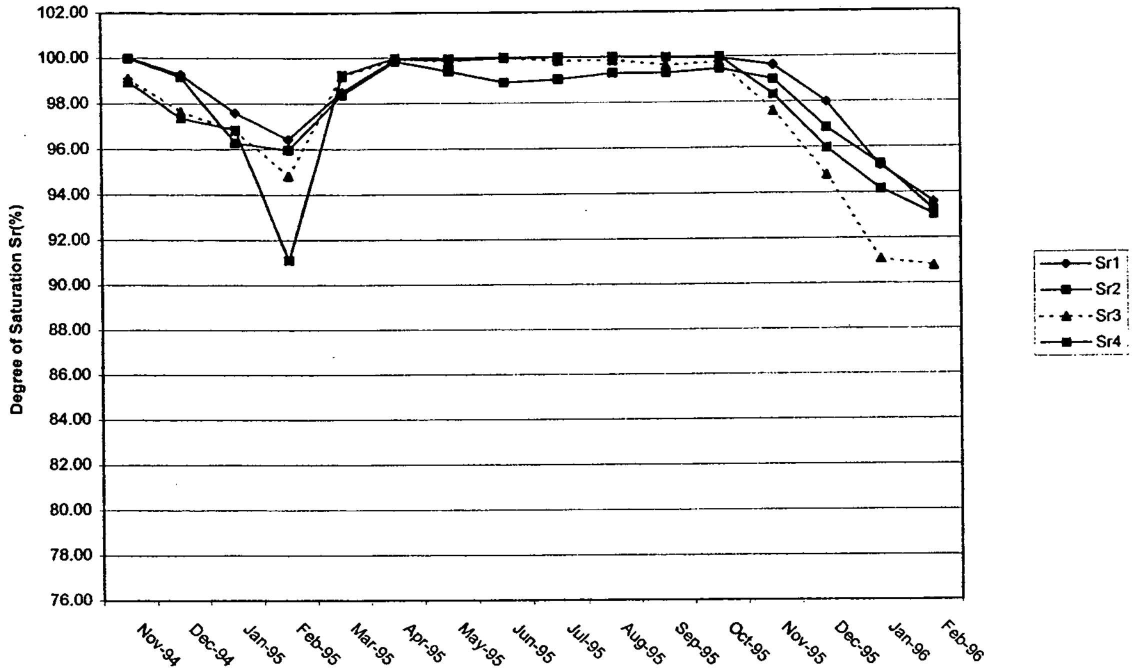


Figure 3.20 Variation of Degree of Saturation CRAWFORD Co.

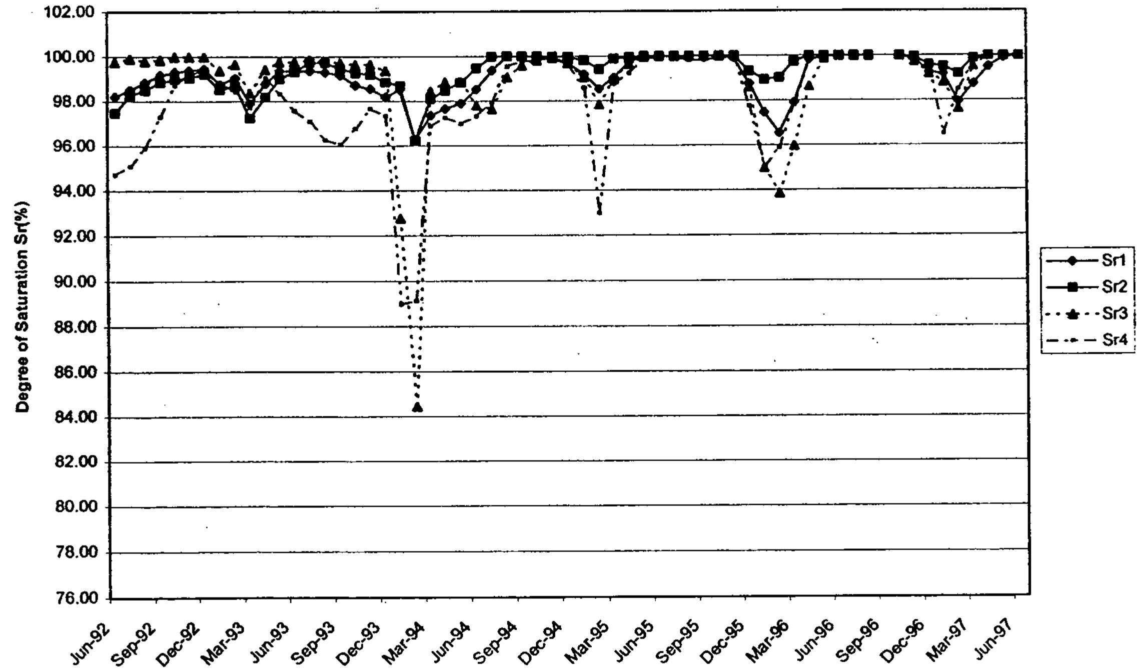


Figure 3.21 Variation of Degree of Saturation KNOX Co.

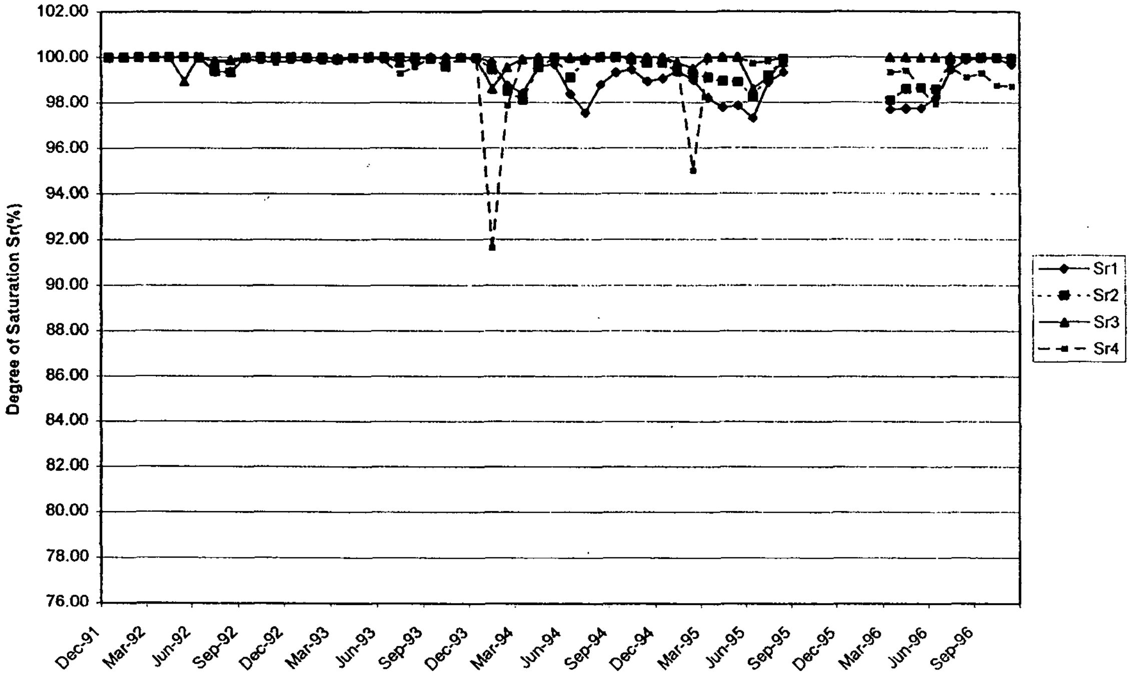


Figure 3.22 Variation of Degree of Saturation LICKING Co.

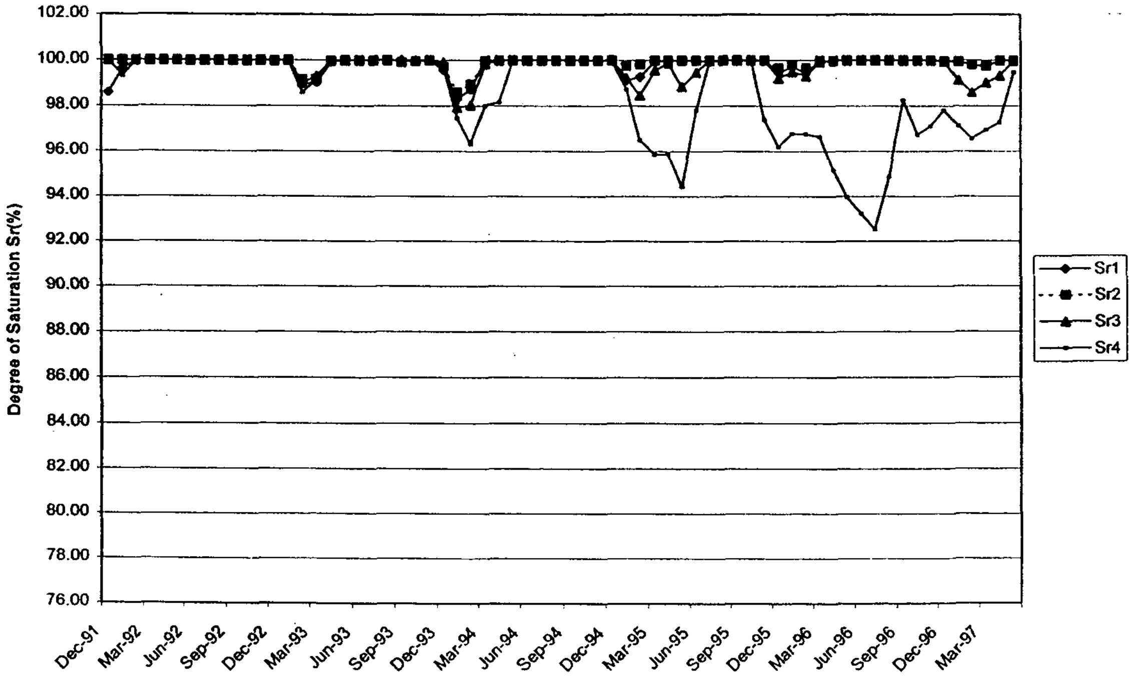


Figure 3.23 Variation of Degree of Saturation WOOD2 Co.

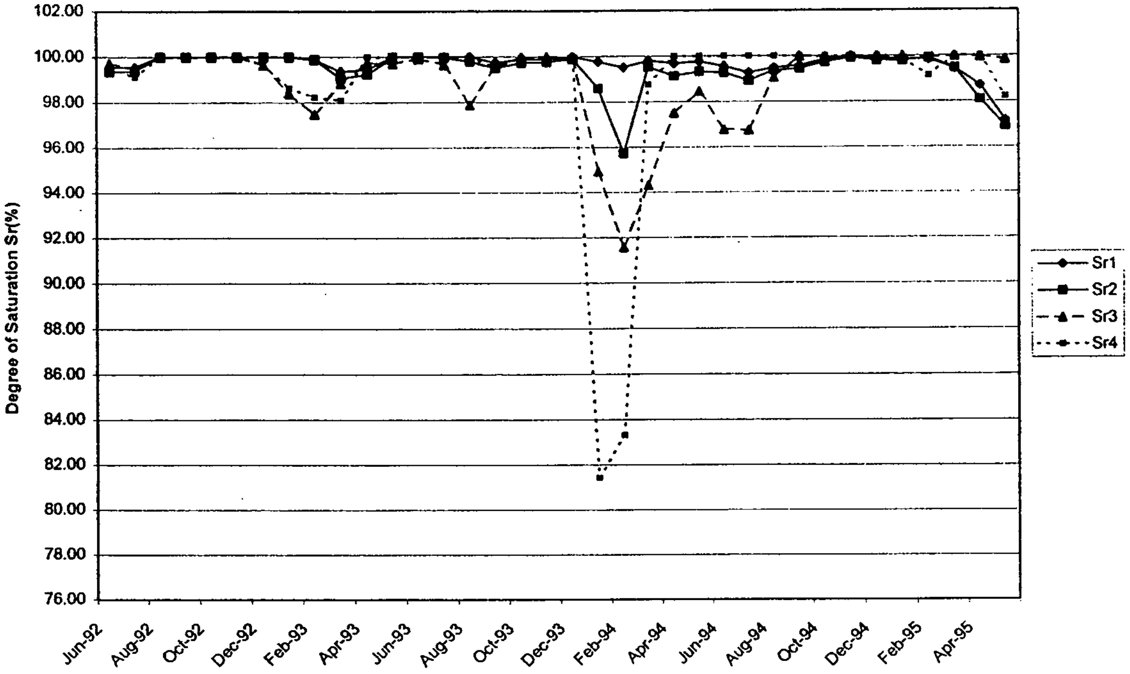


Figure 3.24 Variation of Degree of Saturation WOOD8 Co.

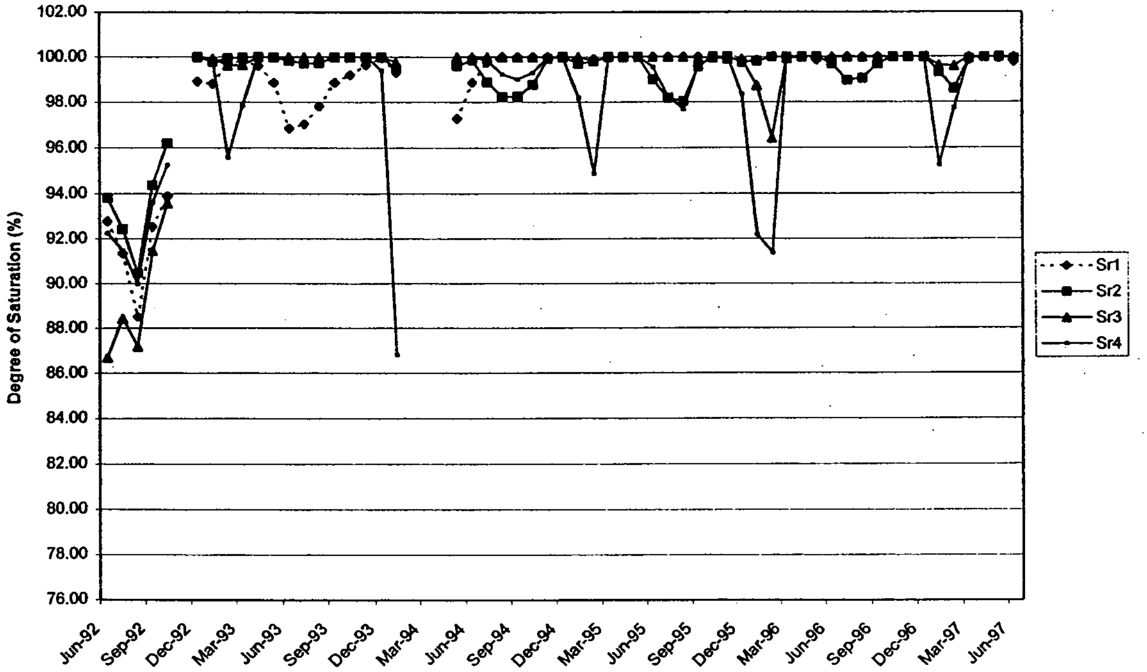


Figure 3.25 Seasonal Degree of Saturation-ADAMS Co.

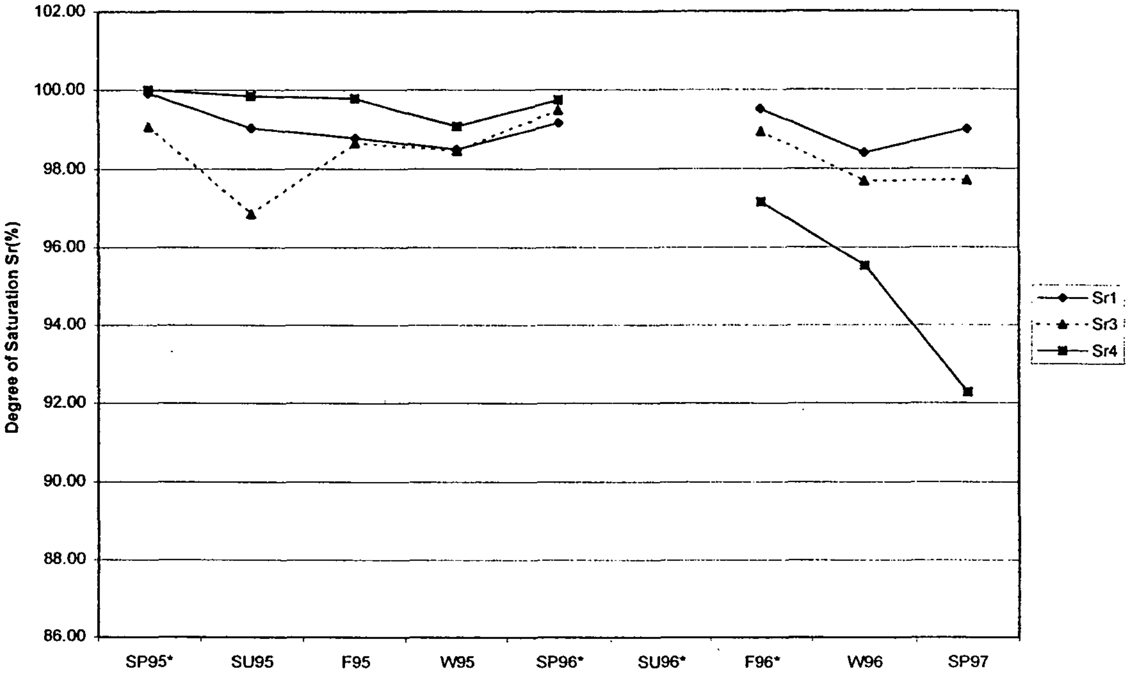


Figure 3.26 Seasonal Degree of Saturation-ATHENS Co.

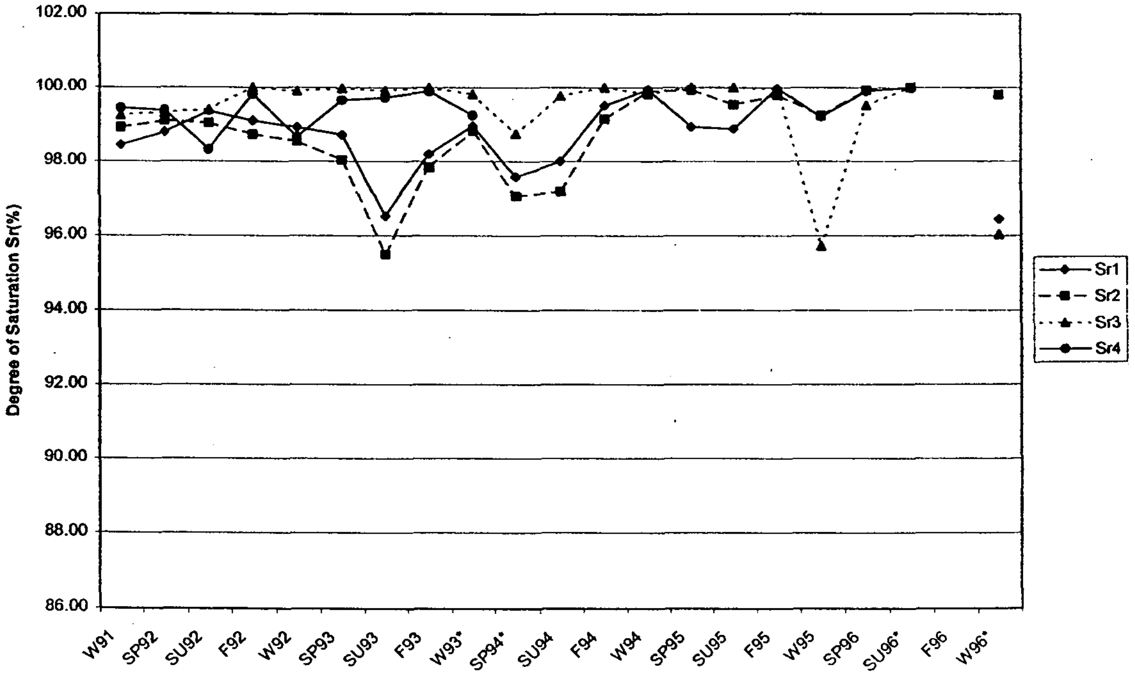


Figure 3.27 Seasonal Degree of Saturation-COLUMBIANA Co.

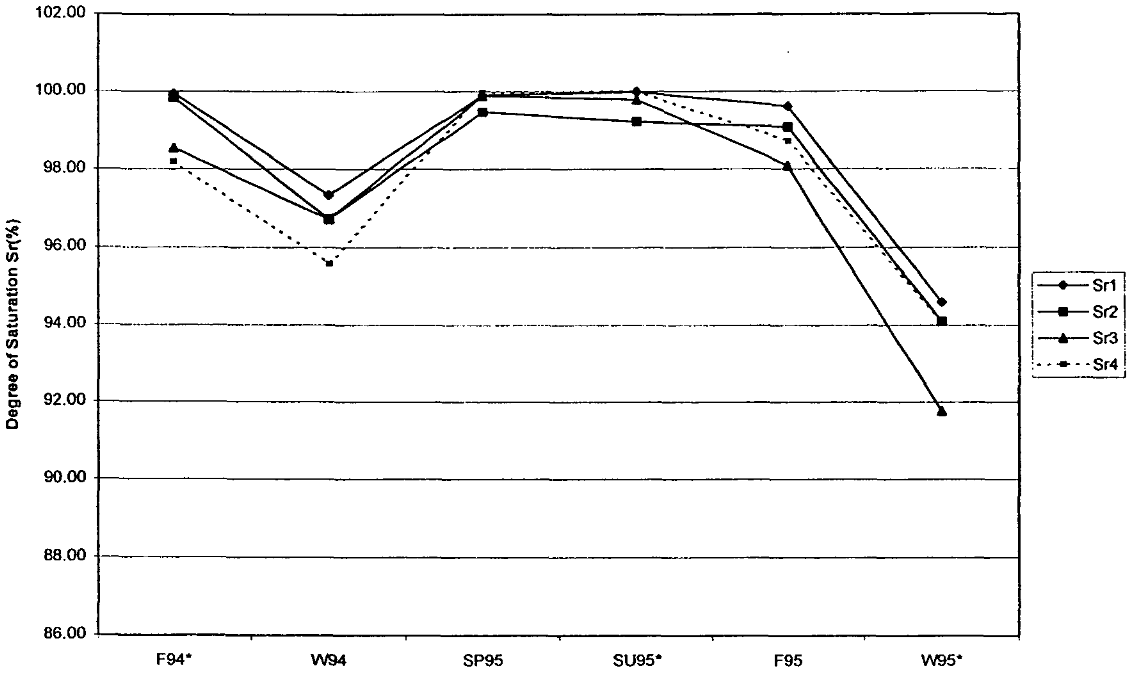


Figure 3.28 Seasonal Degree of Saturation-Cawford Co.

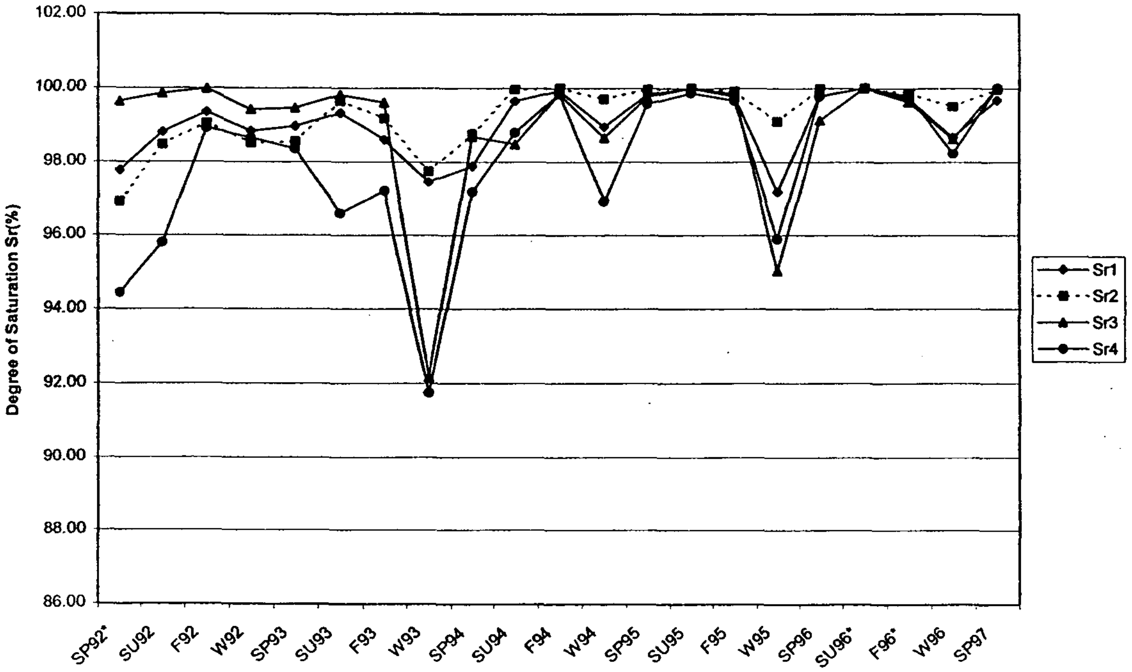


Figure 3.29 Seasonal Degree of Saturation-KNOX Co.

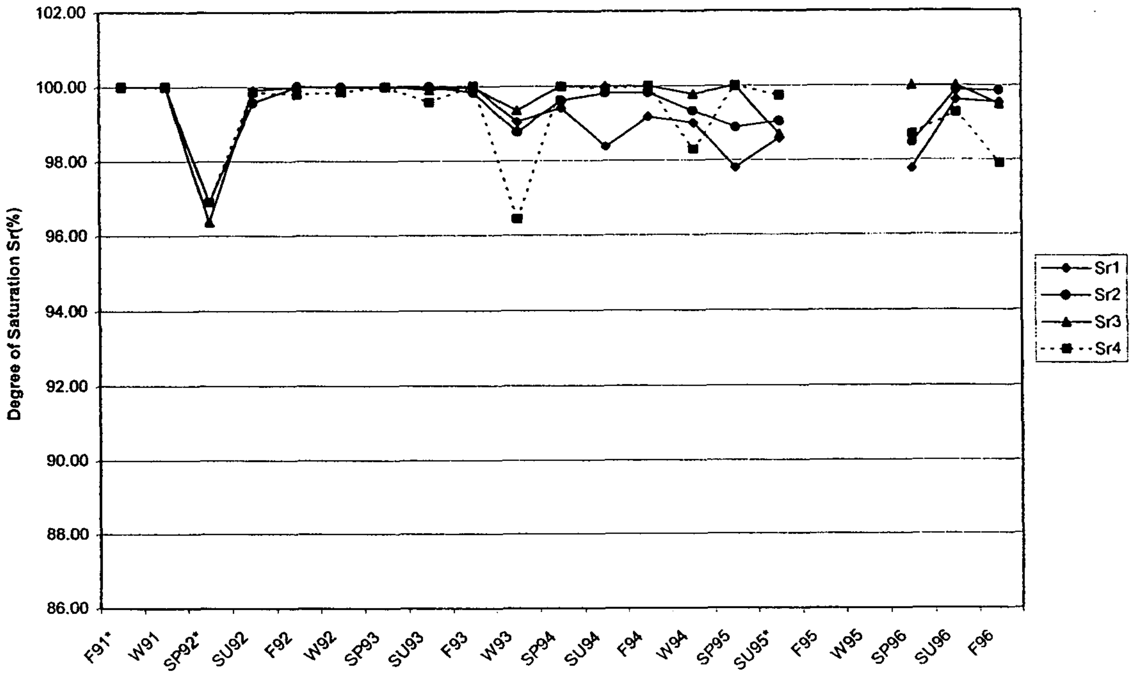


Figure 3.30 Seasonal Degree of Saturation-LICKING Co.

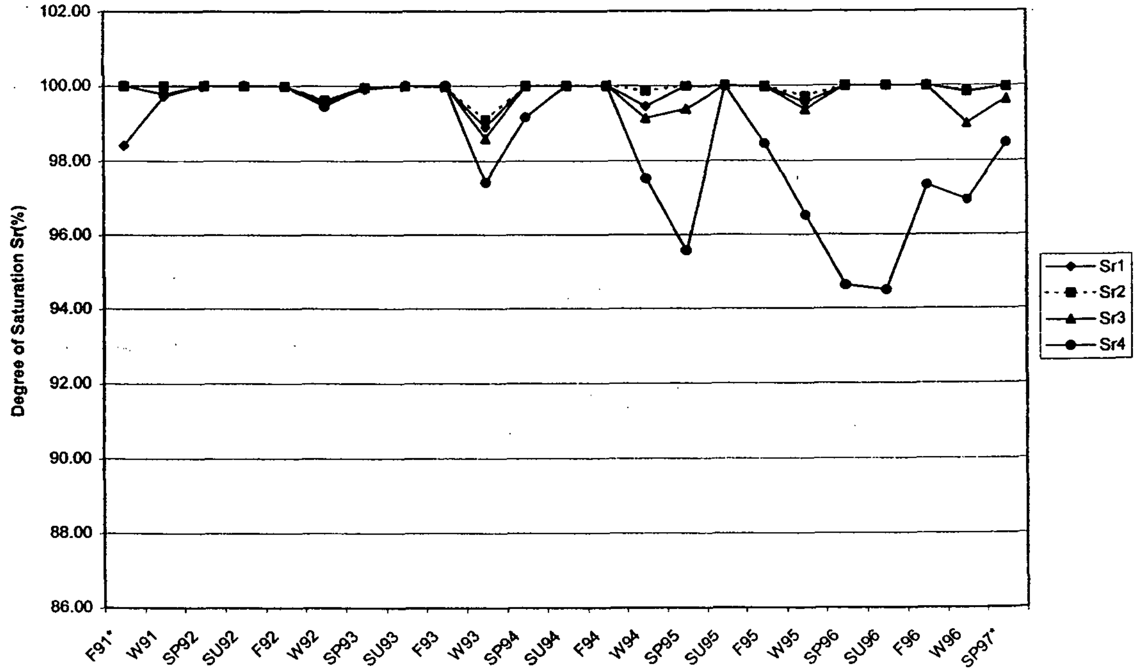


Figure 3.31 Seasonal Degree of Saturation-WOOD2 Co.

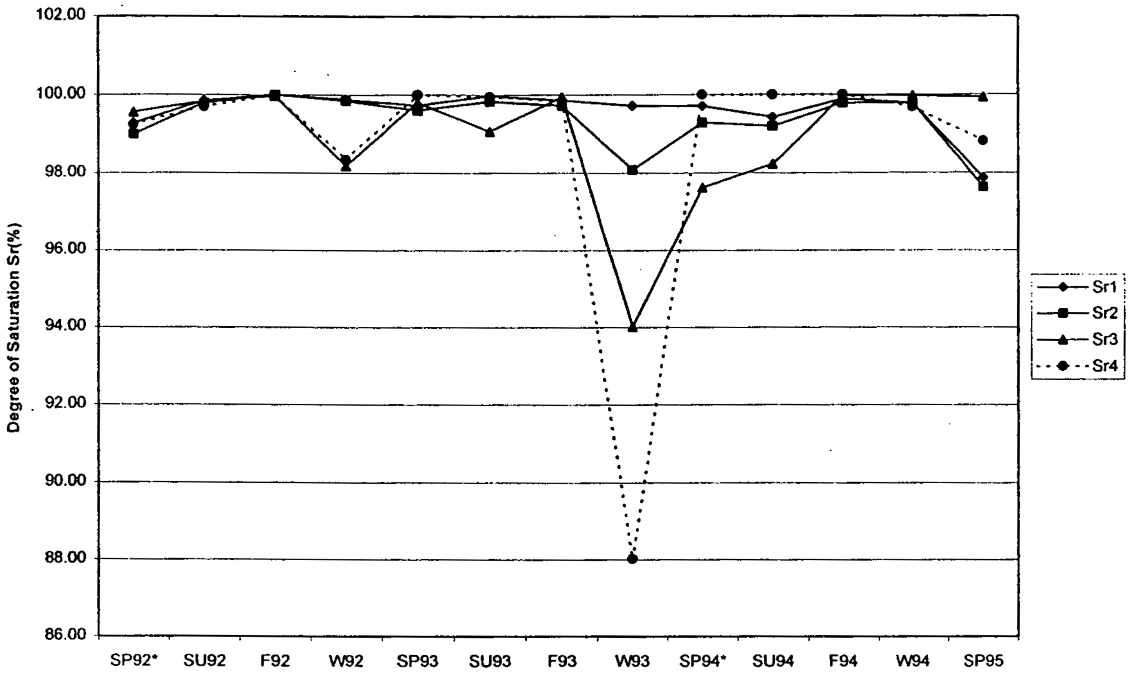
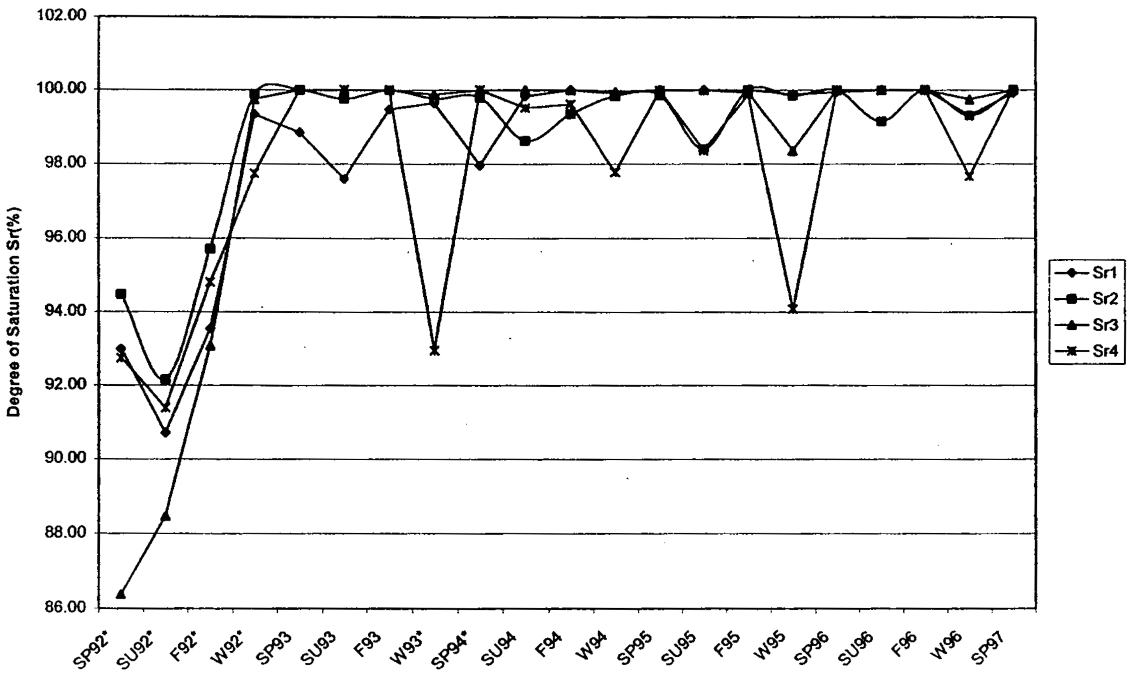


Figure 3.32 Seasonal Degree of Saturation-WOOD8 Co.



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Chapter 4

BACK CALCULATION OF RESILIENT MODULUS OF SUBGRADE SOILS FROM FALLING WEIGHT DEFLECTOMETER TEST RESULTS

An alternate procedure to evaluate the influence of seasonal factors on the material properties of flexible pavements is with the use of non-destructive testing techniques. Proper characterization of the response of a flexible pavement subjected to repeated, dynamic loads and its seasonal variations are essential in the development of mechanistic-based pavement design procedures. Findings from a previous study by Thompson et al. (1976) indicated that the seasonal resilient behavior of the asphalt concrete and the fine-grained soil significantly influence the performance of a flexible pavement.

Recently the Falling Weight Deflectometer (FWD) has gained popularity in the evaluation of pavement layer mechanical properties. As part of this research project, the Ohio Department of Transportation has been conducting FWD testing at six of the station locations, with a frequency of 3 to 4 times per year, in an effort to evaluate material property variation on a seasonal basis. Details of the method developed in this project to back calculate the resilient modulus of subgrade soils at the break point from measured FWD deflections were introduced in Section 2.2.2 of this report and will be expanded next, followed by actual computations.

4.1 Analysis Method

Falling Weight Deflectometer (FWD) tests at three different load levels were performed three to four times a year (once every season, when possible) at six of the station locations. FWD testing was conducted along a 152.4 m. (500 ft.) long section at a spacing of 15.2 m (50 ft.). A reference point at mid-length within the test section was selected to coincide with the seasonal instrumentation installed in the middle of the travel lane.

FWD Loads are applied to the asphalt concrete surface via a rubber coated steel loading plate, with a radius of 15 cm. (5.9 in.), and the corresponding pavement deflections are measured and recorded at seven radial distances including 0.0, 20.3, 30.5, 45.7, 61.0, 91.4 and 152.4 cm. (0.0, 8.0, 12.0, 18.0, 24.0, 36.0 and 60.0 in.) from the center of the loading plate.

As previously indicated, the flexible pavement analysis program (ILLIPAVE) was used to develop nomographs to back calculate the resilient modulus at the break point of the subgrade based on measured maximum Falling Weight Deflectometer (FWD) deflections for a given soil type, during the "Characterization of Ohio Subgrade Types" project (Figueroa et al., 1994). The resilient modulus at the break point was selected as the representative parameter to define both the bilinear stress-dependent model introduced by Thompson et al. (1976), as well as the stiffness characteristics of fine-grained soils.

The back calculation procedure has been previously shown in Figure 2.2. A FORTRAN computer program to follow this procedure was written for each of the six test sites, with the following detail:

- Since FWD testing is conducted at three load levels between approximately 40.03 and 53.38 kN (9000 and 12000 lbs), linear interpolation is used to calculate the deflection at exactly 53.38 kN (12000 lbs) of load. This load level was selected, since nomographs were developed previously to determine the maximum FWD deflection according to Equation 2.5, with the coefficients contained in Table 2.5, for this selected magnitude of load. These coefficients indicate the relative influence of E_{ac} with respect to E_{ri} in affecting the total deflection, leading to the conclusion that the total deflection is very sensitive to the variation of E_{ri}. This influence is evident in the values of the coefficients a_4 and a_3, whereby a_4 is approximately two orders of magnitude higher than a_3, although E_{ac} and E_{ri} do not differ by as much as two orders of magnitude at a given time during the year.
- The air temperature is in most instances measured during FWD tests. Alternatively, when the FWD does not provide the air temperature, it is interpolated from logger air temperature readings obtained at the same time the FWD testing was conducted.

- The air temperature is entered into Equation 2.4 using the coefficients for the specific site and the corresponding average asphalt concrete pavement temperature is obtained.
- The AC pavement temperature is then entered into Equation 2.1 (with coefficients defined in Table 2.4) to obtain the AC modulus at the time of FWD testing.
- The AC modulus is entered into Equation 2.6 with the coefficients corresponding to the soil type existing at the site, along with pavement section characteristics such as the AC thickness, the gravel base thickness, and the maximum FWD deflection [interpolated at 53.38 kN (12000 lbs.) of FWD load] to obtain the resilient modulus of the subgrade soil at the break point E_{ri}.
- The process is repeated for each of the eleven locations along the test section and the program calculates an average resilient modulus for the complete section, as well as for the reference point (where the logger instrumentation is located)

Data to back calculate the resilient modulus at the break point, including date, time and temperature of seasonal FWD testing is included in Tables D1 to D6 for each of the six tested and analyzed locations. These tables also specify whether the air temperature was measured by the FWD or by the data logger. Testing periods have been designated by the four seasons. However, these designations for the most part correspond to the following times of the year:

SPRING:	Late winter – early spring
SUMMER:	Early summer
FALL	Late Summer - early fall
WINTER	Late fall

4.2 Back Calculated Resilient Modulus

Summaries of back calculated resilient modulus by the procedure outlined above are included in Tables D7 to D12 for the testing detail contained in Tables D1 to D6. Tables D7 to D12 include the average value along the section, corresponding to eleven FWD test locations as well as E_{ri} at the reference point where the seasonal instrumentation is located. Overall seasonal averages of both moduli were also calculated and are included in Table 4.1. This table also

Table 4.1 Average Seasonal Resilient Modulus Back Calculated from FWD Deflections (MPa)

STATION	Res. Mod. Eri	SPRING	SUMMER	FALL	WINTER
ADAMS	Av. Along Sect.	32.2	37.8	63.8	19.0
	% From Max.	50.43%	59.28%	100.00%	29.80%
	@ Ref. Pt.	45.2	40.9	71.4	56.5
ATHENS	Av. Along Sect.	151.6	156.1	154.7	143.0
	% From Max.	97.13%	100.00%	99.12%	91.61%
	@ Ref. Pt.	168.1	164.8	162.1	157.9
CRAWFORD	Av. Along Sect.	30.7	38.3	37.2	44.5
	% From Max.	69.15%	86.20%	83.56%	100%
	@ Ref. Pt.	42.6	44.0	43.5	54.0
KNOX	Av. Along Sect.	52.0	78.9	82.9	82.0
	% From Max.	62.67%	95.09%	100.00%	98.91%
	@ Ref. Pt.	38.1	52.4	58.5	65.8
LICKING	Av. Along Sect.	236.8	244.6	255.8	233.3
	% From Max.	92.56%	95.34%	100.00%	91.12%
	@ Ref. Pt.	178.8	187.0	206.0	188.1
WOOD8	Av. Along Sect.	67.4	69.1	82.8	56.2
	% From Max.	81.35%	83.43%	100.00%	67.89%
	@ Ref. Pt.	66.9	69.6	89.6	60.9

contains the percentage of the average seasonal modulus along the section with respect to the maximum value observed at any given season during the year. For example, considering the Adams county section, the maximum average modulus of 63.8 MPa (9.26 ksi) is observed in the designated fall testing period, whereas the spring testing period yields E_{ri} = 32.2 MPa (4.67 ksi), which is 50.43% of 63.8. These percentages are useful in ranking the seasons of higher to lower modulus. By assigning a ranking of 4 to the season with the highest modulus and of 1 to the season with the lowest modulus (obviously ranks of 3 and 2 to the intermediate seasons) at each station location, a total point ranking is obtained by adding the points for individual seasons. In order of higher point ranking and consequently of expected higher resilient modulus the designated "fall" testing period is the highest followed by "summer", "winter" and "spring" in decreasing order. This ranking is expected since the fall testing period follows the generally drier summer season and the spring testing period happens at the spring thaw and normally wetter early spring. The high resilient modulus averages obtained at the Licking Co. station can be explained by the presence of the 45.7 cm (18 in) – thick lime stabilized layer existing beneath the gravel base.

The back calculated average resilient modulus (at the break point) along the test section and at the reference point have been included in dual axis plots with the amount of seasonal rainfall in Figures 4.1 to 4.6, for individual instrumented test sections, in an effort to determine if any relationship exists between amount of rainfall and subgrade modulus. More detailed similar plots containing the monthly rainfall and the average resilient modulus along the section were also drawn for each test section and are included in Figures 4.7 to 4.12.

The observation of the two sets of figures indicates that for the most part a higher back calculated resilient modulus follows generally lower amounts of rainfall. Similarly lower resilient modulus back calculations are generally preceded by higher rainfall. However, no correlation between the amount of rainfall accumulated during either one, two or three months preceding the date of FWD testing with the back calculated resilient modulus was found.

Figure 4.1 Resilient Modulus Variation (Adams Co.)

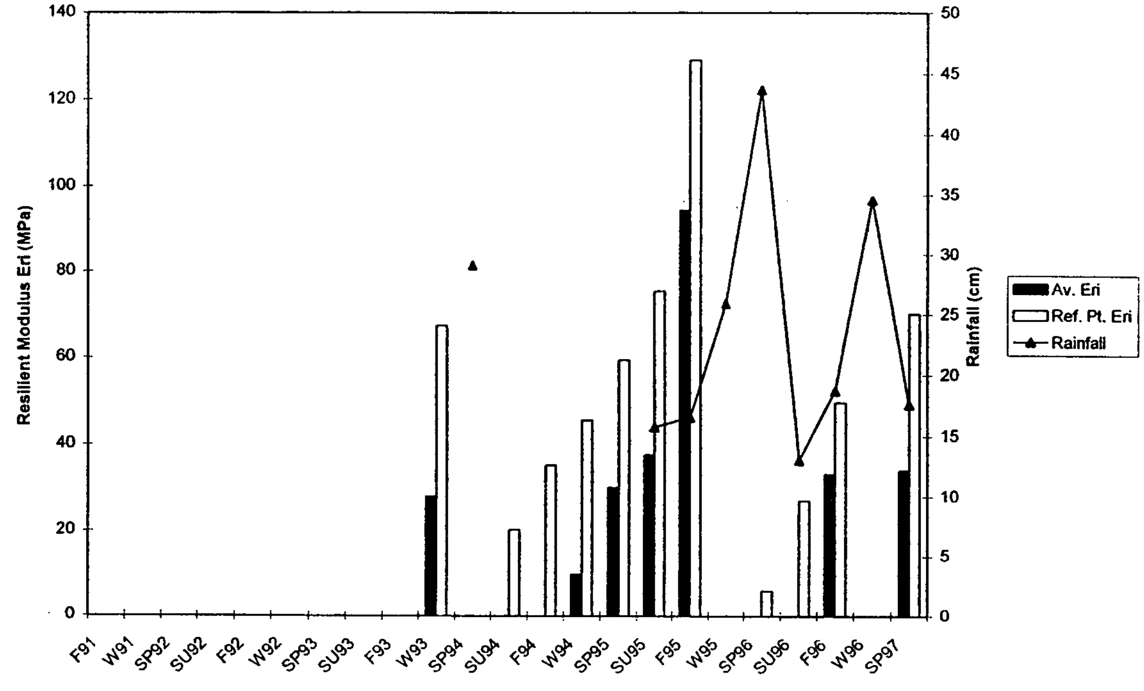


Figure 4.2 Resilient Modulus Variation (Athens Co.)

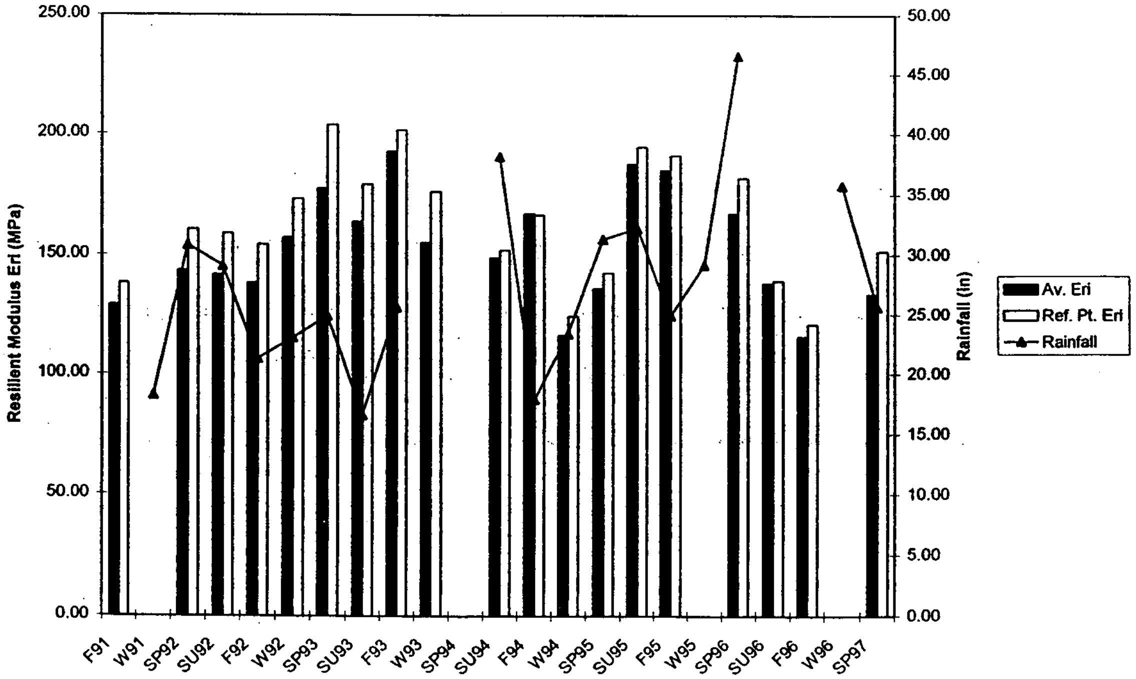


Figure 4.3 Resilient Modulus Variation (Crawford Co.)

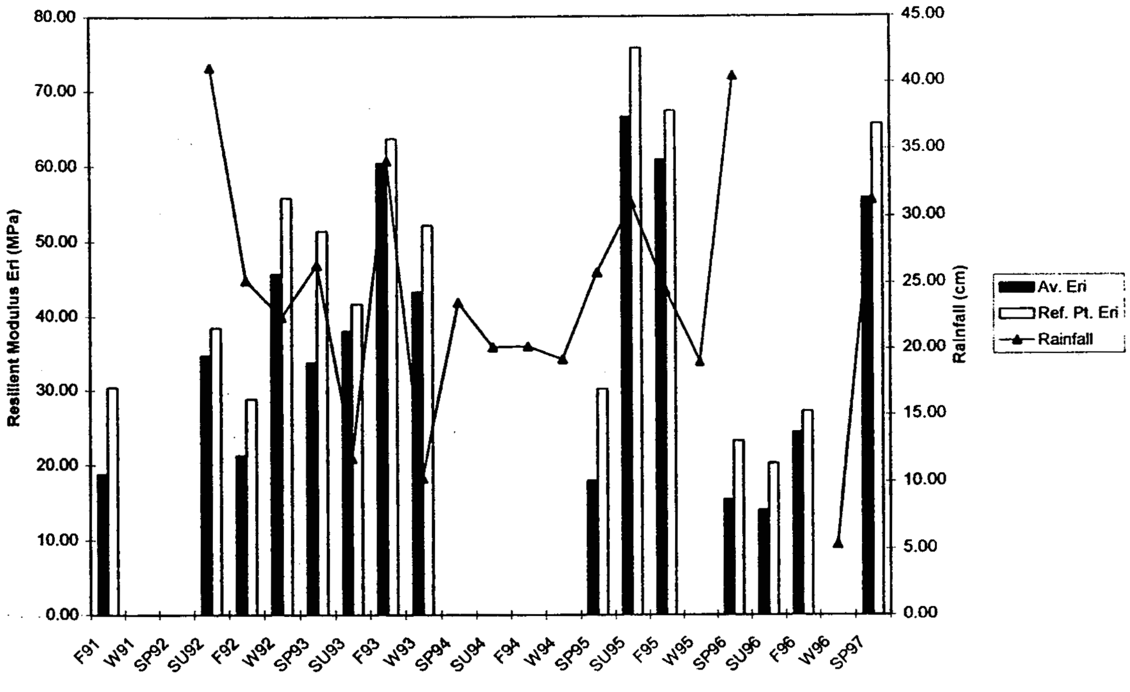


Figure 4.4 Resilient Modulus Variation (Knox Co.)

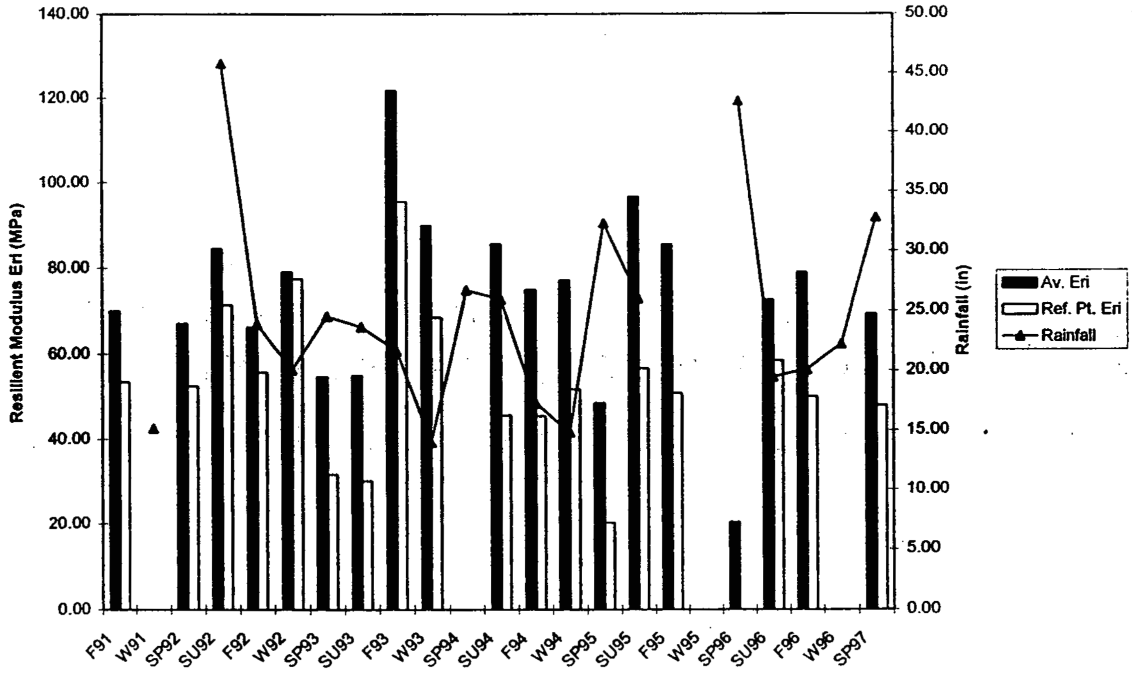


Figure 4.5 Resilient Modulus Variation (Licking Co.)

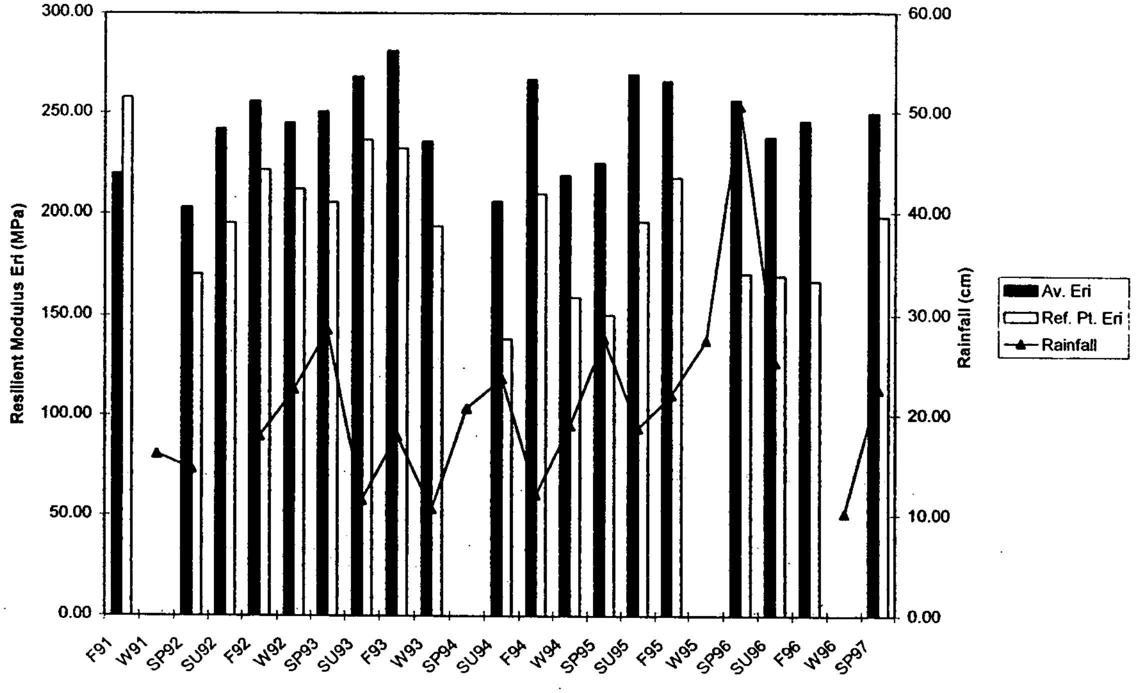


Figure 4.6 Resilient Modulus Variation (Wood8 Co.)

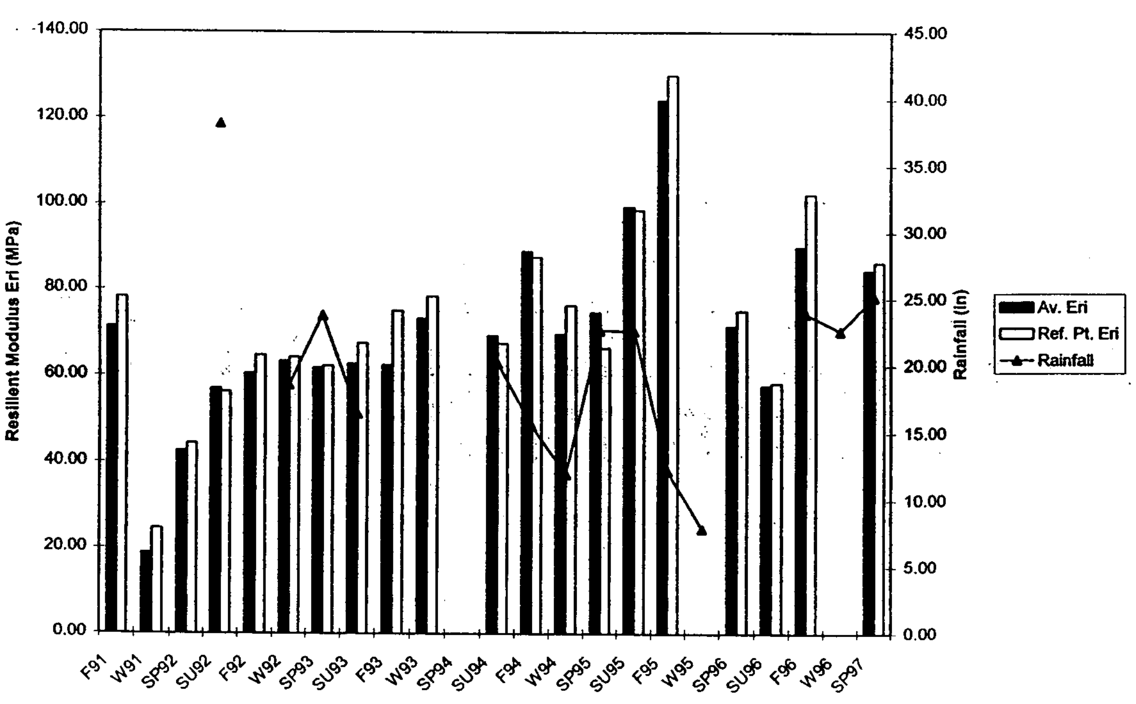


Figure 4.7 Resilient Modulus vs. Monthly Rainfall (Adams Co.)

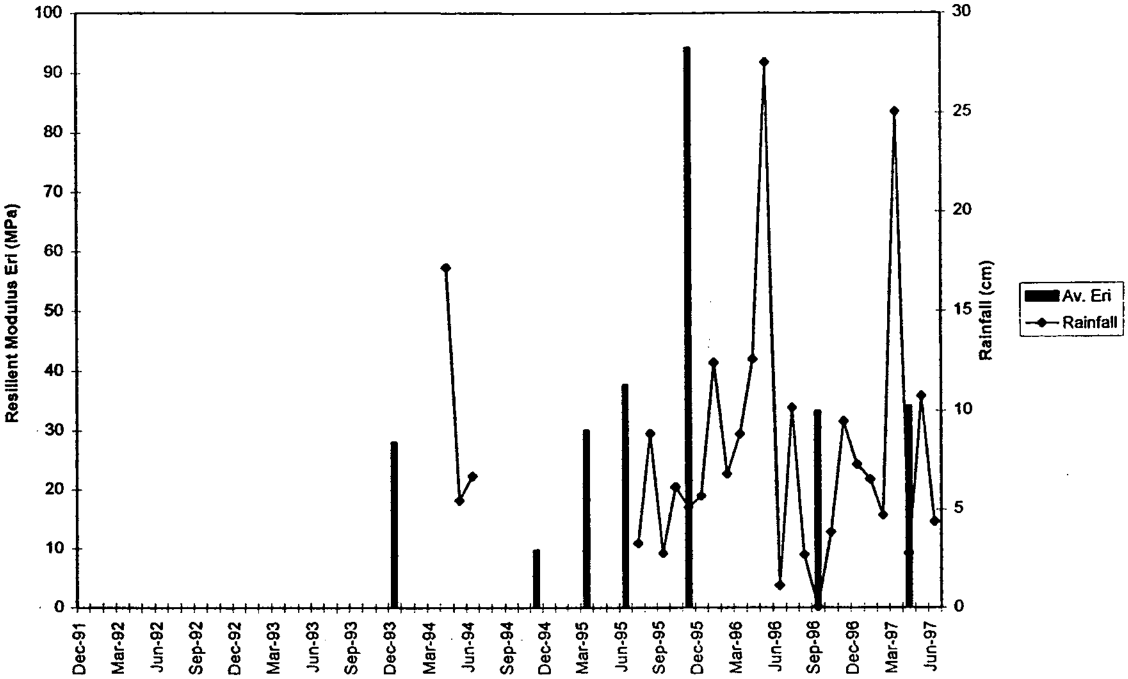


Figure 4.8 Resilient Modulus vs. Monthly Rainfall (Athens Co.)

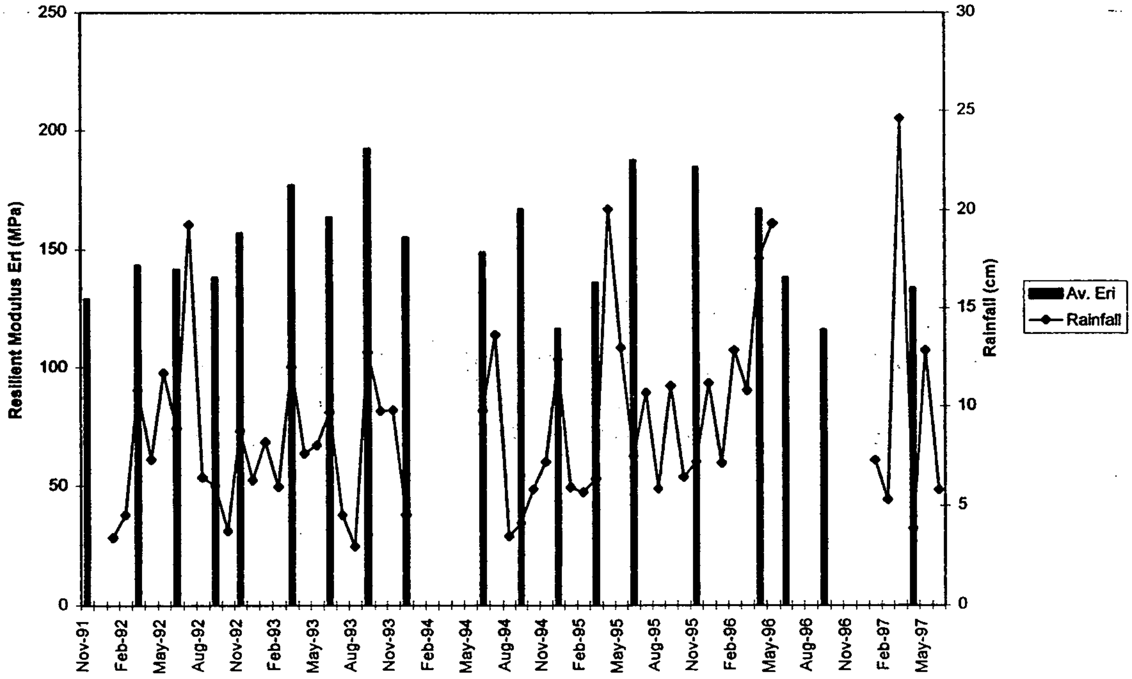


Figure 4.9 Resilient Modulus vs. Monthly Rainfall (Crawford Co.)

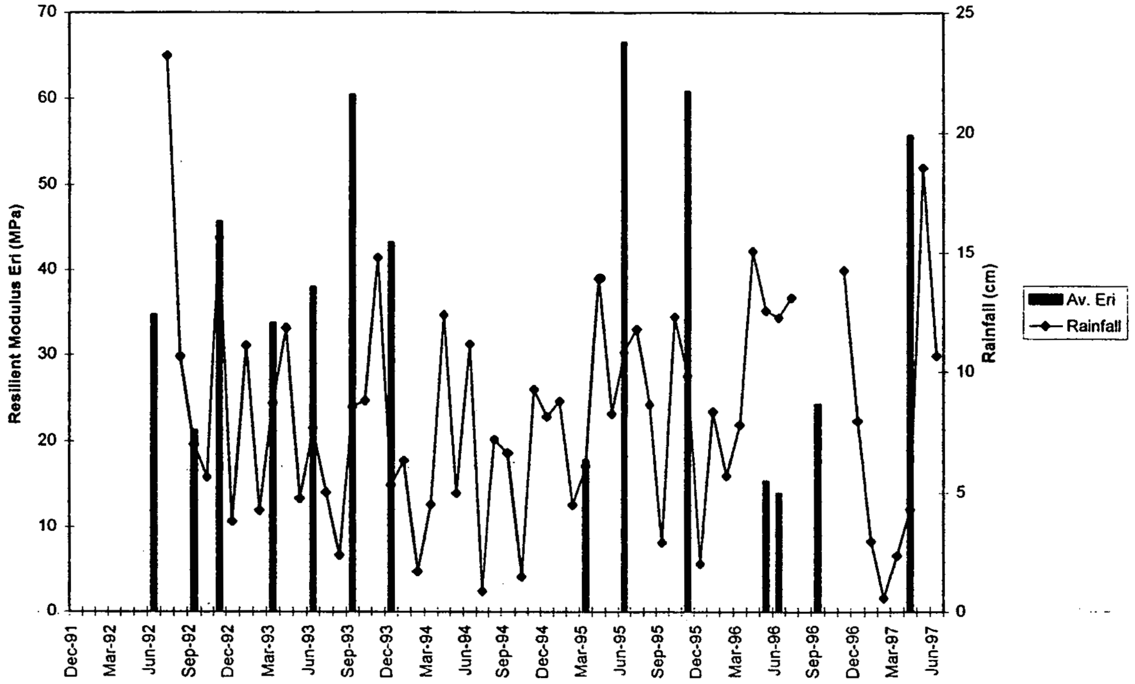


Figure 4.10 Resilient Modulus vs. Monthly Rainfall (Knox Co.)

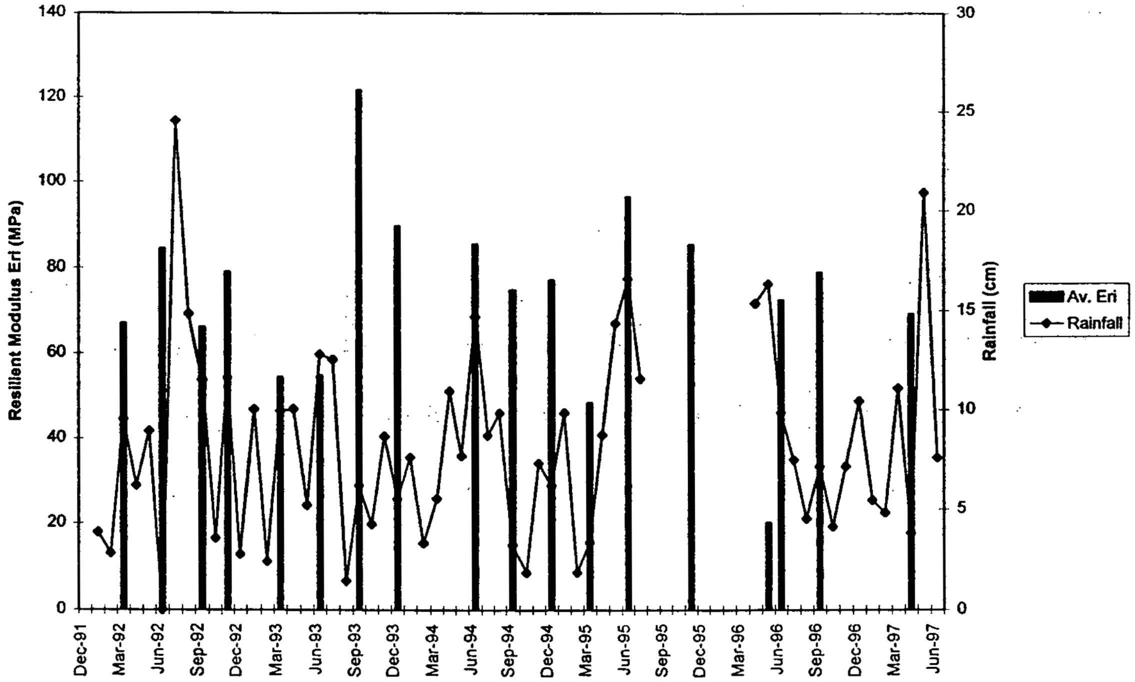


Figure 4.11 Resilient Modulus vs. Monthly Rainfall (Licking Co.)

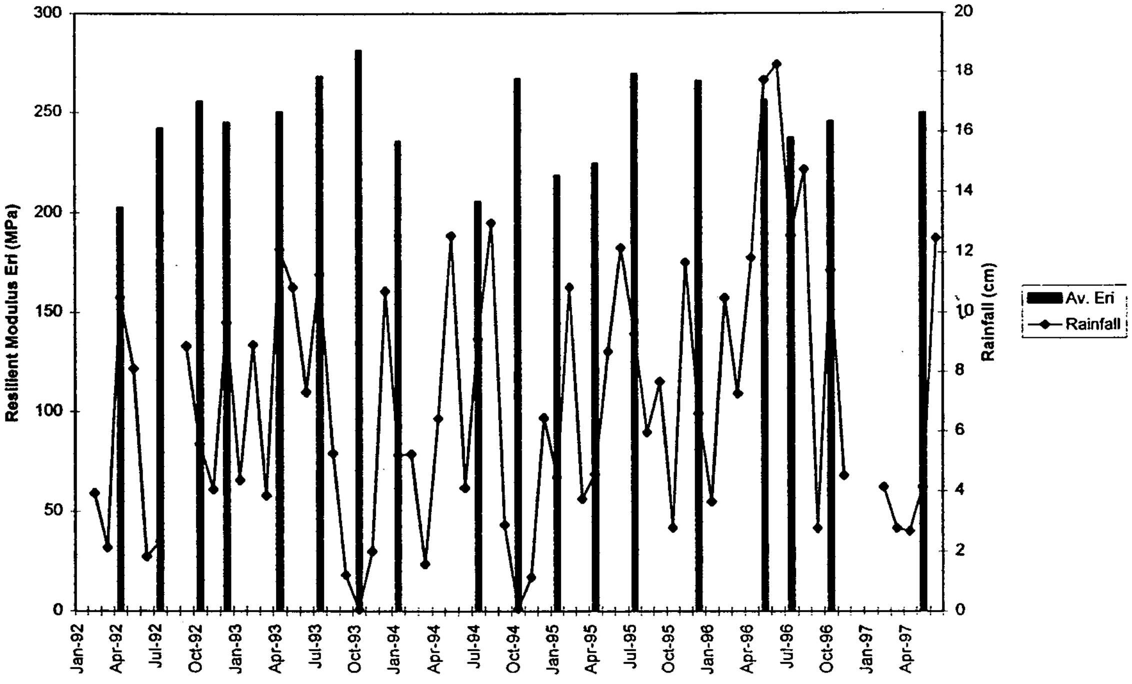
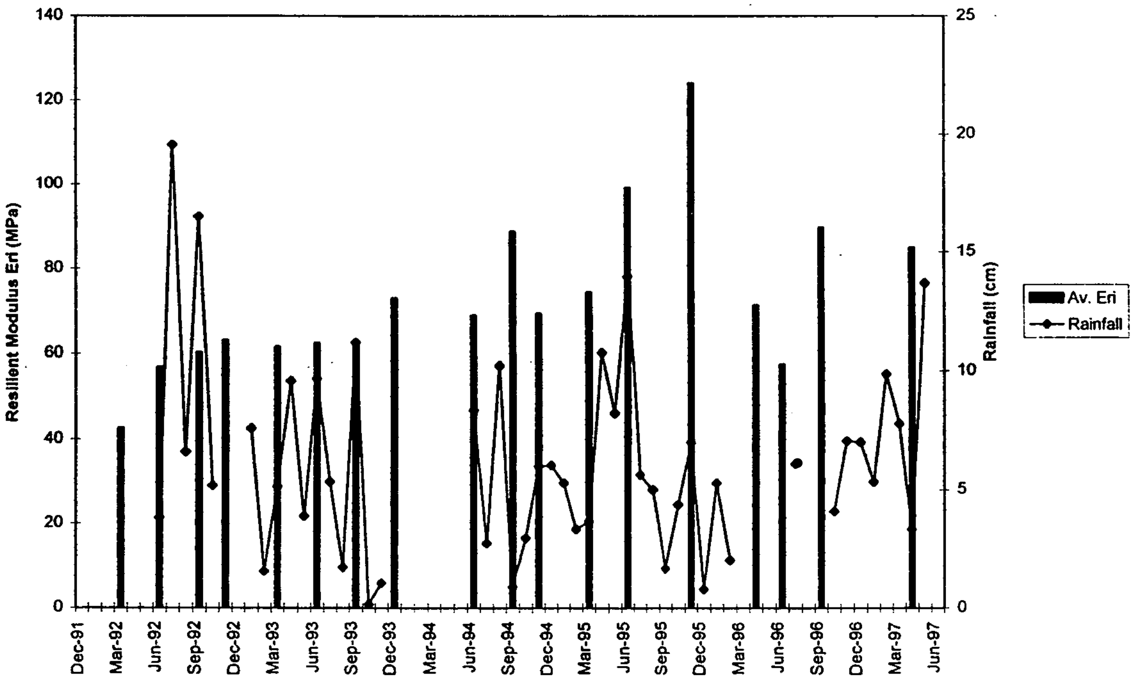


Figure 4.12 Resilient Modulus vs. Monthly Rainfall (Wood8 Co.)



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Chapter 5

SUMMARY AND CONCLUSIONS

Nine moisture-temperature-rainfall recording stations previously installed during the project "Characterization of Ohio Subgrade Types" (Figueroa et al. 1994) were monitored for a period of 2-1/2 years. These stations were located in Adams, Athens, Columbiana, Crawford, Licking, Lucas and Wood (two stations) county. The station locations were selected to include the variation in climate within the state of Ohio and the four most commonly occurring soil types (A-3, A-4, A-6, and A-7). The Columbiana Co. station was destroyed by a vehicle crash and one of the Wood Co. stations had to be dismantled because of new urban development in its vicinity. These stations recorded hourly, daily and seasonal variations in air temperature, rainfall, temperature within the asphalt concrete layer and moisture content (or degree of saturation) and temperature within the subgrade soil.

The temperature sensors recorded air, asphalt concrete pavement and subgrade soil temperatures. Typically, temperature variations within the subgrade soil are minimal on a daily basis. Only the uppermost subgrade soil thermistor shows daily temperature variations, although within a narrower range, following those of the lowest asphalt concrete thermistor.

The thermistors within the asphalt concrete layer exhibit large daily temperature fluctuations. Typically the AC layer exhibits a uniform temperature (no temperature gradient) twice a day, normally occurring between 8:00 and 10:00 AM and around 8:00 PM. After the morning period of no temperature gradient, thermistors closer to the surface show faster warming as compared to those near the bottom of the surface layer. An opposite trend occurs after the evening period of no temperature gradient. This information is important in selecting the optimal times for FWD testing (between 8:00-10:00 AM) since the surface layer exhibits a uniform stiffness throughout its thickness. Similarly, the maximum daytime temperature gradient within the pavement is observed between 2:00 and 4:00 PM at all seasons and the maximum overnight temperature gradient occurs around 6:00 AM. It is to be noted that the temperature gradient is greater in the afternoon than in the early morning and that AC layer temperature variations closely follow air temperature changes.

The average AC pavement temperature was calculated in the middle of the layer at each location, then monthly and seasonal averages were tabulated. The average pavement temperature difference between summer and winter is of the order of 30 to 35 deg. C at all sites. This range also indicates the wide variation in the elastic properties of the AC. As expected the northern sites exhibit slightly lower averages than the southern sites. The average monthly and seasonal asphalt concrete temperatures are summarized in Tables 3.1 and 3.2 respectively for each tested site.

Figueroa et al. (1994) indicated from observations in temperature changes within the pavement and subgrade profiles that the daytime and the nighttime averages for any sensors located at depths in excess of 30.48 cm. (1.0 ft.) (i.e. the subgrade soil sensors) are very similar. In addition, the asphalt concrete sensors show warmer temperatures than the subgrade soil sensors (on the average) during the spring and summer. However, this trend reverses during the fall and winter.

Polynomial equations were derived relating the average asphalt concrete pavement temperature to the air temperature for eight (excluding the Columbiana Co.) of the nine monitored stations. The coefficients included in these equations indicate that asphalt concrete temperature is higher in the southern part than in the northern part of the state. The regression coefficients also point to the fact that the state of Ohio may be subdivided into three general temperature zones: North, (from the North Shore to Mansfield – Mount Vernon) Central (from Mansfield – Mount Vernon to Lancaster) and South (from Lancaster to the southern state line). This division is useful in assessing the average AC modulus on a seasonal or monthly basis for any future implementation of mechanistic pavement design procedures. It is then possible to determine the average asphalt concrete temperature from measured air temperature which is normally obtained during FWD testing.

As a result of temperature differences during the four seasons the resilient modulus of the asphalt concrete also changes in an inverse form to the temperature variation. It was determined that for a typical mid-season day the resilient modulus averages:

3791.7 MPa (550 ksi) in the spring (+/- 1034.1 MPa or +/- 150 ksi)
1723.5 MPa (250 ksi) in the summer (+/- 1034.1 MPa or +/- 150 ksi)
8272.8 MPa (1200 ksi) in the fall (+/- 1378.8 MPa or +/- 200 ksi)
15511.5 MPa (2250 ksi) in the winter (+/- 1551.1 MPa or +/- 225 ksi)

These typical modulus values also indicate that the contribution of the subgrade soil in supporting traffic loads is more important during the warmer months because of the lower stiffness of the surface layer during this time of the year. Unfortunately, this fact is also coupled with the lower stiffness of the subgrade soil itself during and after the rainy spring and early summer as is typical in Ohio. Consequently the two combined effects make the spring-summer the critical time of the year considering environmental effects. Typical monthly and seasonal average values of the resilient modulus of the asphalt concrete for each station, for the three suggested climatic zones and for all of the state have been calculated from the collected data. Average monthly and seasonal asphalt concrete modulus values are listed in Tables 3.4 and 3.5 respectively. These tables contain specific values for each location of direct application as inputs to a mechanistic pavement design procedures.

Recorded depths of frost penetration show, as expected, that they are greater in the northern than in the southern stations. The maximum depth of frost penetration measured to date approached 121.9 cm. (4.0 ft.) at the Wood 2 station during the 1993-1994 winter, which happened to be a severe winter. On a normal season the average depth of frost penetration is about 45 to 61 cm. (1.5 to 2.0 ft) at the southern stations and from 70 to 82 cm. (2.3 to 2.7 ft) at the northern locations. It was also observed that when the frost penetration is high at the northern sites the number of freeze-thaw cycles is lower. This normally occurs during a severe winter. The number of cycles appears to increase during milder winters. Normally, the northern sites experience an average 7 to 12 cycles as compared to between 4 and 5 in the southern sites.

Detailed curves of depth of frost penetration and number of freeze-thaw cycles are included in section 3.1.5 and in Appendix B

Collected precipitation was summarized on a monthly and seasonal basis to determine if a correlation existed between the amount of precipitation and the degree of saturation of the subgrade soil, as well as the value of the back calculated resilient modulus from Falling Weight Deflectometer-measured deflections.

A calibration equation previously developed was used to obtain monthly and seasonal averages of the degree of saturation from moisture and temperature sensor readings at each of four moisture sensor locations. The degree of saturation typically varied between about 90% and 100% throughout the monitoring period. It was also observed that the degree of saturation "appears" to consistently decrease in the winter months. This may not actually be an actual decrease in Sr but a peculiarity of the sensor, in particular when the frost line reaches the sensor depth. Minor variations in Sr (between 96 and 100%) are observed throughout the year which may be associated to previous rainfall regime affecting this zone. The late spring to early summer period seems to consistently lead to slightly higher (nearing 100%) degree of saturation at all depths. The delay in the increase with respect to the higher rainfall may be attributed to the low permeability of the subgrade soil and the time it takes for moisture to migrate from the shoulder to the center of the lane. In late summer and fall the flow will be reversed from the center of the lane to the shoulder, also leading to somewhat lower degree of saturation prior to the beginning of the winter.

Finally a method to back calculate the resilient modulus of subgrade soils (Eri) at the break point from measured FWD deflections was developed. The method, explained in Section 2.2.2, requires the input of the maximum FWD deflection, the resilient modulus of the asphalt concrete (alternatively determined from air temperature readings in combination with Equations 2.4 and 2.1) and the thickness of the asphalt concrete and the base layers. Eri is back calculated through equation 2.6 using the coefficients listed in Tables 2.5a and 2.5b depending on the soil type (A-4, A-6 or A-7) and the applied FWD load. If the exact FWD load is not found in these tables, interpolation is required.

Overall seasonal averages of Eri were obtained at each of six station locations where FWD testing was conducted. Seasons were ranked in terms of expected higher resilient modulus. The designated "fall" testing period (early fall) showed the highest followed by "summer", "winter" and "spring" in decreasing order. This ranking is expected since the fall testing period follows the generally drier summer season and the spring testing period happens at the spring thaw and normally wetter early spring, also reflected in a higher degree of saturation, as described above.

Generally, for the most part a higher back-calculated resilient modulus followed lower amounts of rainfall. Similarly lower resilient modulus back calculations were generally preceded by higher rainfall.

Attempts to correlate the amount of rainfall accumulated over either one month, two or three months preceding the date of FWD testing with the back calculated resilient modulus were unsuccessful.

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Table A1. AVERAGE SEASONAL ASPHALT CONCRETE TEMPERATURE (Adams Co.)
(deg C)

YEAR		SPRING	SUMMER	FALL	WINTER
1991	day				
	night				
	total				
1992	day				
	night				
	total				
1993	day				-*
	night				-*
	total				-*
1994	day	22.37	-*	-	-
	night	21.37	-*	-	-
	total	21.87	-*	-	-
1995	day	-*	32.78	12.53	2.90
	night	-*	31.93	11.97	2.64
	total	-*	32.35	12.25	2.77
1996	day	-*	-	-*	5.40
	night	-*	-	-*	4.98
	total	-*	-	-*	5.19
1997	day	19.90			
	night	18.68			
	total	19.29			

* Incomplete Data
- Data not available

Table A2. AVERAGE SEASONAL ASPHALT CONCRETE TEMPERATURE (Athens Co.) (deg C)

YEAR		SPRING	SUMMER	FALL	WINTER
1991	day				5.72
	night				4.32
	total				5.02
1992	day	21.59	30.28	13.10	4.14
	night	18.73	28.91	12.27	3.66
	total	20.16	29.59	12.69	3.90
1993	day	22.22	33.46	12.86	*
	night	20.13	31.23	11.77	*
	total	21.18	32.34	12.32	*
1994	day	*	31.43	14.77	4.58
	night	*	29.05	13.39	3.70
	total	*	30.24	14.98	4.14
1995	day	22.34	33.92	12.24	1.97
	night	20.27	31.98	11.25	1.72
	total	21.30	32.95	11.75	1.84
1996	day	20.08	-*	-	-*
	night	18.58	-*	-	-*
	total	19.33	-*	-	-*
1997	day	-*			
	night	-*			
	total	-*			

* Incomplete Data

\- Data not available

Table A3. AVERAGE SEASONAL ASPHALT CONCRETE TEMPERATURE
(Columbiana Co.)
(deg C)

YEAR		SPRING	SUMMER	FALL	WINTER
1991	day				
	night				
	total				
1992	day				
	night				
	total				
1993	day				
	night				
	total				
1994	day			6.48*	0.42
	night			4.22*	-2.03
	total			5.34*	-0.80
1995	day	13.85	23.62*	6.92	-3.47*
	night	9.45	19.12*	4.74	-4.40*
	total	11.69	21.37*	5.83	-3.94*
1996	day				
	night				
	total				
1997	day				
	night				
	total				

* Incomplete Data
\- Data not available

Table A4. AVERAGE SEASONAL ASPHALT CONCRETE TEMPERATURE (Crawford Co.)
(deg C)

YEAR		SPRING	SUMMER	FALL	WINTER
1991	day				
	night				
	total				
1992	day	*	26.81	10.22	1.95
	night	*	26.78	10.14	2.06
	total	*	26.80	10.18	2.01
1993	day	18.68	30.75	10.61	-0.81
	night	17.61	28.85	9.81	-1.45
	total	18.15	29.80	10.21	-1.13
1994	day	20.01	29.33	13.32	2.55
	night	17.88	27.37	12.27	1.78
	total	18.95	28.35	12.80	2.17
1995	day	18.42	30.29	9.47	-1.40
	night	16.62	28.54	8.70	-1.60
	total	17.52	29.41	9.08	-1.50
1996	day	15.92	-*	-*	5.46
	night	14.41	-*	-*	4.97
	total	15.16	-*	-*	5.22
1997	day	20.90			
	night	18.98			
	total	19.94			

* Incomplete Data
\- Data not available

Table A5. AVERAGE SEASONAL ASPHALT CONCRETE TEMPERATURE (Knox Co.)
(deg C)

YEAR		SPRING	SUMMER	FALL	WINTER
1991	day			-*	3.50
	night			-*	2.84
	total			-*	3.17
1992	day	18.49	27.62	10.91	2.47
	night	16.66	27.69	10.80	2.35
	total	17.58	27.65	10.85	2.41
1993	day	19.04	30.59	11.37	-0.02
	night	18.60	30.24	11.16	-0.05
	total	18.82	30.42	11.27	-0.05
1994	day	19.54	28.67	13.30	2.70
	night	18.93	28.23	12.97	2.70
	total	19.24	28.45	13.14	2.70
1995	day	18.11	-*	-	-
	night	17.60	-*	-	-
	total	17.85	-*	-	-
1996	day	18.31	32.12	12.04	2.96
	night	17.97	31.83	11.82	2.97
	total	18.14	31.97	11.93	2.96
1997	day	15.60			
	night	15.08			
	total	15.34			

* Incomplete Data

\- Data not available

Table A6. AVERAGE SEASONAL ASPHALT CONCRETE TEMPERATURE (Licking Co.) (deg C)

YEAR		SPRING	SUMMER	FALL	WINTER
1991	day			-*	4.42
	night			-*	4.21
	total			-*	4.32
1992	day	18.03	25.73	11.18	2.92
	night	17.33	26.26	11.40	3.05
	total	17.68	25.99	11.29	2.98
1993	day	18.74	29.01	11.73	0.57
	night	17.85	28.15	11.42	0.35
	total	18.30	28.58	11.58	0.46
1994	day	19.35	27.30	13.81	3.70
	night	18.46	26.35	13.37	3.50
	total	18.91	26.82	13.59	3.60
1995	day	18.63	28.89	10.80	1.46
	night	17.85	28.27	10.63	1.48
	total	18.24	28.58	10.71	1.47
1996	day	17.60	28.27	10.99	3.78
	night	16.91	27.60	10.76	3.63
	total	17.26	27.94	10.87	3.71
1997	day	16.66			
	night	15.88			
	total	16.27			

* Incomplete Data

\- Data not available

Table A7. AVERAGE SEASONAL ASPHALT CONCRETE TEMPERATURE (Lucas Co.) (deg C)

YEAR		SPRING	SUMMER	FALL	WINTER
1991	day				
	night				
	total				
1992	day		25.70	-*	1.45
	night		24.85	-*	1.16
	total		25.28	-*	1.31
1993	day	17.33	27.70	10.42	-1.06
	night	17.07	27.35	10.24	-1.36
	total	17.20	27.52	10.33	-1.21
1994	day	18.79	26.77	12.32	2.29
	night	18.71	26.64	12.27	2.04
	total	18.75	26.70	12.29	2.16
1995	day	16.70	28.44	9.54	-0.18
	night	16.63	27.97	9.28	-0.18
	total	16.66	28.20	9.41	-0.18
1996	day	16.90	27.01	10.37	-
	night	15.89	25.49	10.17	-
	total	16.39	26.25	10.27	-
1997	day	-			
	night	-			
	total	-			

* Incomplete Data

\- Data not available

Table A8. AVERAGE SEASONAL ASPHALT CONCRETE TEMPERATURE (Wood 2 Co.)
(deg C)

YEAR		SPRING	SUMMER	FALL	WINTER
1991	day				
	night				
	total				
1992	day	-*	26.15	9.90	0.91
	night	-*	26.03	9.78	0.70
	total	-*	26.09	9.84	0.81
1993	day	18.68	29.78	9.69	-2.40
	night	16.81	27.88	8.89	-2.91
	total	17.74	28.83	9.29	-2.66
1994	day	20.06	29.33	13.19	2.08
	night	18.11	29.72	13.39	2.29
	total	19.08	29.53	13.29	2.19
1995	day	17.34			
	night	17.54			
	total	17.44			
1996	day				
	night				
	total				
1997	day				
	night				
	total				

* Incomplete Data
\- Data not available

Table A9. AVERAGE SEASONAL ASPHALT CONCRETE TEMPERATURE (Wood 8 Co.)
(deg C)

YEAR		SPRING	SUMMER	FALL	WINTER
1991	day				
	night				
	total				
1992	day	-*	25.60	-*	0.05
	night	-*	25.92	-*	-0.03
	total	-*	25.76	-*	0.01
1993	day	17.20	28.99	10.18	-*
	night	16.00	27.84	10.04	-*
	total	16.60	28.41	10.11	-*
1994	day	-*	29.09	13.01	1.89
	night	-*	28.71	12.79	1.72
	total	-*	28.90	12.90	1.81
1995	day	17.94	30.53	9.50	-0.88
	night	17.39	30.32	9.41	-0.88
	total	17.66	30.42	9.46	-0.88
1996	day	16.00	28.81	8.92	-0.23
	night	15.60	28.53	8.79	-0.33
	total	15.80	28.67	8.86	-0.28
1997	day	15.20			
	night	14.73			
	total	14.97			

* Incomplete Data
- Data not available

Table A10 AVERAGE MONTHLY ASPHALT CONCRETE TEMPERATURE (Adams Co.) (deg C)

YEAR		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
	day												
1991	night												
	total												
	day												
1992	night												
	total												
	day												-
1993	night												-
	total												-
	day	-	-	9.72	18.14	23.38	32.42	-	-	-	-	-	-
1994	night	-	-	9.06	17.30	22.30	31.22	-	-	-	-	-	-
	total	-	-	9.39	17.72	22.84	31.82	-	-	-	-	-	-
	day	-	-	--	-	-	32.54*	34.24	34.57	26.24	18.93	8.02	2.64
1995	night	-	-	--	-	-	31.47*	33.26	33.70	25.54	18.23	7.60	2.46
	total	-	-	--	-	-	32.00*	33.75	34.13	25.89	18.58	7.81	2.55
	day	1.19	3.24	8.11	15.74	-	-	-	-	-	-	7.90	5.69
1996	night	1.09	2.90	7.37	14.74	-	-	-	-	-	-	7.52	5.34
	total	1.14	3.07	7.74	15.24	-	--	-	-	-	-	7.71	5.51
	day	1.88	5.81	11.73	17.26	21.37	27.61						
1997	night	1.76	5.28	10.94	15.96	20.07	26.41						
	total	1.82	5.54	11.34	16.61	20.72	27.01						

* Incomplete Data
- Data not available

Table A11 AVERAGE MONTHLY ASPHALT CONCRETE TEMPERATURE (Athens Co.)
(deg C)

YEAR		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
	day												3.70*
1991	night												2.73*
	total												3.22*
	day	2.71	5.83	10.42	18.09	24.92	28.96	32.00	30.11	26.57	17.67	10.56	4.31
1992	night	1.68	4.38	8.32	15.08	21.39	26.98	30.69	28.83	25.38	16.52	10.00	3.94
	total	2.19	5.10	9.38	16.59	23.16	27.97	31.35	29.47	26.07	17.10	10.28	4.13
	day	4.49	2.83	7.86	16.32	25.92	31.44	36.10	34.03	26.42	17.05	9.79	3.86
1993	night	4.22	2.19	6.84	14.61	23.50	28.99	33.52	31.88	24.63	15.63	8.76	3.34
	total	4.36	2.51	7.35	15.46	24.71	30.22	34.81	32.96	25.53	16.34	9.28	3.60
	day	-	-	-	-	-	33.64	33.98	31.34	26.54	18.55	12.66	6.11
1994	night	-	-	-	-	-	30.86	31.38	29.08	24.27	16.78	11.38	5.51
	total	-	-	-	-	-	32.26	32.68	30.21	25.40	17.66	12.02	5.81
	day	2.14	2.26	12.43	18.17	23.24	31.58	35.83	35.83	26.52	18.72	7.56	2.19
1995	night	1.73	1.38	10.83	16.19	21.71	29.22	33.72	33.76	24.97	17.36	6.82	1.86
	total	1.93	1.82	11.62	17.18	22.73	30.40	34.77	34.80	25.75	18.04	7.19	2.02
	day	0.57	2.48	6.18	15.48	22.65	31.48	-	-	-	-	-	*
1996	night	0.45	2.16	5.67	14.33	21.14	29.02	-	-	-	-	-	*
	total	0.51	2.32	5.93	14.91	21.90	30.25	-	-	-	-	-	*
	day	2.74	*	-	-	-	-						
1997	night	2.52	*	-	-	-	-						
	total	2.63	*	-	-	-	-						

* Incomplete Data
- Data not available

Table A12 AVERAGE MONTHLY ASPHALT CONCRETE TEMPERATURE (Columbiana Co.) (deg C)

YEAR		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
	day												
1991	night												
	total												
	day												
1992	night												
	total												
	day												
1993	night												
	total												
	day												
1994	night											8.68*	3.13
	total											6.28*	0.85
	day											7.48*	1.99
1995	night	-1.57	-2.94	6.28	8.97	16.45	-	24.91*	25.37	18.14	13.82	2.58	-2.95
	total	-2.81	-5.28	2.42	5.42	11.84	-	20.50*	20.75	13.78	10.60	1.46	-4.24
	day	-2.19	-4.11	4.35	7.19	14.15	-	22.70*	23.06	15.96	12.21	2.02	-3.63
1996	night	-4.16	-2.30										
	total	-4.65	-3.21										
	day	-4.40	-2.76										
1997	night												
	total												

* Incomplete Data

\- Data not available

Table A13 AVERAGE MONTHLY ASPHALT CONCRETE TEMPERATURE (Crawford Co.) (deg C)

YEAR		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
	day												
1991	night												
	total												
	day			-	-	-	26.44	28.12	27.29	23.21	14.21	7.51	2.68
1992	night			-	-	-	26.23	28.02	27.39	23.07	14.12	7.44	2.73
	total			-	-	-	26.34	28.07	27.34	23.13	14.16	7.48	2.70
	day	2.22	1.17	4.21	12.85	23.29	27.35	32.88	32.07	23.36	15.60	7.11	2.17
1993	night	2.37	1.39	4.02	12.21	22.24	25.31	30.76	30.11	22.03	14.36	6.58	1.76
	total	2.30	1.28	4.12	12.53	22.77	26.33	31.82	31.09	22.70	14.98	6.85	1.96
	day	-3.60	-0.97	6.17	15.28	21.27	29.57	32.16	28.76	25.53	17.97	10.82	4.45
1994	night	-4.01	-1.49	4.75	13.55	18.87	27.38	29.89	26.99	23.66	16.43	9.97	3.98
	total	-3.80	-1.23	5.46	14.41	20.07	28.47	31.03	27.87	24.60	17.20	10.40	4.21
	day	0.80	-0.15	8.86	12.97	21.01	28.81	31.60	31.76	23.79	16.16	4.95	-1.26
1995	night	0.51	-0.87	7.33	11.39	18.87	26.88	29.48	30.18	22.32	15.17	4.45	-1.55
	total	0.65	-0.51	8.09	12.18	19.94	27.85	30.54	30.97	23.05	15.66	4.70	-1.40
	day	-3.05	-1.03	3.46	11.06	18.74	26.79	30.26	30.59*	-	16.46*	7.64	5.55
1996	night	-2.99	-1.24	2.43	9.79	17.06	25.10	28.34	28.60*	-	15.64*	6.99	5.22
	total	-3.02	-1.14	2.95	10.42	17.90	25.95	29.30	29.58*	-	16.05*	7.31	5.38
	day	1.84	5.92	11.95	18.13	21.46	30.23						
1997	night	1.61	5.33	11.02	16.19	19.41	28.14						
	total	1.73	5.63	11.48	17.16	20.44	29.18						

* Incomplete Data

\- Data not available

Table A14 AVERAGE MONTHLY ASPHALT CONCRETE TEMPERATURE (Knox Co.)
(deg C)

YEAR		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
	day												2.65*
1991	night												2.09*
	total												2.37*
	day	1.11	3.48	7.14	14.55	22.78	26.62	29.13	28.00	23.92	15.14	8.10	3.21
1992	night	0.73	2.75	6.00	12.73	20.28	26.23	29.15	28.12	23.94	15.05	8.06	2.99
	total	0.92	3.12	6.57	13.64	21.53	26.44	29.14	28.06	23.93	15.10	8.08	3.10
	day	2.70	1.71	5.25	13.45	23.01	27.38	32.51	31.75	23.92	15.74	8.36	3.04
1993	night	2.59	1.59	5.09	13.14	22.55	26.77	32.04	31.51	23.56	15.46	8.14	3.06
	total	2.64	1.65	5.17	13.29	22.78	27.08	32.27	31.63	23.74	15.60	8.25	3.05
	day	-2.66	-0.10	6.47	15.05	20.62	29.11	31.19	28.53	24.52	17.41	11.02	5.09
1994	night	-2.69	-0.08	6.13	14.76	19.91	28.39	30.56	28.13	24.08	16.92	10.72	5.00
	total	-2.67	-0.09	6.30	14.90	20.26	28.75	30.88	28.33	24.30	17.16	10.87	5.04
	day	0.98	-0.15	8.93	13.36	20.00	27.93	31.39	-*	-*	-*	-*	-*
1995	night	1.08	-0.07	8.65	12.96	19.33	27.41	30.91	-*	-*	-*	-*	-*
	total	1.03	-0.11	8.79	13.16	19.66	27.67	31.15	-*	-*	-*	-*	-*
	day	-	-	-*	13.90	20.78	30.06	34.14	32.74	24.43	17.53	7.90	5.02
1996	night	-	-	-*	13.65	20.41	29.69	33.85	32.35	24.30	17.24	7.70	4.90
	total	-	-	-*	13.77	20.59	29.88	34.00	32.55	24.37	17.38	7.80	4.96
	day	0.33	2.94	7.33	12.86	16.03	25.98						
1997	night	0.59	2.84	7.12	12.46	15.20	25.64						
	total	0.46	2.89	7.22	12.66	15.61	25.81						

* Incomplete Data

\- Data not available

Table A15 AVERAGE MONTHLY ASPHALT CONCRETE TEMPERATURE (Licking Co.)
(deg C)

YEAR		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
	day												4.49
1991	night												4.18
	total												4.34
	day	2.02	4.56	7.86	14.50	21.00	24.65	27.04	25.68	22.92	15.28	8.96	3.55
1992	night	1.92	4.31	7.48	13.67	19.88	24.79	27.49	26.34	23.39	15.62	9.12	3.58
	total	1.97	4.43	7.67	14.09	20.44	24.72	27.27	26.01	23.16	15.45	9.04	3.57
	day	3.30	1.88	5.64	13.69	22.30	26.46	30.83	29.67	23.18	15.60	9.15	3.42
1993	night	3.51	2.07	5.26	12.99	21.30	25.45	29.80	28.86	22.62	15.20	8.81	3.31
	total	3.40	1.97	5.45	13.34	21.80	25.91	30.31	29.26	22.90	15.40	8.98	3.37
	day	-2.54	1.32	6.89	15.47	20.29	28.10	29.39	27.27	23.56	17.42	12.05	6.23
1994	night	-2.72	1.17	6.35	14.82	19.20	27.14	28.33	26.34	22.75	16.79	11.67	6.04
	total	-2.63	1.24	6.62	15.15	19.74	27.62	28.86	26.80	23.16	17.10	11.86	6.14
	day	1.61	1.07	10.01	14.41	20.46	27.36	30.02	30.47	23.05	17.12	6.52	1.20
1995	night	1.60	0.92	9.53	13.73	19.53	26.51	29.22	29.92	22.60	16.85	6.44	1.23
	total	1.60	1.00	9.77	14.07	20.00	26.94	29.62	30.19	22.83	16.98	6.48	1.22
	day	0.01	1.68	6.12	13.77	19.95	26.82	29.29	29.02	22.90	16.25	6.30	5.04
1996	night	0.14	1.68	5.87	13.24	19.24	25.90	28.65	28.31	22.42	15.93	6.13	4.89
	total	0.08	1.68	6.00	13.50	19.60	26.35	28.97	28.66	22.65	16.09	6.21	4.96
	day	0.59	4.16	9.07	14.00	18.58	-*						
1997	night	0.74	3.87	8.67	13.27	17.66	-*						
	total	0.66	4.01	8.87	13.64	18.12	-*						

* Incomplete Data
- Data not available

Table A16 AVERAGE MONTHLY ASPHALT CONCRETE TEMPERATURE (Lucas Co.)
(deg C)

YEAR		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
	day												
1991	night												
	total												
	day						25.29	26.80	26.10	22.55		-	-*
1992	night						24.17	26.03	25.53	21.80		-	-*
	total						24.74	26.41	25.67	22.18		-	-*
	day	1.62	0.51	3.81	12.42	21.39	24.88	29.99	28.74	20.92	14.47	7.66	2.52
1993	night	1.36	0.11	2.92	12.20	21.13	24.54	29.60	28.36	20.79	14.28	7.40	2.40
	total	1.49	0.31	3.70	12.31	21.26	24.71	29.79	28.55	20.85	14.37	7.53	2.46
	day	-3.82	-1.05	5.55	14.41	20.35	27.77	29.26	25.73	23.50	16.24	10.29	4.50
1994	night	-4.09	-1.56	5.44	14.22	20.36	27.77	29.03	25.60	23.48	16.19	10.17	4.38
	total	-3.95	-1.31	5.50	14.32	20.35	27.71	29.14	25.66	23.49	16.22	10.23	4.43
	day	0.86	-0.05	7.38	11.18	19.44	26.52	29.74	30.03	22.07	16.05	5.55	0.34
1995	night	0.61	-0.30	7.16	11.18	19.19	26.30	29.18	29.59	21.59	15.76	5.37	0.12
	total	0.73	-0.17	7.27	11.13	19.31	26.41	29.46	29.81	21.83	15.90	5.46	0.23
	day	-1.63	-0.65	5.08	12.59	19.32	26.30	26.99	28.12	22.50	12.22	7.66	
1996	night	-1.74	-0.60	4.48	11.78	18.21	24.89	25.27	26.59	21.65	12.07	7.41	
	total	-1.69	-0.62	4.78	12.18	18.76	25.59	26.13	27.35	22.08	12.14	7.54	
	day	-	-	-	-	-	-						
1997	night	-	-	-	-	-	-						
	total	-	-	-	-	-	-						

* Incomplete Data
- Data not available

Table A17 AVERAGE MONTHLY ASPHALT CONCRETE TEMPERATURE (Wood 2 Co.)
(deg C)

YEAR		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
	day												
1991	night												
	total												
	day			-			25.90	27.12	26.60	22.92	13.92	7.11	2.34
1992	night			-			25.90	27.06	26.46	22.66	13.82	6.91	2.38
	total			-			25.90	27.09	26.53	22.79	13.87	7.01	2.36
	day	1.10	0.20	3.52	13.21	23.40	26.84	32.49	30.98	22.05	14.54	6.28	1.24
1993	night	0.97	0.03	2.62	11.49	21.17	24.89	30.31	29.03	20.73	13.34	5.70	0.90
	total	1.03	0.11	3.07	12.35	22.28	25.86	31.40	30.01	21.39	13.94	5.99	1.06
	day	-5.50	-2.46	4.59	14.14	22.17	31.06	31.99	27.98	26.11	17.90	10.52	4.25
1994	night	-5.58	-3.01	3.22	12.52	19.76	29.89	32.46	28.33	26.51	18.11	10.68	4.36
	total	-5.54	-2.74	3.90	13.33	20.97	30.48	32.22	28.16	26.31	18.01	10.60	4.31
	day	0.48	-0.29	8.04	12.46	21.27	26.02*						
1995	night	0.65	-0.06	8.29	12.62	21.37	26.31*						
	total	0.57	-0.17	8.16	12.54	21.32	26.17*						
	day												
1996	night												
	total												
	day												
1997	night												
	total												

* Incomplete Data
- Data not available

Table A18 AVERAGE MONTHLY ASPHALT CONCRETE TEMPERATURE (Wood 8 Co.)
(deg C)

YEAR		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
	day												
1991	night												
	total												
	day						25.43	26.64	26.12	22.19	-*	-	-*
1992	night						25.86	26.95	26.44	22.41	-*	-	-*
	total						25.65	26.80	26.28	22.30	-*	-	-*
	day	0.38	-0.91	2.21	11.91	21.68	25.34	31.45	30.52	21.82	14.98	6.86	1.79
1993	night	0.41	-0.94	1.69	10.79	20.28	24.11	30.04	29.32	21.29	14.78	6.77	1.71
	total	0.40	-0.93	1.95	11.35	20.98	24.72	30.74	29.92	21.56	14.88	6.81	1.75
	day	-*	-	-	-	-*	26.25	31.71	27.88	25.90	17.61	10.39	4.26
1994	night	-*	-	-	-	-*	25.78	31.33	27.56	25.50	17.23	10.24	4.17
	total	-*	-	-	-	-*	26.02	31.52	27.72	25.70	17.42	10.31	4.21
	day	0.48	-0.76	7.65	11.84	20.78	28.61	31.87	32.04	23.97	16.35	5.04	-0.47
1995	night	0.41	-0.92	7.29	11.33	20.05	28.17	31.57	31.86	23.88	16.26	4.97	-0.50
	total	0.45	-0.84	7.47	11.58	20.42	28.39	31.72	31.95	23.93	16.30	5.01	-0.48
	day	-2.10	-1.35	3.80	11.49	18.21	26.74	29.98	29.64	22.89	14.91	4.22	0.81
1996	night	-2.04	-1.34	3.50	11.18	17.74	26.41	29.68	29.33	22.72	14.78	4.08	0.69
	total	-2.07	-1.34	3.65	11.33	17.97	26.57	29.83	29.49	22.80	14.84	4.15	0.75
	day	-2.55	-0.26	4.92	12.08	15.82	25.80						
1997	night	-2.58	-0.42	4.74	11.60	15.28	25.34						
	total	-2.56	-0.34	4.83	11.84	15.55	25.57						

* Incomplete Data

\- Data not available

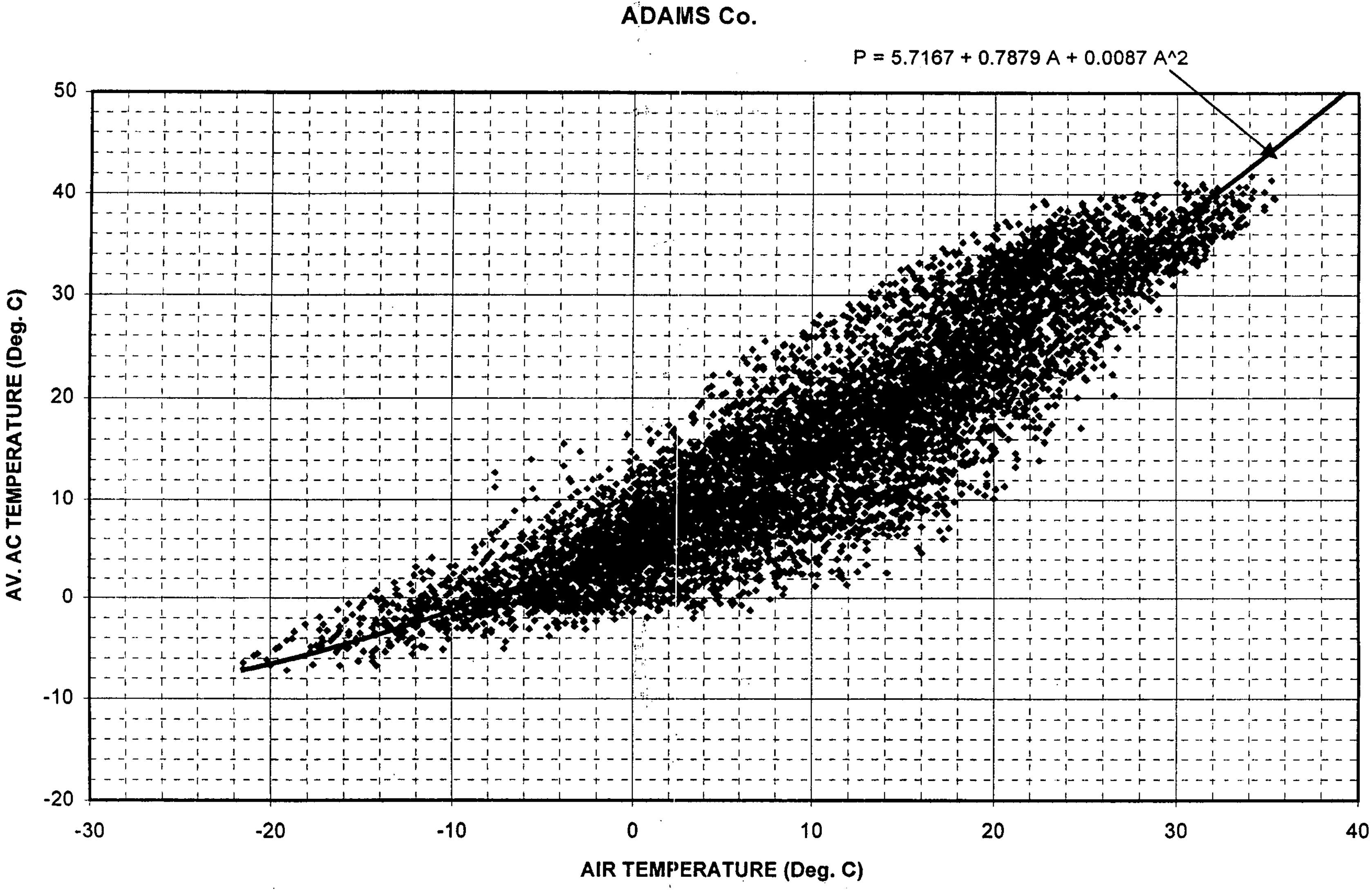
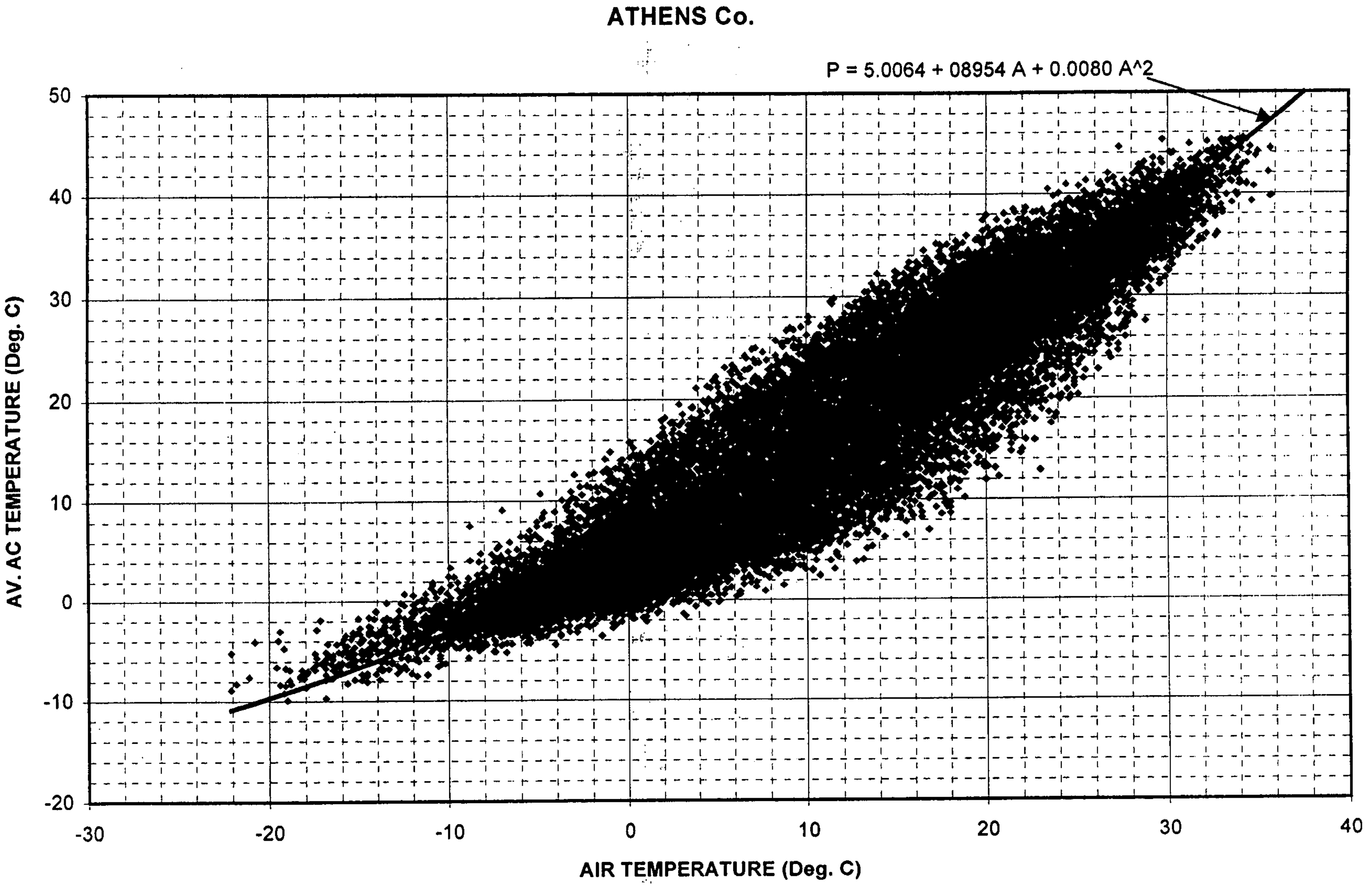


Figure A1 AIR TEMPERATURE vs. AVERAGE ASPHALT CONCRETE TEMPERATURE (Adams Co.)



ATHENS Co.

Figure A2 AIR TEMPERATURE vs. AVERAGE ASPHALT CONCRETE TEMPERATURE (Athens Co.)

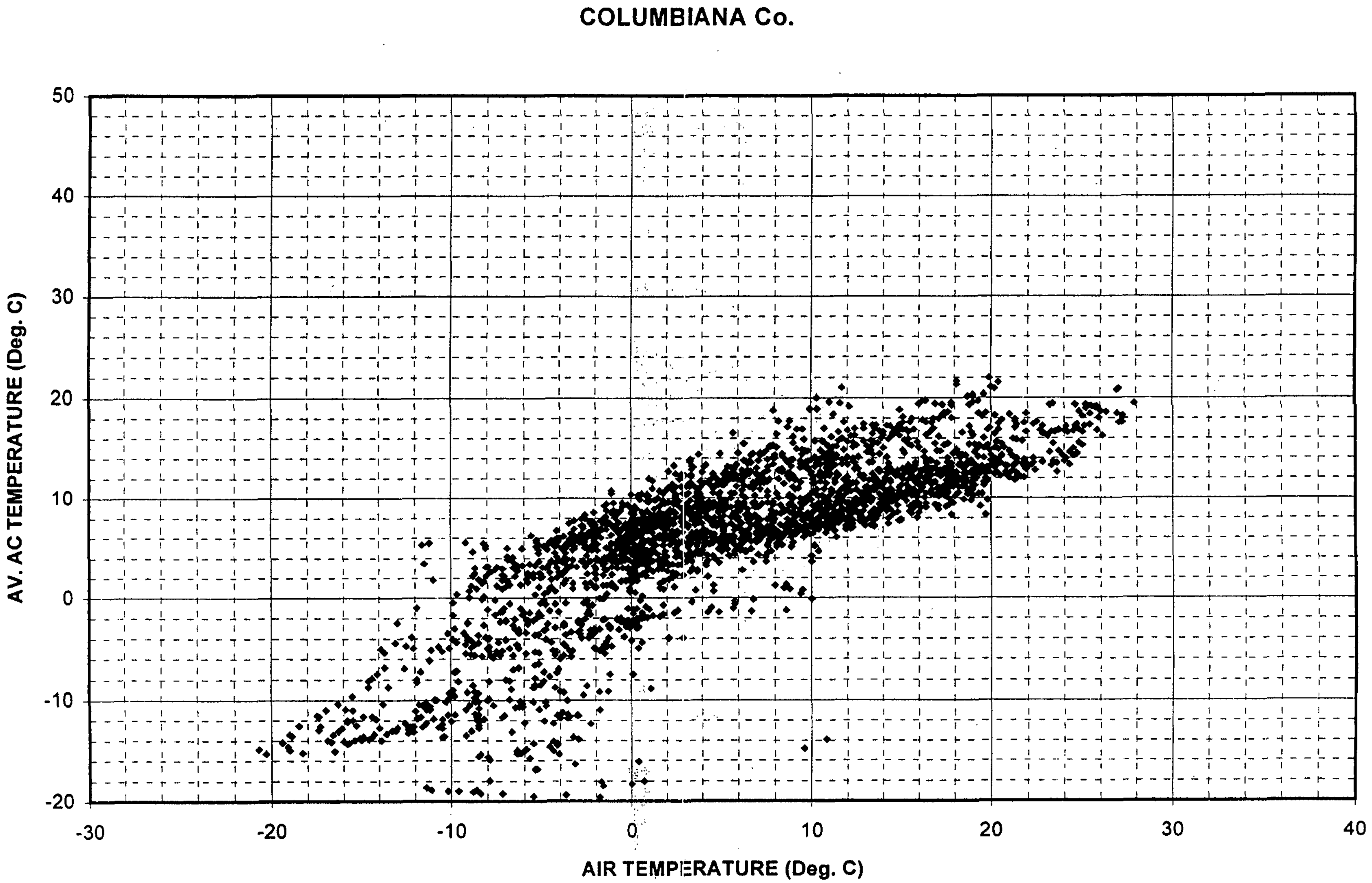


Figure A3 AIR TEMPERATURE vs. AVERAGE ASPHALT CONCRETE TEMPERATURE (Columbiana Co.)

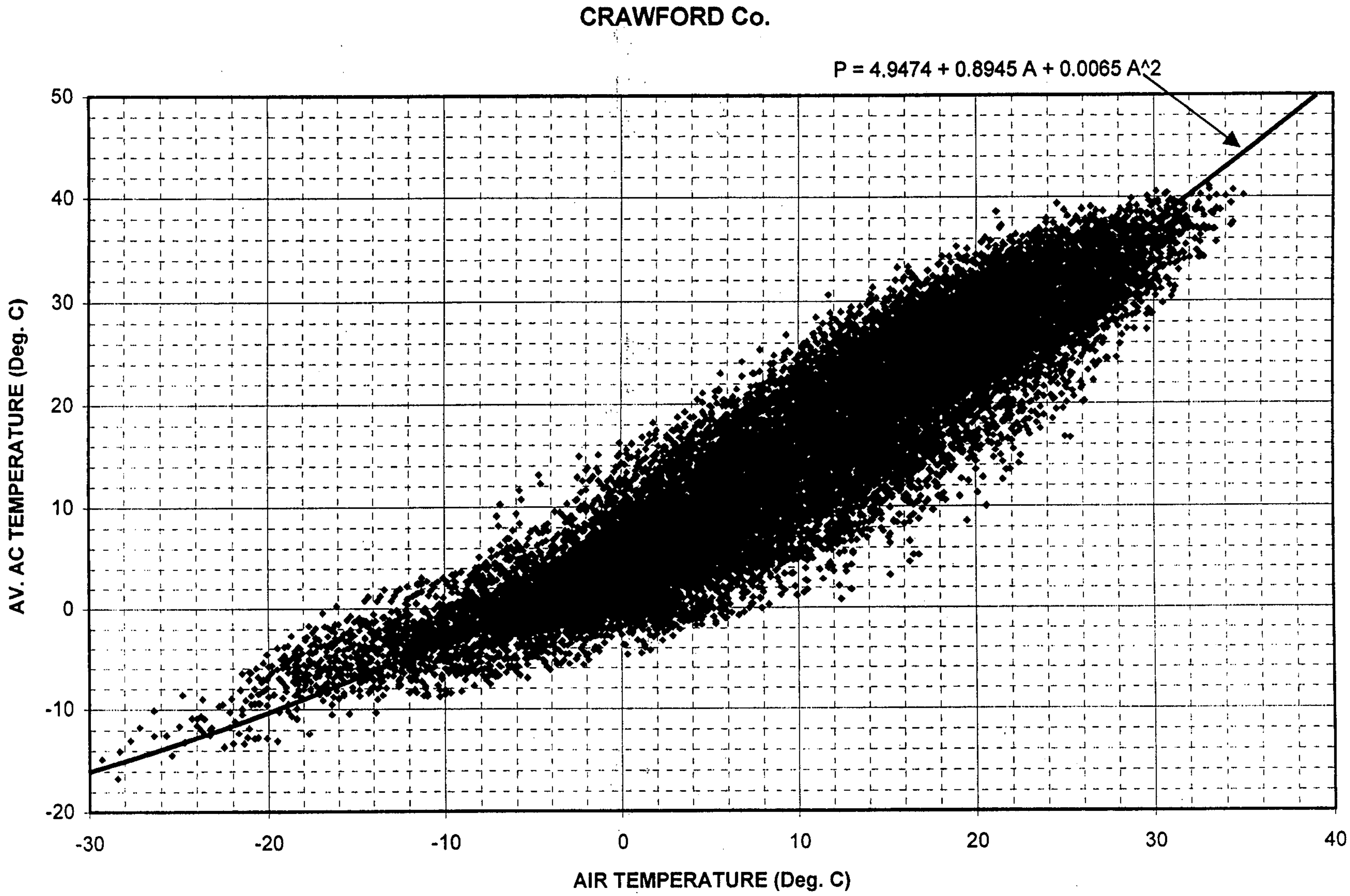


Figure A4 AIR TEMPERATURE vs. AVERAGE ASPHALT CONCRETE TEMPERATURE (Crawford Co.)

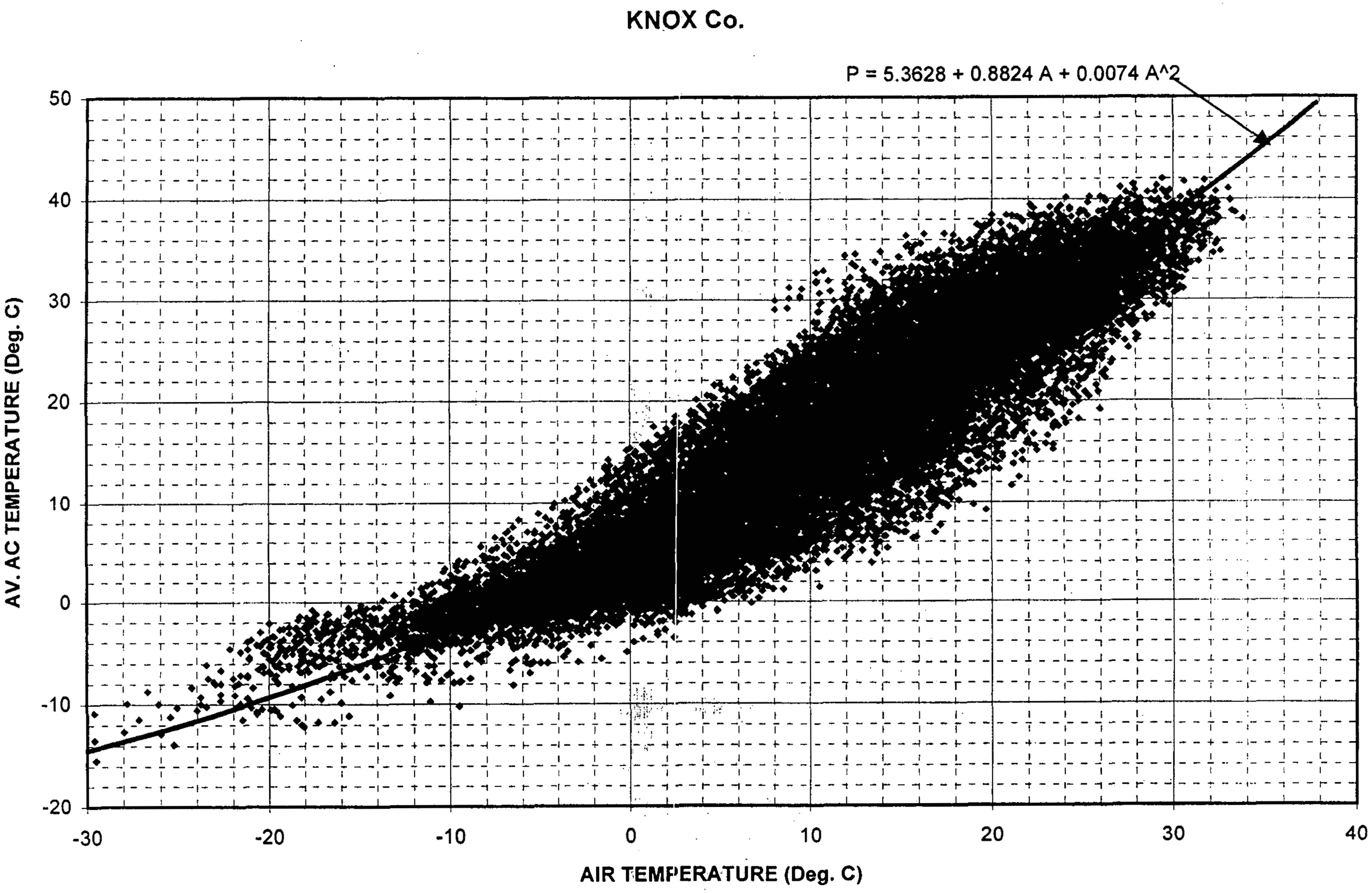


Figure A5 AIR TEMPERATURE vs. AVERAGE ASPHALT CONCRETE TEMPERATURE (Knox Co.)

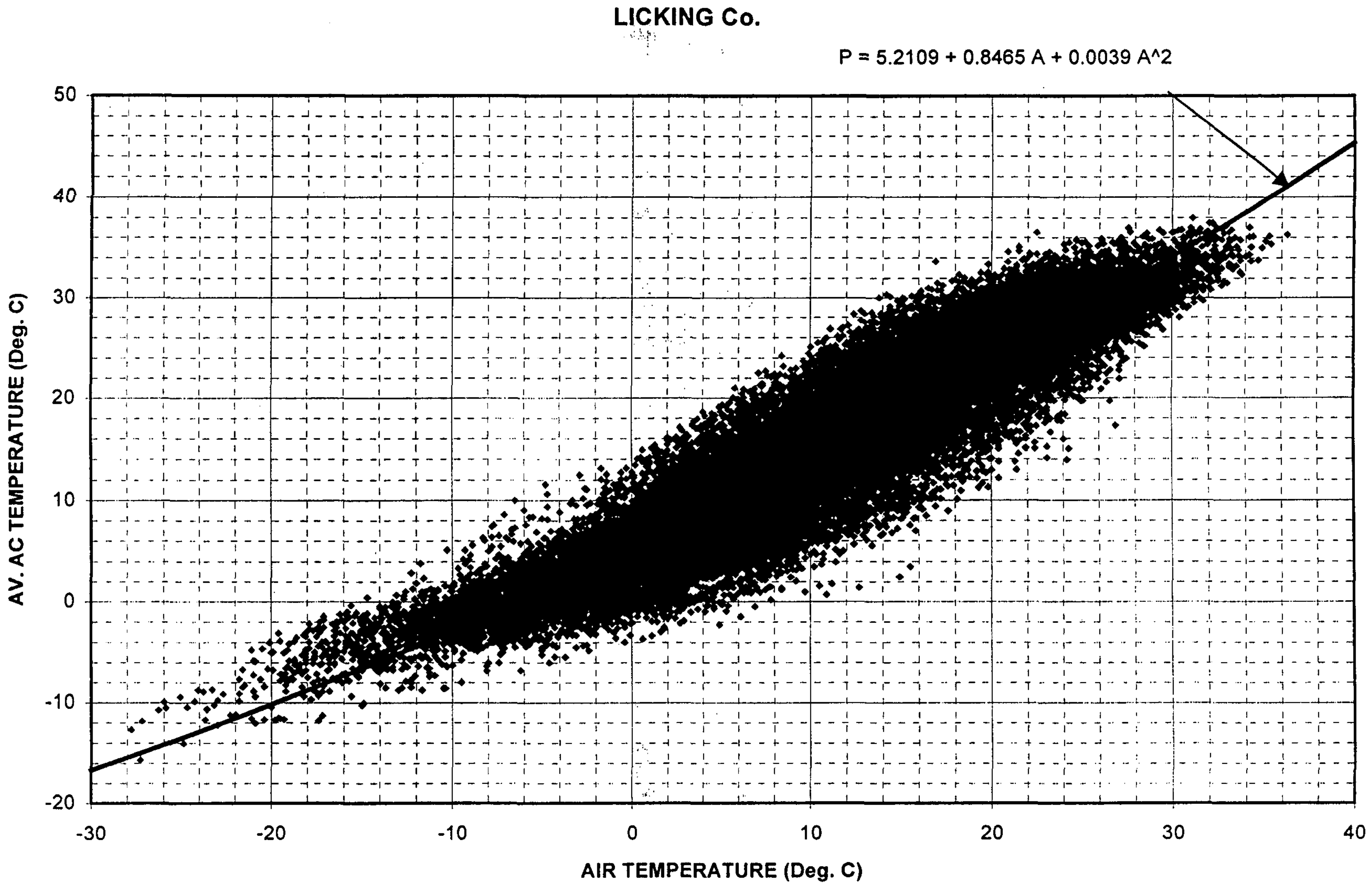


Figure A6 AIR TEMPERATURE vs. AVERAGE ASPHALT CONCRETE TEMPERATURE (Licking Co.)

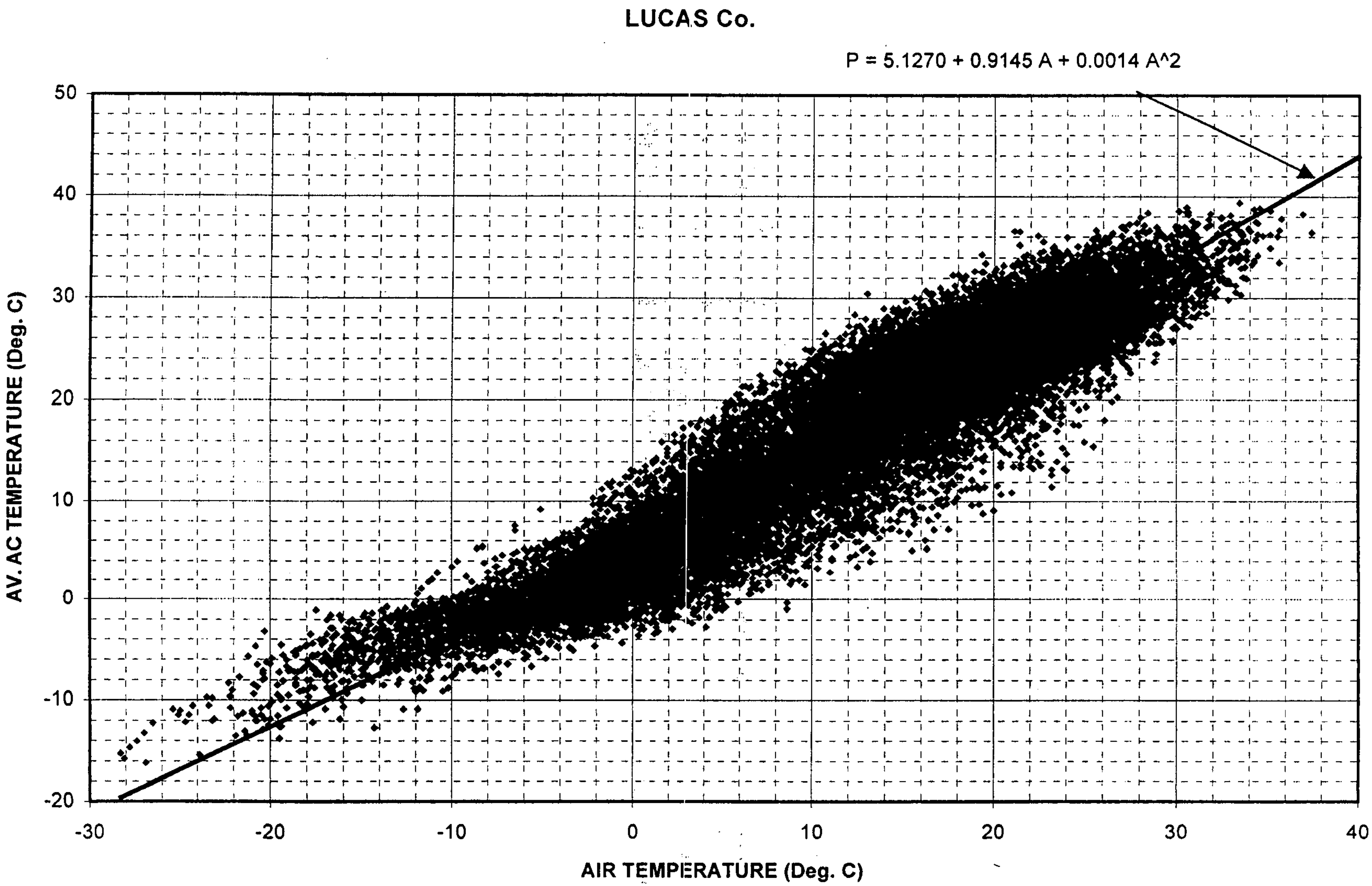


Figure A7 AIR TEMPERATURE vs. AVERAGE ASPHALT CONCRETE TEMPERATURE (Lucas Co.)

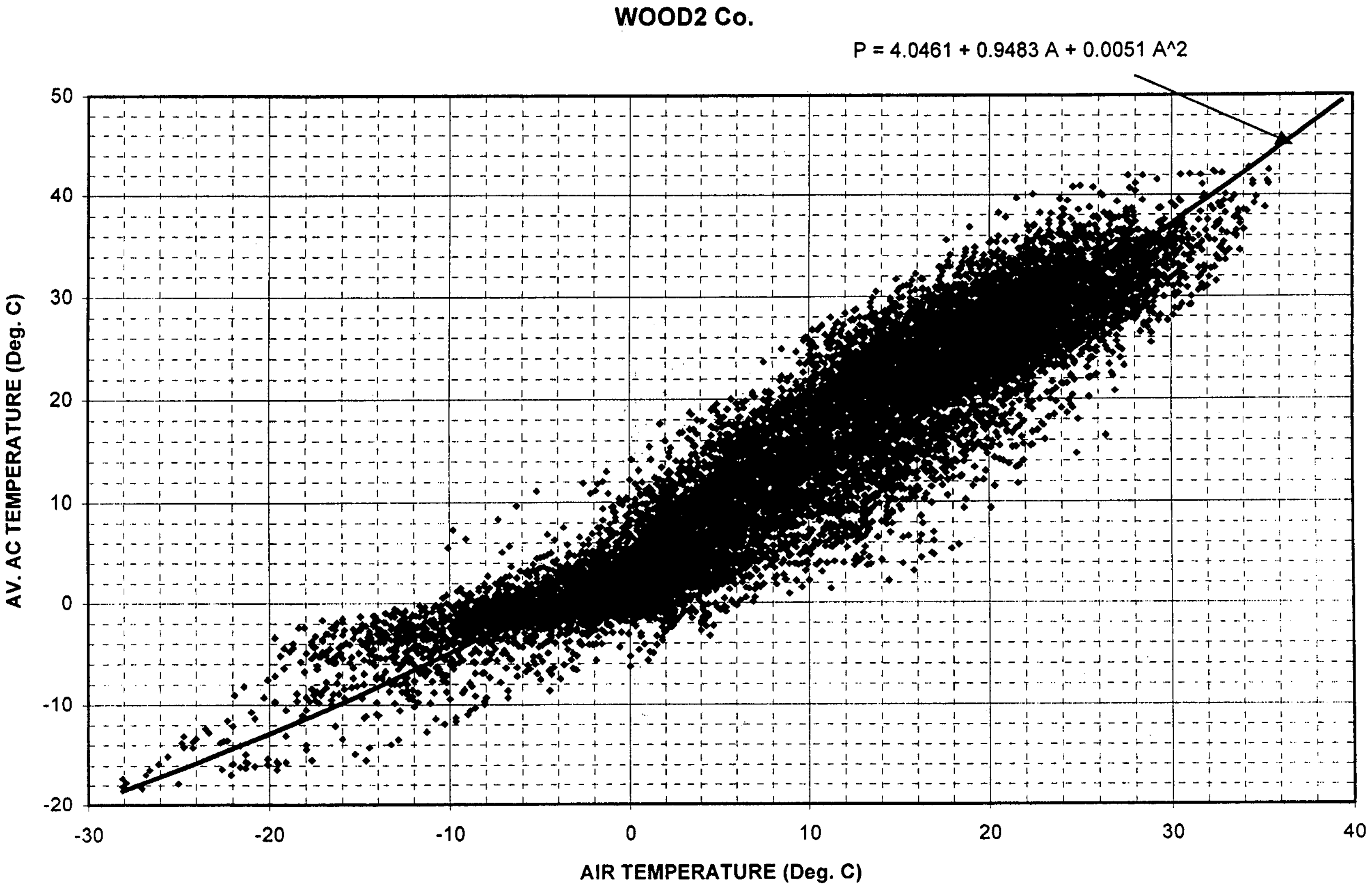


Figure A8 AIR TEMPERATURE vs. AVERAGE ASPHALT CONCRETE TEMPERATURE (Wood2 Co.)

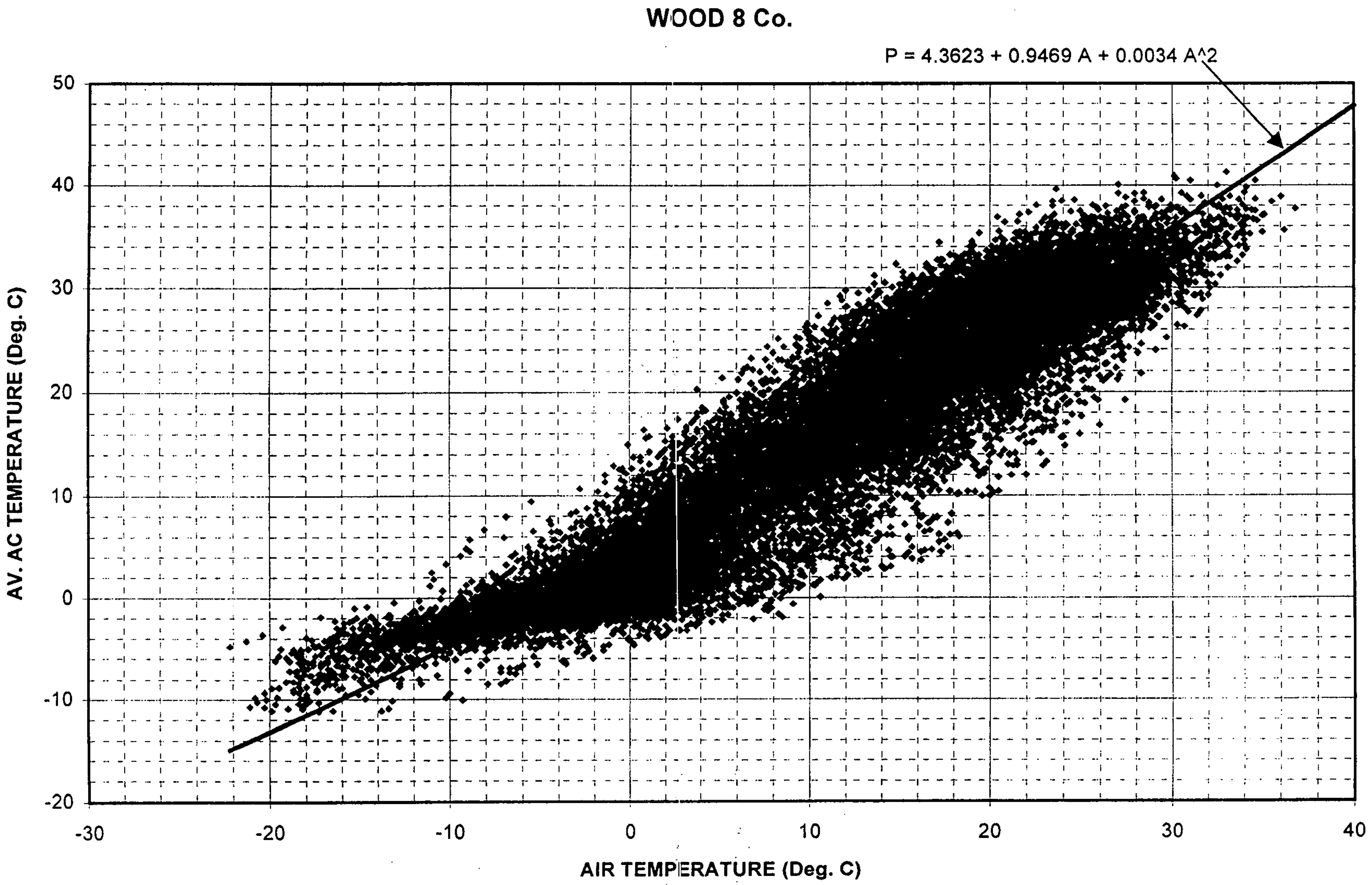


Figure A9 AIR TEMPERATURE vs. AVERAGE ASPHALT CONCRETE TEMPERATURE (Wood8 Co.)

Appendix B

DEPTH OF FROST PENETRATION AND NUMBER OF FREEZE-THAW CYCLES SUMMARY

Table B1. Frost Cycles and Frost Depth (Adams Co.)

SEASON	No. OF FROST CYCLES	MAX. FROST DEPTH(cm)
1991-1992		
1992-1993		
1993-1994	-*	-*
1994-1995	-*	-*
1995-1996	4	-67.06 (-2.20’)
1996-1997	3	-61.26 (-2.01’)
AVERAGE	4	-64.0 (-2.10’)

* Incomplete Data - Data not available

Table B2. Frost Cycles and Frost Depth (Athens Co.)

SEASON	No. OF FROST CYCLES	MAX. FROST DEPTH(cm)
1991-1992	5	-40.54 (-1.33’)
1992-1993	2	-33.22 (-1.09’)
1993-1994	6*	-46.33* (-1.52’)
1994-1995	8	-55.17 (-1.81’)
1995-1996	4	-66.75 (-2.19’)
1996-1997	-*	In AC
AVERAGE	4	-44.8 (-1.47’)

* Incomplete Data - Data not available

Table B3. Frost Cycles and Frost Depth (Crawford Co.)

SEASON	No. OF FROST CYCLES	MAX. FROST DEPTH(cm)
1991-1992		
1992-1993	9	-46.33 (-1.52’)
1993-1994	4	-95.71 (-3.14’)
1994-1995	15	-73.76 (-2.42’)
1995-1996	14	-85.04 (-2.79’)
1996-1997	5	-70.41 (-2.31’)
AVERAGE	6	-74.4 (-2.44’)

* Incomplete Data - Data not available

Table B4. Frost Cycles and Frost Depth (Knox Co.)

SEASON	No. OF FROST CYCLES	MAX. FROST DEPTH(cm)
1991-1992	3	-58.83 (-1.93’)
1992-1993	7	-43.59 (-1.43’)
1993-1994	11	-103.94 (-3.41’)
1994-1995	3	-96.01 (-3.15’)
1995-1996	-*	-*
1996-1997	2	-98.15 (-3.22’)
AVERAGE	7	-79.9 (-2.62’)

* Incomplete Data - Data not available

Table B5. Frost Cycles and Frost Depth (Licking Co.)

SEASON	No. OF FROST CYCLES	MAX. FROST DEPTH(cm)
1991-1992	5	-58.52 (-1.92')
1992-1993	5	-58.83 (-1.93')
1993-1994	9	-84.43 (-2.77')
1994-1995	5	-71.63 (-2.35')
1995-1996	13	-77.42 (-2.54')
1996-1997	5	-71.93 (-2.36')
AVERAGE	6	-70.4 (-2.31')

* Incomplete Data - Data not available

Table B6. Frost Cycles and Frost Depth (Lucas Co.)

SEASON	No. OF FROST CYCLES	MAX. FROST DEPTH(cm)
1991-1992		
1992-1993	17	-57.61 (-1.89')
1993-1994	2	-113.08 (-3.71')
1994-1995	15	-65.23 (-2.14')
1995-1996	14	-89.00 (-2.92')
1996-1997	-	-
AVERAGE	12	-81.1 (-2.66')

* Incomplete Data - Data not available

Table B7. Frost Cycles and Frost Depth (Wood 2 Co.)

SEASON	No. OF FROST CYCLES	MAX. FROST DEPTH(cm)
1991-1992		
1992-1993	34	-54.86 (-1.80')
1993-1994	7	120.09 (-3.94')
1994-1995	13	-52.12 (-1.71')
1995-1996		
1996-1997		
AVERAGE	18	-75.59 (-2.48')

* Incomplete Data - Data not available

Table B8. Frost Cycles and Frost Depth (Wood 8 Co.)

SEASON	No. OF FROST CYCLES	MAX. FROST DEPTH(cm)
1991-1992		
1992-1993	18	-66.14 (-2.17')
1993-1994	2	-74.37* (-2.44')
1994-1995	7	-92.35 (-3.03')
1995-1996	5	-79.86 (-2.62')
1996-1997	3	-75.29 (-2.47')
AVERAGE	6	-77.7 (-2.55')

* Incomplete Data - Data not available

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Appendix C

MONTHLY AND SEASONAL RAINFALL AND DEGREE OF SATURATION SUMMARIES

Table C1 SEASONAL RAINFALL (Adams Co.)
(cm)

YEAR	SPRING	SUMMER	FALL	WINTER
1991				
1992				
1993				
1994	29.08	4.88*	-	-
1995	1.35*	15.75	16.56	25.91
1996	43.66	13.06	18.72	34.54
1997	17.60			

* Incomplete Data
- Data not available

Table C2 SEASONAL RAINFALL (Athens Co.)
(cm)

YEAR	SPRING	SUMMER	FALL	WINTER
1991				18.26
1992	30.81	29.08	21.29	23.06
1993	24.87	16.59	25.60	5.92*
1994	7.29*	38.13	17.91	23.39
1995	31.32	32.21	24.92	29.18
1996	46.56	-	-	35.76
1997	25.65			

* Incomplete Data
- Data not available

Table C3 SEASONAL RAINFALL (Columbiana Co.)
(cm)

YEAR	SPRING	SUMMER	FALL	WINTER
1991				
1992				
1993				
1994			14.48*	11.51
1995	29.92	3.00*		
1996				
1997				

* Incomplete Data
- Data not available

Table C4 SEASONAL RAINFALL (Crawford Co.)
(cm)

YEAR	SPRING	SUMMER	FALL	WINTER
1991				
1992	8.51*	41.17	25.22	22.45
1993	26.37	11.73	34.16	10.29
1994	23.55	20.14	20.19	19.23
1995	25.81	31.01	24.43	19.05
1996	40.49	17.22*	25.32*	5.36
1997	31.24			

* Incomplete Data
- Data not available

Table C5 SEASONAL RAINFALL (Knox Co.)
(cm)

YEAR	SPRING	SUMMER	FALL	WINTER
1991				15.21
1992	21.28*	45.80	23.90	20.12
1993	24.54	23.67	21.67	14.00
1994	26.75	25.96	17.27	14.83
1995	32.28	26.03*	-	-
1996	42.62	19.46	20.09	22.23
1997	32.77			

* Incomplete Data
- Data not available

Table C6 SEASONAL RAINFALL (Licking Co.)
(cm)

YEAR	SPRING	SUMMER	FALL	WINTER
1991			2.31*	16.10
1992	14.66	-*	17.93	22.61
1993	28.58	11.51	17.93	10.59
1994	20.70	23.67	12.04	18.97
1995	27.66	18.69	22.02	27.46
1996	50.55	25.27	-	10.16
1997	22.58*			

* Incomplete Data
- Data not available

Table C7 SEASONAL RAINFALL (Lucas Co.)
(cm)

YEAR	SPRING	SUMMER	FALL	WINTER
1991				
1992	3.99*	28.80*	13.34*	19.30
1993	20.98	18.11	7.85	9.17
1994	4.72	17.75	16.71	10.77
1995	22.50	19.53	14.05	-
1996	-	-	28.80	-
1997	15.95			

* Incomplete Data
- Data not available

Table C8 SEASONAL RAINFALL (Wood 2 Co.)
(cm)

YEAR	SPRING	SUMMER	FALL	WINTER
1991				
1992	4.27*	36.50	24.08	21.82
1993	26.37	12.09	17.19*	-
1994	-	-	15.62	11.30
1995	19.51			
1996				
1997				

* Incomplete Data
- Data not available

Table C9 SEASONAL RAINFALL (Wood 8 Co.)
(cm)

YEAR	SPRING	SUMMER	FALL	WINTER
1991				
1992	3.53*	38.15	3.91*	18.57
1993	23.72	16.46	5.31*	-
1994	1.83*	20.19	15.54	11.99
1995	22.63	22.58	12.22	7.87
1996	*	*	23.90	22.58
1997	25.12			

* Incomplete Data
- Data not available

Table C10 MONTHLY RAINFALL (Adams Co.)
(cm)

YEAR	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.
1991												
1992												
1993												
1994			3.81*	17.20	5.46	6.71	0.79*	-	-	-	-	-
1995	-	-	-	-	-	2.26*	3.28	8.86	2.77	6.15	5.11	5.69
1996	12.42	6.81	8.84	12.60	27.53	1.12	10.16	2.69	0.05	3.84	9.47	7.29
1997	6.53	4.70	25.04	2.77	10.74	4.37						

* Incomplete Data
\- Data not available

Table C11 MONTHLY RAINFALL (Athens Co.)
(cm)

YEAR	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.
1991												
1992	3.40	4.55	10.85	7.34	11.71	8.92	19.25	6.43	5.99	3.73	8.79	6.27
1993	8.20	5.94	12.01	7.62	8.03	9.70	4.52	2.95	12.75	9.78	9.80	4.55
1994	5.38*	-	-	-	3.43*	9.78	16.13	13.61	3.45	4.11	5.82	7.19
1995	12.40	5.92	5.66	6.35	20.04	12.98	7.49	10.69	5.84	11.02	6.43	7.21
1996	11.18	7.14	12.85	10.80	17.53	19.30	-	-	-	-	-	-
1997	7.29	5.31	24.61	3.86	12.83	5.79						

* Incomplete Data
- Data not available

Table C12 MONTHLY RAINFALL (Columbiana Co.)
(cm)

YEAR	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.
1991												
1992												
1993												
1994									-	-	7.98	6.58
1995	4.62	3.56	3.94	7.67	15.67	5.64	2.82*	.18*	0.00*			
1996												

* Incomplete Data
\- Data not available

Table C13 MONTHLY RAINFALL (Crawford Co.)
(cm)

YEAR	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.
1991												
1992						10.41*	23.19	10.64	7.01	5.66	15.62	3.81
1993	11.10	4.27	8.71	11.84	4.78	7.70	5.03	2.39	8.56	8.81	14.78	5.33
1994	6.35	1.70	4.52	12.37	5.00	11.15	0.86	7.21	6.65	1.47	9.27	8.15
1995	8.79	4.50	6.12	13.89	8.28	10.82	11.79	8.66	2.92	12.29	9.83	2.03
1996	8.36	5.72	7.82	15.06	12.55	12.27	13.11	1.85*	-	4.78*	14.25	7.98
1997	2.97	0.58	2.36	4.32	18.57	10.67						

* Incomplete Data
\- Data not available

Table C14 MONTHLY RAINFALL (Knox Co.)
(cm)

YEAR	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.
1991												1.60*
1992	3.84	2.79	9.55	6.20	8.94	5.51*	24.51	14.83	11.53	3.56	11.63	2.74
1993	10.03	2.39	9.96	10.06	5.18	12.80	12.55	1.42	6.17	4.24	8.66	5.49
1994	7.59	3.30	5.51	10.95	5.13	14.68	8.71	9.83	3.20	1.83	7.29	6.17
1995	9.86	1.85	3.35	8.74	14.35	16.59	11.58	6.60*	-	-	-	-
1996	-	-	2.13*	15.34	16.31	9.86	7.47	4.52	7.14	4.11	7.14	10.44
1997	5.44	4.83	11.07	3.78	20.90	7.34						

* Incomplete Data
- Data not available

Table C15 MONTHLY RAINFALL (Licking Co.)
(cm)

YEAR	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.
1991												4.78*
1992	3.94	2.13	10.52	8.10	1.83	2.34	-*	8.86	5.56	4.06	9.65	4.37
1993	8.92	3.86	12.12	10.85	7.32	11.28	5.26	1.22	0.05	2.01	10.72	5.21
1994	5.23	1.57	6.43	12.57	4.11	9.12	13.00	2.90	0.08	1.14	6.45	4.47
1995	10.85	3.76	4.57	8.69	12.17	9.27	5.97	7.67	2.79	11.68	6.60	3.66
1996	10.49	7.26	11.84	17.73	18.26	12.57	14.76	2.77	11.40	4.52	-	2.97*
1997	4.14	2.77	2.67	4.14	12.47	3.58*						

* Incomplete Data
- Data not available

Table C16 MONTHLY RAINFALL (Lucas Co.)
(cm)

YEAR	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.
1991												
1992						4.14*	18.54	4.04	11.13	8.26*	-	3.78
1993	8.26	1.45	9.98	7.80	2.49	8.99	3.86	4.39	7.70	0.53	4.45	2.57
1994	3.99	1.32	5.28	0.03*	0.08*	8.84	6.53	5.31	2.39	0.18	7.39	7.75
1995	6.12	0.56	3.86	9.58	6.86	12.75	5.97	4.09	3.18	11.61	1.57	-
1996	-	-	-	-	-	-	-	-	6.55	12.45	8.15	5.08
1997	-	-	1.50	3.28	11.15	2.29						

* Incomplete Data
- Data not available

Table C17 MONTHLY RAINFALL (Wood 2 Co.)
(cm)

YEAR	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.
1991												
1992						4.57	20.29	7.26	13.84	5.08	11.58	9.88
1993	6.73	0.91	9.55	10.49	4.27	10.21	5.61	3.48	1.88	4.50	-	12.17*
1994	-	-	-	-	-	-	-	-	0.86	2.34	7.75	4.95
1995	5.66	3.23	3.20	9.93	8.23	0.28*						
1996												

* Incomplete Data
- Data not available

Table C18 MONTHLY RAINFALL (Wood 8 Co.)
(cm)

YEAR	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.
1991												
1992						3.81	19.53	6.60	16.48	5.18*	-	7.24*
1993	7.59	1.52	5.13	9.58	3.89	9.68	5.33	1.70	11.18	0.15	1.04	0.03*
1994	-	-	-	-	0.66*	8.36	2.72	10.21	0.89	2.95	5.99	6.05
1995	5.28	3.33	3.66	10.77	8.23	13.94	5.64	5.00	1.65	4.37	7.01	0.79
1996	5.28	2.01	-	-	-	-	6.10	-	-	4.09	7.06	7.01
1997	5.33	9.86	7.80	3.33	13.67	8.20*						

* Incomplete Data
Data not available

Table C19 Monthly Degree of Saturation-Adams Co.

	Sr1	Sr2	Sr3	Sr4
Jun-95	99.97		98.90	100.00
Jul-95	99.77		97.08	100.00
Aug-95	98.30		95.78	99.55
Sep-95	98.41		97.51	100.00
Oct-95	98.47		98.64	99.94
Nov-95	99.46		98.88	100.00
Dec-95	98.82		98.85	99.36
Jan-96	98.87		98.89	99.60
Feb-96	98.28		98.15	98.67
Mar-96	98.13		98.17	98.80
Apr-96	99.38		99.76	99.86
May-96	98.81		99.50	99.98
Jun-96				
Jul-96				
Aug-96				
Sep-96				
Oct-96	99.78		99.41	97.32
Nov-96	99.37		98.83	97.05
Dec-96	99.28		98.51	96.92
Jan-97	98.79		97.78	94.46
Feb-97	97.99		97.60	96.27
Mar-97	98.42		97.61	95.89
Apr-97	99.51		98.25	96.70
May-97	99.00		97.53	92.06
Jun-97	98.57		97.37	

Table C20 Monthly Degree of Saturation-Athens Co.

	Sr1	Sr2	Sr3	Sr4
Dec-91	97.79	98.55	98.84	98.95
Jan-92	98.58	99.00	99.44	99.50
Feb-92	98.56	99.00	99.39	99.58
Mar-92	98.42	98.83	99.11	99.40
Apr-92	98.61	98.98	99.25	99.48
May-92	98.76	99.19	99.63	99.69
Jun-92	99.31	99.19	98.81	98.19
Jul-92	99.45	99.16	98.75	96.97
Aug-92	99.75	99.60	99.91	99.25
Sep-92	98.33	97.75	100.00	99.52
Oct-92	98.80	98.39	100.00	99.99
Nov-92	99.71	99.38	100.00	99.96
Dec-92	99.10	98.78	100.00	99.22
Jan-93	98.72	98.35	99.81	98.56
Feb-93	98.88	98.51	99.94	98.41
Mar-93	99.53	99.14	100.00	99.11
Apr-93	99.36	98.85	100.00	99.45
May-93	98.58	97.85	100.00	99.99
Jun-93	97.26	96.27	99.80	99.61
Jul-93	96.54	95.49	99.84	99.50
Aug-93	96.23	95.17	99.99	99.80
Sep-93	96.96	96.19	100.00	100.00
Oct-93	97.89	97.46	100.00	99.99
Nov-93	98.42	98.17	100.00	99.95
Dec-93	98.74	98.54	99.93	99.46
Jan-94	99.07	98.97	99.73	99.26
Feb-94				
Mar-94				
Apr-94				
May-94	97.76	97.25	98.69	
Jun-94	97.69	97.12	98.99	
Jul-94	97.93	97.09	99.56	
Aug-94	98.00	97.12	99.96	
Sep-94	98.06	97.31	99.99	
Oct-94	99.13	98.46	100.00	
Nov-94	100.00	99.94	100.00	
Dec-94	99.82	99.67	100.00	
Jan-95	99.99	99.97	99.99	
Feb-95	99.98	99.95	99.40	
Mar-95	99.94	99.97	100.00	
Apr-95	99.35	99.88	100.00	
May-95	98.52	99.94	100.00	
Jun-95	98.34	99.99	100.00	
Jul-95	98.33	99.99	100.00	
Aug-95	99.62	99.58	100.00	
Sep-95	99.21	98.83	100.00	
Oct-95	100.00	99.92	100.00	
Nov-95	100.00	100.00	100.00	
Dec-95	99.74	99.25	98.29	
Jan-96	98.98	99.30	94.63	
Feb-96	99.42	99.32	96.06	
Mar-96	98.99	99.34	96.94	
Apr-96	100.00	99.99	99.69	
May-96	100.00	99.92	100.00	
Jun-96	100.00	100.00	100.00	
Jul-96	100.00	100.00	100.00	
Aug-96				
Sep-96				
Oct-96				
Nov-96				
Dec-96	99.07	99.71	98.63	
Jan-97	96.54	99.80	95.73	
Feb-97	94.98	99.85	95.18	

Table C21 Monthly Degree of Saturation-Columbiana Co.

	Sr1	Sr2	Sr3	Sr4
Nov-94	100.00	99.98	99.10	98.93
Dec-94	99.28	99.18	97.65	97.36
Jan-95	97.59	96.27	96.83	96.85
Feb-95	96.43	95.96	94.83	91.10
Mar-95	98.50	98.37	99.18	99.26
Apr-95	99.92	99.84	99.93	99.97
May-95	99.87	99.40	99.83	99.95
Jun-95	99.96	98.90	99.97	100.00
Jul-95	100.00	99.03	99.85	100.00
Aug-95	100.00	99.30	99.86	100.00
Sep-95	99.97	99.29	99.64	99.99
Oct-95	99.94	99.46	99.76	99.99
Nov-95	99.61	99.00	97.60	98.32
Dec-95	97.97	96.84	94.79	95.96
Jan-96	95.17	95.25	91.08	94.15
Feb-96	93.58	93.24	90.78	93.03

Table C22 Monthly Degree of Saturation-Crawford Co.

	Sr1	Sr2	Sr3	Sr4
Jun-92	98.21	97.47	99.76	94.72
Jul-92	98.49	98.24	99.90	95.09
Aug-92	98.84	98.49	99.79	95.91
Sep-92	99.17	98.84	99.86	97.29
Oct-92	99.30	98.99	99.99	98.71
Nov-92	99.38	99.05	99.99	99.21
Dec-92	99.45	99.21	99.99	99.35
Jan-93	98.75	98.51	99.38	98.82
Feb-93	99.04	98.66	99.65	98.43
Mar-93	97.89	97.24	98.36	97.70
Apr-93	98.78	98.18	99.43	99.06
May-93	99.36	99.00	99.77	98.34
Jun-93	99.35	99.33	99.75	97.57
Jul-93	99.36	99.73	99.85	97.09
Aug-93	99.29	99.72	99.80	96.26
Sep-93	99.17	99.46	99.71	96.06
Oct-93	98.72	99.27	99.64	96.76
Nov-93	98.55	99.19	99.66	97.66
Dec-93	98.19	98.85	99.35	97.34
Jan-94	98.52	98.68	92.75	88.98
Feb-94	96.25	96.22	84.45	89.14
Mar-94	97.35	98.09	98.45	96.88
Apr-94	97.64	98.47	98.85	97.26
May-94	97.89	98.83	98.85	96.99
Jun-94	98.51	99.47	97.81	97.33
Jul-94	99.37	99.98	97.62	97.94
Aug-94	99.99	100.00	99.07	99.55
Sep-94	100.00	100.00	99.60	99.78
Oct-94	99.98	100.00	99.82	99.82
Nov-94	99.93	99.99	99.93	99.93
Dec-94	99.70	99.97	99.68	99.60

	Sr1	Sr2	Sr3	Sr4
Jan-95	99.19	99.81	99.06	98.58
Feb-95	98.53	99.42	97.83	92.99
Mar-95	99.04	99.88	98.95	98.76
Apr-95	99.73	99.94	99.64	99.24
May-95	99.98	100.00	99.95	99.85
Jun-95	100.00	100.00	100.00	99.99
Jul-95	100.00	100.00	100.00	99.96
Aug-95	100.00	100.00	100.00	99.80
Sep-95	100.00	100.00	100.00	99.82
Oct-95	99.97	100.00	99.99	99.90
Nov-95	99.90	100.00	100.00	99.97
Dec-95	98.75	99.32	98.60	97.77
Jan-96	97.45	98.93	94.98	95.03
Feb-96	96.53	99.02	93.85	95.88
Mar-96	97.90	99.73	95.96	97.79
Apr-96	99.82	100.00	98.64	99.77
May-96	99.95	100.00	99.87	99.99
Jun-96	100.00	100.00	100.00	100.00
Jul-96	100.00	100.00	100.00	100.00
Aug-96	100.00	100.00	100.00	100.00
Sep-96				
Oct-96	99.98	100.00	100.00	99.99
Nov-96	99.87	99.94	99.73	99.91
Dec-96	99.25	99.59	99.19	99.60
Jan-97	99.17	99.51	98.82	96.50
Feb-97	97.93	99.19	97.62	98.48
Mar-97	98.73	99.87	99.54	99.74
Apr-97	99.50	99.99	100.00	100.00
May-97	99.90	99.97	99.99	100.00
Jun-97	99.97	99.99	99.99	100.00

Table C23 Monthly Degree of Saturation-Knox Co.

	Sr1	Sr2	Sr3	Sr4
Dec-91	100.00	100.00	100.00	100.00
Jan-92	100.00	100.00	100.00	100.00
Feb-92	100.00	100.00	100.00	100.00
Mar-92	100.00	100.00	100.00	100.00
Apr-92	100.00	100.00	100.00	100.00
May-92	100.00	100.00	98.93	100.00
Jun-92	100.00	100.00	100.00	100.00
Jul-92	99.35	99.39	99.83	99.80
Aug-92	99.37	99.34	99.87	99.80
Sep-92	99.99	99.98	100.00	99.89
Oct-92	100.00	100.00	100.00	99.83
Nov-92	100.00	100.00	100.00	99.77
Dec-92	100.00	100.00	100.00	99.84
Jan-93	99.99	99.99	100.00	99.87
Feb-93	99.98	99.98	100.00	99.82
Mar-93	99.95	99.91	99.98	99.82
Apr-93	100.00	99.98	100.00	100.00
May-93	100.00	100.00	100.00	100.00
Jun-93	100.00	100.00	100.00	99.85
Jul-93	100.00	99.97	99.77	99.28
Aug-93	100.00	100.00	99.94	99.57
Sep-93	100.00	99.93	99.95	99.99
Oct-93	100.00	99.59	99.96	100.00
Nov-93	100.00	99.97	100.00	100.00
Dec-93	99.99	99.97	99.98	99.89
Jan-94	99.76	99.44	98.61	91.64
Feb-94	98.74	98.50	99.55	97.88
Mar-94	98.41	98.11	99.91	99.89
Apr-94	99.60	99.56	100.00	100.00
May-94	99.68	99.99	100.00	99.98
Jun-94	98.37	99.10	100.00	99.88
Jul-94	97.54	99.88	100.00	99.91
Aug-94	98.78	100.00	100.00	99.93
Sep-94	99.32	100.00	100.00	100.00
Oct-94	99.44	99.87	100.00	100.00
Nov-94	98.92	99.74	100.00	100.00
Dec-94	99.05	99.74	100.00	100.00
Jan-95	99.40	99.37	99.77	99.59
Feb-95	98.99	99.27	99.51	95.00
Mar-95	98.21	99.10	100.00	100.00
Apr-95	97.77	98.93	100.00	100.00
May-95	97.85	98.90	100.00	100.00
Jun-95	97.30	98.23	98.59	99.71
Jul-95	98.88	99.19	99.11	99.82
Aug-95	99.33	99.92	99.78	99.96
Sep-95				
Oct-95				
Nov-95				
Dec-95				
Jan-96				
Feb-96				
Mar-96	97.68	98.09	100.00	99.32
Apr-96	97.71	98.59	100.00	99.39
May-96	97.73	98.64	100.00	98.58
Jun-96	98.19	98.59	100.00	97.92
Jul-96	99.43	99.87	100.00	99.52
Aug-96	99.88	99.99	100.00	99.12
Sep-96	99.95	100.00	100.00	99.31
Oct-96	99.95	99.99	100.00	98.75
Nov-96	99.68	99.96	100.00	98.71

Table C24 Monthly Degree of Saturation-Licking Co.

	Sr1	Sr2	Sr3	Sr4
Dec-91	98.58	100.00	100.00	100.00
Jan-92	99.61	100.00	100.00	99.33
Feb-92	100.00	100.00	100.00	100.00
Mar-92	99.99	100.00	100.00	100.00
Apr-92	100.00	100.00	100.00	100.00
May-92	100.00	100.00	100.00	100.00
Jun-92	100.00	99.99	100.00	100.00
Jul-92	100.00	99.98	100.00	100.00
Aug-92	100.00	100.00	100.00	100.00
Sep-92	100.00	100.00	100.00	100.00
Oct-92	100.00	100.00	100.00	100.00
Nov-92	100.00	100.00	100.00	100.00
Dec-92	99.97	99.97	99.97	99.97
Jan-93	99.99	100.00	100.00	99.99
Feb-93	98.96	99.16	99.00	98.58
Mar-93	99.03	99.18	99.31	99.14
Apr-93	99.92	99.97	99.98	99.97
May-93	100.00	100.00	100.00	100.00
Jun-93	100.00	100.00	100.00	100.00
Jul-93	100.00	99.99	100.00	100.00
Aug-93	100.00	100.00	100.00	100.00
Sep-93	99.98	99.90	100.00	100.00
Oct-93	99.94	99.95	100.00	100.00
Nov-93	99.99	100.00	100.00	100.00
Dec-93	99.59	99.72	99.90	99.66
Jan-94	98.30	98.61	97.93	97.45
Feb-94	98.72	98.97	98.04	96.32
Mar-94	99.97	99.97	99.83	98.01
Apr-94	99.99	99.99	99.97	98.16
May-94	100.00	100.00	100.00	100.00
Jun-94	100.00	100.00	100.00	100.00
Jul-94	100.00	100.00	100.00	100.00
Aug-94	100.00	100.00	100.00	100.00
Sep-94	100.00	100.00	100.00	100.00
Oct-94	100.00	100.00	100.00	100.00
Nov-94	100.00	100.00	100.00	100.00
Dec-94	99.97	100.00	100.00	99.96
Jan-95	99.11	99.76	99.25	98.73
Feb-95	99.27	99.82	98.46	96.49
Mar-95	99.95	99.98	99.57	95.86
Apr-95	99.99	100.00	99.87	95.87
May-95	99.98	100.00	98.86	94.44
Jun-95	99.99	100.00	99.49	97.82
Jul-95	99.95	100.00	100.00	100.00
Aug-95	99.97	100.00	100.00	100.00
Sep-95	99.99	100.00	100.00	100.00
Oct-95	99.98	100.00	100.00	100.00
Nov-95	99.99	100.00	100.00	97.40
Dec-95	99.47	99.66	99.22	96.20
Jan-96	99.70	99.80	99.50	96.76
Feb-96	99.47	99.67	99.32	96.75
Mar-96	99.95	99.98	99.94	96.65
Apr-96	99.97	99.99	99.97	95.17
May-96	100.00	100.00	100.00	93.96
Jun-96	100.00	100.00	100.00	93.24
Jul-96	100.00	100.00	100.00	92.53
Aug-96	100.00	100.00	100.00	94.90
Sep-96	100.00	100.00	100.00	98.24
Oct-96	100.00	100.00	100.00	96.73
Nov-96	100.00	100.00	100.00	97.11
Dec-96	99.98	99.96	99.94	97.80
Jan-97	99.94	99.94	99.13	97.13
Feb-97	99.79	99.80	98.60	96.56
Mar-97	99.74	99.75	99.01	96.94
Apr-97	99.98	99.98	99.33	97.27
May-97	99.99	99.99	99.96	99.46

Table C25 Monthly Degree of Saturation-Wood2 Co.

	Sr1	Sr2	Sr3	Sr4
Jun-92	99.54	99.35	99.72	99.51
Jul-92	99.54	99.38	99.48	99.12
Aug-92	100.00	100.00	100.00	100.00
Sep-92	100.00	100.00	100.00	100.00
Oct-92	100.00	100.00	100.00	100.00
Nov-92	100.00	100.00	100.00	100.00
Dec-92	100.00	100.00	99.66	99.67
Jan-93	100.00	100.00	98.39	98.64
Feb-93	99.87	99.88	97.48	98.23
Mar-93	99.37	99.07	98.84	98.09
Apr-93	99.47	99.24	99.75	100.00
May-93	100.00	99.99	99.70	100.00
Jun-93	100.00	100.00	99.91	100.00
Jul-93	100.00	99.96	99.66	100.00
Aug-93	100.00	99.79	97.88	100.00
Sep-93	99.74	99.51	99.56	99.53
Oct-93	99.88	99.73	99.98	99.96
Nov-93	99.89	99.77	99.99	99.91
Dec-93	99.98	99.88	99.96	99.88
Jan-94	99.77	98.60	94.92	81.43
Feb-94	99.52	95.72	91.56	83.32
Mar-94	99.80	99.53	94.32	98.77
Apr-94	99.69	99.14	97.51	100.00
May-94	99.77	99.33	98.47	100.00
Jun-94	99.57	99.28	96.77	100.00
Jul-94	99.28	98.92	96.74	100.00
Aug-94	99.49	99.38	99.08	100.00
Sep-94	99.58	99.45	100.00	100.00
Oct-94	99.85	99.73	99.96	100.00
Nov-94	99.99	99.93	99.99	100.00
Dec-94	99.90	99.80	100.00	100.00
Jan-95	99.85	99.81	100.00	99.85
Feb-95	99.86	99.91	99.92	99.15
Mar-95	99.44	99.48	100.00	100.00
Apr-95	98.71	98.09	99.96	100.00
May-95	97.17	96.90	99.85	98.22

Table C26 Monthly Degree of Saturation-Wood8 Co.

	Sr1	Sr2	Sr3	Sr4
Jun-92	92.77	93.81	86.69	92.24
Jul-92	91.34	92.42	88.42	91.48
Aug-92	88.49	90.46	87.18	89.97
Sep-92	92.52	94.37	91.45	93.60
Oct-92	93.88	96.20	93.57	95.25
Nov-92				
Dec-92	98.91	100.00	100.00	100.00
Jan-93	98.81	99.78	99.93	99.85
Feb-93	99.72	99.95	99.61	95.59
Mar-93	99.82	99.97	99.64	97.85
Apr-93	99.60	100.00	99.99	100.00
May-93	98.85	99.99	100.00	100.00
Jun-93	96.83	99.83	100.00	100.00
Jul-93	97.03	99.71	100.00	100.00
Aug-93	97.82	99.72	100.00	100.00
Sep-93	98.86	99.99	100.00	100.00
Oct-93	99.19	100.00	100.00	100.00
Nov-93	99.64	99.99	100.00	100.00
Dec-93	99.95	99.99	99.99	99.40
Jan-94	99.30	99.48	99.76	86.82
Feb-94				
Mar-94				
Apr-94				
May-94	97.27	99.60	100.00	100.00
Jun-94	98.86	99.86	100.00	100.00
Jul-94	99.73	98.88	100.00	99.84
Aug-94	100.00	98.23	100.00	99.23
Sep-94	100.00	98.25	100.00	99.01
Oct-94	100.00	98.77	100.00	99.30
Nov-94	100.00	99.91	100.00	99.99
Dec-94	100.00	100.00	100.00	100.00
Jan-95	99.83	99.69	100.00	98.19
Feb-95	99.90	99.79	99.81	94.87
Mar-95	100.00	100.00	100.00	100.00
Apr-95	100.00	100.00	100.00	100.00
May-95	100.00	100.00	100.00	100.00
Jun-95	100.00	98.99	100.00	99.54
Jul-95	100.00	98.18	100.00	98.23
Aug-95	100.00	98.04	100.00	97.69
Sep-95	100.00	99.55	99.96	99.58
Oct-95	100.00	100.00	99.96	100.00
Nov-95	100.00	100.00	99.90	100.00
Dec-95	99.82	99.76	99.90	98.35
Jan-96	99.85	99.80	98.73	92.17
Feb-96	100.00	99.99	96.41	91.37
Mar-96	99.99	99.98	99.92	99.94
Apr-96	100.00	100.00	100.00	100.00
May-96	99.85	100.00	100.00	100.00
Jun-96	99.96	99.69	100.00	100.00
Jul-96	100.00	98.95	100.00	99.99
Aug-96	100.00	99.05	100.00	99.99
Sep-96	100.00	99.69	100.00	99.97
Oct-96	100.00	100.00	100.00	100.00
Nov-96	100.00	100.00	100.00	100.00
Dec-96	100.00	100.00	100.00	100.00
Jan-97	99.38	99.32	99.62	95.26
Feb-97	98.62	98.58	99.59	97.75
Mar-97	99.85	99.92	100.00	99.97
Apr-97	99.99	99.99	100.00	99.99
May-97	99.93	100.00	100.00	100.00
Jun-97	99.75	99.91	100.00	99.92

Table C27 Seasonal Degree of Saturation ADAMS Co.

	Sr1	Sr2	Sr3	Sr4
SP95*	99.92		99.08	100.00
SU95	99.04		96.86	99.85
F95	98.79		98.66	99.79
W95	98.49		98.46	99.08
SP96*	99.17		99.50	99.75
SU96*				
F96*	99.52		98.95	97.16
W96	98.40		97.69	95.53
SP97	98.99		97.71	92.28

* Incomplete Data

Table C28 Seasonal Degree of Saturation ATHENS Co.

	Sr1	Sr2	Sr3	Sr4
W91	98.43	98.91	99.25	99.43
SP92	98.78	99.09	99.32	99.37
SU92	99.35	99.03	99.39	98.31
F92	99.09	98.72	100.00	99.81
W92	98.91	98.54	99.90	98.64
SP93	98.70	98.03	99.97	99.65
SU93	96.52	95.50	99.91	99.72
F93	98.19	97.84	99.99	99.89
W93*	98.95	98.81	99.81	99.24
SP94*	97.58	97.06	98.74	
SU94	97.99	97.18	99.77	
F94	99.50	99.14	100.00	
W94	99.94	99.89	99.81	
SP95	98.92	99.93	100.00	
SU95	98.87	99.53	100.00	
F95	99.97	99.79	99.96	
W95	99.19	99.23	95.72	
SP96	99.89	99.93	99.51	
SU96*	100.00	100.00	100.00	
F96				
W96*	96.44	99.80	96.04	

* Incomplete Data

Table C29 Seasonal Degree of Saturation COLUMBIANA Co.

	Sr1	Sr2	Sr3	Sr4
F94*	99.94	99.84	98.54	98.19
W94	97.34	96.73	96.72	95.59
SP95	99.90	99.47	99.89	99.98
SU95*	99.99	99.22	99.79	100.00
F95	99.62	99.08	98.09	98.72
W95*	94.59	94.09	91.77	94.07

* Incomplete Data

Table C30 Seasonal Degree of Saturation CRAWFORD Co.

	Sr1	Sr2	Sr3	Sr4
SP92*	97.77	96.91	99.64	94.43
SU92	98.80	98.47	99.85	95.80
F92	99.34	99.05	99.98	98.91
W92	98.83	98.51	99.42	98.64
SP93	98.96	98.55	99.46	98.35
SU93	99.32	99.65	99.81	96.60
F93	98.60	99.18	99.61	97.21
W93	97.45	97.74	92.17	91.75
SP94	97.88	98.76	98.68	97.18
SU94	99.65	99.96	98.48	98.79
F94	99.93	100.00	99.84	99.84
W94	98.95	99.71	98.66	96.92
SP95	99.83	99.97	99.77	99.58
SU95	100.00	100.00	100.00	99.87
F95	99.77	99.91	99.84	99.67
W95	97.19	99.10	95.02	95.89
SP96	99.79	99.98	99.13	99.78
SU96*	100.00	100.00	100.00	100.00
F96*	99.70	99.85	99.63	99.79
W96	98.67	99.51	98.62	98.23
SP97	99.68	99.97	99.99	100.00

• Incomplete Data

Table C31 Seasonal Degree of Saturation KNOX Co.

	Sr1	Sr2	Sr3	Sr4
F91*	100.00	100.00	100.00	100.00
W91	100.00	100.00	100.00	100.00
SP92*	96.90	96.90	96.36	96.90
SU92	99.57	99.57	99.90	99.86
F92	100.00	100.00	100.00	99.79
W92	99.98	99.98	99.99	99.85
SP93	100.00	99.98	100.00	99.99
SU93	100.00	99.98	99.90	99.57
F93	100.00	99.83	99.97	100.00
W93	99.04	98.77	99.35	96.44
SP94	99.41	99.61	100.00	99.99
SU94	98.37	99.81	100.00	99.92
F94	99.17	99.82	100.00	100.00
W94	99.00	99.32	99.77	98.29
SP95	97.79	98.88	100.00	100.00
SU95*	98.58	99.04	98.69	99.73
F95				
W95				
SP96	97.76	98.47	100.00	98.71
SU96	99.61	99.88	100.00	99.27
F96	99.54	99.85	99.49	97.90

* Incomplete Data

Table C32 Seasonal Degree of Saturation LICKING Co.

	Sr1	Sr2	Sr3	Sr4
F91*	98.41	100.00	100.00	100.00
W91	99.72	100.00	100.00	99.78
SP92	100.00	100.00	100.00	100.00
SU92	100.00	99.99	100.00	100.00
F92	99.99	99.99	99.99	99.99
W92	99.55	99.62	99.60	99.45
SP93	99.91	99.95	99.96	99.96
SU93	100.00	99.98	100.00	100.00
F93	99.96	99.96	100.00	100.00
W93	98.89	99.10	98.60	97.42
SP94	100.00	100.00	99.99	99.16
SU94	100.00	100.00	100.00	100.00
F94	100.00	100.00	100.00	100.00
W94	99.45	99.86	99.14	97.52
SP95	99.98	99.99	99.38	95.57
SU95	99.97	100.00	100.00	100.00
F95	99.98	99.99	99.96	98.45
W95	99.54	99.70	99.36	96.52
SP96	99.99	100.00	99.99	94.63
SU96	100.00	100.00	100.00	94.49
F96	100.00	99.99	99.99	97.34
W96	99.82	99.83	98.99	96.94
SP97*	99.97	99.97	99.64	98.47

* Incomplete Data

Table C33 Seasonal Degree of Saturation WOOD2 Co.

	Sr1	Sr2	Sr3	Sr4
SP92*	99.28	98.99	99.56	99.24
SU92	99.85	99.79	99.83	99.70
F92	100.00	100.00	99.97	99.99
W92	99.88	99.85	98.18	98.36
SP93	99.73	99.60	99.80	100.00
SU93	99.97	99.83	99.07	99.95
F93	99.86	99.73	99.94	99.85
W93	99.72	98.08	94.01	88.02
SP94*	99.71	99.29	97.62	100.00
SU94	99.43	99.20	98.23	100.00
F94	99.89	99.79	99.98	100.00
W94	99.78	99.79	99.97	99.68
SP95	97.87	97.63	99.93	98.82

* Incomplete Data

Table C34 Seasonal Degree of Saturation WOOD8 Co.

	Sr1	Sr2	Sr3	Sr4
SP92*	92.99	94.48	86.38	92.74
SU92*	90.71	92.16	88.47	91.39
F92*	93.54	95.71	93.08	94.81
W92*	99.33	99.88	99.74	97.74
SP93	98.84	99.99	100.00	100.00
SU93	97.60	99.75	100.00	100.00
F93	99.47	99.99	100.00	100.00
W93*	99.64	99.76	99.87	92.95
SP94*	97.96	99.79	100.00	100.00
SU94	99.83	98.62	100.00	99.51
F94	100.00	99.34	100.00	99.61
W94	99.91	99.83	99.94	97.78
SP95	100.00	99.85	100.00	99.98
SU95	100.00	98.40	100.00	98.36
F95	100.00	100.00	99.92	99.87
W95	99.88	99.84	98.36	94.08
SP96	99.94	99.98	100.00	100.00
SU96	100.00	99.14	100.00	99.98
F96	100.00	100.00	100.00	100.00
W96	99.31	99.30	99.74	97.66
SP97	99.91	100.00	100.00	100.00

* Incomplete Data

Appendix D

BACK CALCULATION OF RESILIENT MODULUS OF SUBGRADE SOILS FROM FWD DEFLECTIONS

Table D1. DATA to BACKCALCULATE RESILIENT MODULUS AT THE BREAK POINT FROM FWD TESTING (Adams Co.)

YEAR	Eri	SPRING	SUMMER	FALL	WINTER
1991	Time/Tem (FWD)	*	*	*	*
	Air Temp (Logger)				
1992	Time/Tem (FWD)	*	*	*	*
	Air Temp (Logger)				
1993	Time/Tem (FWD)	*	*	*	12/8/93 9:21 31F
	Air Temp (Logger)				FWD -0.5C -
1994	Time/Tem (FWD)	*	6/23/94 11:01 75F	9/20/94 9:22 58F	11/29/94 9:19 32F
	Air Temp (Logger)		LOG 29.3C	FWD 14.4C -	FWD 0C -
1995	Time/Tem (FWD)	3/21/95 9:42 50F	6/6/95 9:15 67F	11/7/95 9:56 45F	*
	Air Temp (Logger)	FWD 10.0C -	FWD 19.4C -	LOG 9.2C	*
1996	Time/Tem (FWD)	4/30/96 9:54 49F	7/8/96 8:45 79F	9/17/96 9:03 64F	*
	Air Temp (Logger)	LOG 5.2C	FWD 26.5C -	FWD 17.8C -	*
1997	Time/Tem (FWD)	4/1/97 9:24 35F			
	Air Temp (Logger)	LOG 6.9C			

* No FWD Files

Table D2. DATA to BACKCALCULATE RESILIENT MODULUS AT THE BREAK POINT FROM FWD TESTING (Athens Co.)

YEAR	Eri	SPRING	SUMMER	FALL	WINTER
1991	Time/Tem (FWD)	*	*	11/14/91 10:35 39F	*
	Air Temp (Logger)			FWD 3.9C	
1992	Time/Tem (FWD)	3/19/92 9:01 31F	6/10/92 8:44 55F	9/24/92 9:21 45F	11/23/92 9:25 43F
	Air Temp (Logger)	LOG 4.2C	LOG 16.3	LOG 9.8C	LOG 9.6C
1993	Time/Tem (FWD)	3/24/93 9:56 55F	6/30/93 9:32 70F	9/20/93 8:43 51F	12/6/93 8:45 39F
	Air Temp (Logger)	LOG 13.0C	LOG 21.8C	LOG 16.3	LOG 6.5C
1994	Time/Tem (FWD)	*	6/16/94 9:28 75F	9/21/94 8:59 60F	12/01/94 9:32 24F
	Air Temp (Logger)		LOG 26.5C	LOG 19.6C	LOG -1.6C
1995	Time/Tem (FWD)	3/23/95 9:14 41F	6/8/95 10:54 75F	11/15/95 9:58 30F	*
	Air Temp (Logger)	LOG 4.9C	LOG 28.1C	LOG 1.3C	
1996	Time/Tem (FWD)	4/25/96 9:47 62F	6/26/96 8:57 70F	9/19/96 9:31 49F	*
	Air Temp (Logger)	LOG 18.0C	LOG 20.2C	FWD 9.4C	
1997	Time/Tem (FWD)	4/3/97 8:37 44F			
	Air Temp (Logger)	LOG 8.2C			

* No FWD Files

Table D3. DATA to BACKCALCULATE RESILIENT MODULUS AT THE BREAK POINT FROM FWD TESTING (Crawford Co.)

YEAR	Eri	SPRING	SUMMER	FALL	WINTER
1991	Time/Tem (FWD)	*	*	11/7/91 9:56 26F	*
	Air Temp (Logger)			FWD –3.3C	
1992	Time/Tem (FWD)	3/18/92 9:44 28F	6/9/92 8:55 65F	9/23/92 9:18 43	11/25/92 8:52 41F
	Air Temp (Logger)	FWD -2.2C	LOG 17.1C	LOG 7.4C	LOG 5.9C
1993	Time/Tem (FWD)	3/23/93 8:52 42F	6/29/93 10:08 67F	9/23/93 8:53 64F	12/2/93 9:04 39F
	Air Temp (Logger)	LOG 7.8C	LOG 20.9C	LOG 18.0C	LOG 4.8C
1994	Time/Tem (FWD)	Incomplete FWD File	Incomplete FWD File	Incomplete FWD File	Incomplete FWD File
	Air Temp (Logger)				
1995	Time/Tem (FWD)	3/27/95 8:32 45F	6/12/95 9:11 58F	11/8/95 9:56 35F	*
	Air Temp (Logger)	LOG 3.2C	LOG 19.8C	LOG -0.4C	
1996	Time/Tem (FWD)	5/1/96 9:29 47F	6/27/96 9:21 76F	9/20/96 8:53 54F	*
	Air Temp (Logger)	LOG 8.1C	LOG 21.2C	FWD 12.2C	
1997	Time/Tem (FWD)	4/4/97 8:57 50F			
	Air Temp (Logger)	LOG 16.2C			

* No FWD Files

Table D4. DATA to BACKCALCULATE RESILIENT MODULUS AT THE BREAK POINT FROM FWD TESTING (Knox Co.)

YEAR	Eri	SPRING	SUMMER	FALL	WINTER
1991	Time/Tem (FWD)	*	*	11/12/91 10:59 33F	*
	Air Temp (Logger)			FWD 0.6C	
1992	Time/Tem (FWD)	3/18/92 12:22 34F	6/9/92 11:47 71F	9/23/92 12:59 58F	11/25/92 10:48 41F
	Air Temp (Logger)	LOG 7.3C	FWD 21.7C	LOG 11.8C	LOG 7.3C
1993	Time/Tem (FWD)	3/23/93 10:37 44F	6/30/93 2:07 74F	9/23/93 10:49 65F	12/2/93 10:54 44F
	Air Temp (Logger)	LOG 8.4C	LOG 14.1C	LOG 18.6C	LOG 8.3C
1994	Time/Tem (FWD)	*	6/17/94 12:05 84F	9/23/94 1130 65F	12/02/94 11:45 39F
	Air Temp (Logger)		LOG 30.9C	LOG 16.9C	LOG 10.5C
1995	Time/Tem (FWD)	3/27/95 10:19 44F	6/12/95 11:07 58F	11/8/95 11:51 36F	*
	Air Temp (Logger)	LOG 6.1C	LOG 18.6C	FWD 2.2C	
1996	Time/Tem (FWD)	5/1/96 11:52 46F	6/27/96 10:58 81F	9/20/96 11:18 80F	*
	Air Temp (Logger)	LOG 8.8C	LOG 23.4C	LOG 20.6C	
1997	Time/Tem (FWD)	4/4/97 12:26 73			
	Air Temp (Logger)	LOG 22.9C			

* No FWD Files

Table D5. DATA to BACKCALCULATE RESILIENT MODULUS AT THE BREAK POINT FROM FWD TESTING (Licking Co.)

YEAR	Eri	SPRING	SUMMER	FALL	WINTER
1991	Time/Tem (FWD)	*	*	11/13/91 11:07 36F	*
	Air Temp (Logger)			FWD 2.2C	
1992	Time/Tem (FWD)	3/19/92 12:57 34F	6/10/92 12:28 73F	9/24/92 12:32 59F	11/23/92 12:00 45F
	Air Temp (Logger)	LOG 0.0C	LOG 21.9C	LOG 15.3C	LOG 7.8C
1993	Time/Tem (FWD)	3/24/93 12:35 58F	6/30/93 11:35 70F	9/20/93 11:36 62F	12/6/93 12:56 38F
	Air Temp (Logger)	LOG 9.7C	LOG 22.3C	LOG 17.0F	LOG 4.0C
1994	Time/Tem (FWD)	*	6/16/94 13:19 91F	9/21/94 11:31 71F	12/01/94 12:51 34F
	Air Temp (Logger)		LOG 28.8C	LOG 23.2C	LOG 4.0C
1995	Time/Tem (FWD)	3/23/95 11:39 46F	6/8/95 13:03 76F	11/15/95 12:58 33F	
	Air Temp (Logger)	LOG 5.0C	LOG 23.6C	LOG 1.3C	
1996	Time/Tem (FWD)	4/25/96 12:32 64F	6/26/96 12:46 98F	9/19/96 11:59 83F	*
	Air Temp (Logger)	LOG 19.2C	FWD 75F LOG 24.5C	LOG 21.2C	
1997	Time/Tem (FWD)	4/3/97 12:07 55F			
	Air Temp (Logger)	LOG 18.1C			

* No FWD Files

Table D6. DATA to BACKCALCULATE RESILIENT MODULUS AT THE BREAK POINT FROM FWD TESTING (Wood 8 Co.)

YEAR	Eri	SPRING	SUMMER	FALL	WINTER
1991	Time/Tem (FWD)	*	*	10/20/91 9:45 60F	11/5/91 9:08 19F
	Air Temp (Logger)			FWD 15.6C	FWD -7.2C
1992	Time/Tem (FWD)	3/14/92 9:38 37F	6/8/92 8:44 60F	9/28/92 9:01 49F	11/24/92 8:51 40F
	Air Temp (Logger)	FWD 2.8C	LOG 16.5C	LOG 11.4C	FWD 4.4C
1993	Time/Tem (FWD)	3/22/93 9:14 32F	6/28/93 8:51 66F	9/21/93 9:07 50F	12/1/93 9:13 27F
	Air Temp (Logger)	LOG 1.5C	LOG 19.5C	LOG 15.9C	LOG -1.7C
1994	Time/Tem (FWD)	*	6/21/94 9:24 71F	9/22/94 8:53 57F	11/30/94 9:41 29F
	Air Temp (Logger)		LOG 28.6C	LOG 20.4C	LOG -0.4C
1995	Time/Tem (FWD)	3/22/95 9:04 35F	6/7/95 8:52 63F	11/20/95 9:40 39F	*
	Air Temp (Logger)	LOG 4.7C	LOG 25.2C	LOG 4.0C	
1996	Time/Tem (FWD)	4/24/96 8:37 40F	6/25/96 9:07 74F	9/18/96 8:36 59F	*
	Air Temp (Logger)	LOG 6.2C	FWD 61F LOG 18.7C	LOG 16.3C	
1997	Time/Tem (FWD)	4/2/97 9:15 35F			
	Air Temp (Logger)	LOG 10.2C			

* No FWD Files

Table D7 BACK CALCULATED RESILIENT MODULUS AT THE BREAK POINT FROM FWD TESTING (MPa)
(Adams Co.)

YEAR	Eri	SPRING	SUMMER	FALL	WINTER
1991	Average				
	at Ref. Pt.				
1992	Average				
	at Ref. Pt.				
1993	Average				28.13
	at Ref. Pt.				67.42
1994	Average		- X	- X	9.86
	at Ref. Pt.		20.27	35.44	45.71
1995	Average	30.20	37.85	94.31	
	at Ref. Pt.	59.50	75.49	129.12	
1996	Average	- X	- X	33.37	
	at Ref. Pt.	5.93	27.16	49.77	
1997	Average	34.19			
	at Ref. Pt.	70.18			

X High FWD Deflections

Table D8 BACK CALCULATED RESILIENT MODULUS AT THE BREAK POINT FROM FWD TESTING (MPa)
(Athens Co.)

YEAR	Eri	SPRING	SUMMER	FALL	WINTER
1991	Average			129.06	
	at Ref. Pt.			138.29	
1992	Average	143.53	141.74	138.36	157.25
	at Ref. Pt.	160.70	159.04	154.29	173.25
1993	Average	177.52	163.94	192.83	155.25
	at Ref. Pt.	203.79	179.18	201.72	176.14
1994	Average		148.84	167.32	116.44
	at Ref. Pt.		152.01	166.63	124.37
1995	Average	136.02	187.86	185.03	
	at Ref. Pt.	142.64	194.76	191.17	
1996	Average	167.39	138.16	115.96	
	at Ref. Pt.	181.86	139.19	120.99	
1997	Average	133.61			
	at Ref. Pt.	151.39			

X High FWD Deflections

Table D9 BACK CALCULATED RESILIENT MODULUS AT THE BREAK POINT FROM FWD TESTING (MPa)
(Crawford Co.)

YEAR	Eri	SPRING	SUMMER	FALL	WINTER
1991	Average			18.82	
	at Ref. Pt.			30.40	
1992	Average	- X	34.75	21.30	45.71
	at Ref. Pt.	8.82 X	38.40	28.82	55.84
1993	Average	33.78	37.99	60.46	43.29
	at Ref. Pt.	51.43	41.71	63.70	52.19
1994	Average				
	at Ref. Pt.				
1995	Average	17.92	66.60	60.87	
	at Ref. Pt.	30.20	75.77	67.35	
1996	Average	15.44	14.06	24.34	
	at Ref. Pt.	23.16	20.20	27.16	
1997	Average	55.77			
	at Ref. Pt.	65.49			

X High FWD Deflections

Table D10 BACK CALCULATED RESILIENT MODULUS AT THE BREAK POINT FROM FWD TESTING (MPa)
(Knox Co.)

YEAR	Eri	SPRING	SUMMER	FALL	WINTER
1991	Average			70.04	
	at Ref. Pt.			53.50	
1992	Average	67.15	84.52	66.25	79.14
	at Ref. Pt.	52.53	71.42	55.70	77.49
1993	Average	54.60	54.95	121.82	89.83
	at Ref. Pt.	31.57	30.06	95.48	68.39
1994	Average		85.62	74.94	77.14
	at Ref. Pt.		45.64	45.36	51.71
1995	Average	48.46	96.72	85.49	
	at Ref. Pt.	20.13	56.60	50.74	
1996	Average	20.27	72.52	79.01	
	at Ref. Pt.	- X	58.32	49.91	
1997	Average	69.28			
	at Ref. Pt.	47.91			

X High FWD Deflections

Table D11 BACK CALCULATED RESILIENT MODULUS AT THE BREAK POINT FROM FWD TESTING (MPa)

(Licking Co.)

YEAR	Eri	SPRING	SUMMER	FALL	WINTER
1991	Average			219.71	
	at Ref. Pt.			188.83	
1992	Average	203.03	242.12	255.84	245.08
	at Ref. Pt.	170.28	195.17	221.57	211.99
1993	Average	250.53	268.31	281.41	235.91
	at Ref. Pt.	205.37	236.46	232.12	193.58
1994	Average		205.92	266.94	218.82
	at Ref. Pt.		138.29	209.65	158.91
1995	Average	224.81	269.49	265.90	
	at Ref. Pt.	150.15	195.79	217.44	
1996	Average	256.18	237.36	245.43	
	at Ref. Pt.	170.07	169.04	166.49	
1997	Average	249.56			
	at Ref. Pt.	197.93			

X High FWD Deflections

Table D12 BACK CALCULATED RESILIENT MODULUS AT THE BREAK POINT FROM FWD TESTING (MPa)
(Wood 8 Co.)

YEAR	Eri	SPRING	SUMMER	FALL	WINTER
1991	Average			71.28	18.89
	at Ref. Pt.			78.18	24.68
1992	Average	42.74	56.94	60.39	63.22
	at Ref. Pt.	44.40	56.32	64.60	64.11
1993	Average	61.77	62.67	62.39	73.15
	at Ref. Pt.	62.25	67.42	75.01	78.38
1994	Average		69.15	88.93	69.56
	at Ref. Pt.		67.42	87.55	76.25
1995	Average	74.52	99.41	124.23	
	at Ref. Pt.	66.32	98.65	130.02	
1996	Average	71.42	57.63	89.90	
	at Ref. Pt.	75.01	58.19	102.38	
1997	Average	84.38			
	at Ref. Pt.	86.24			

X High FWD Deflections

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