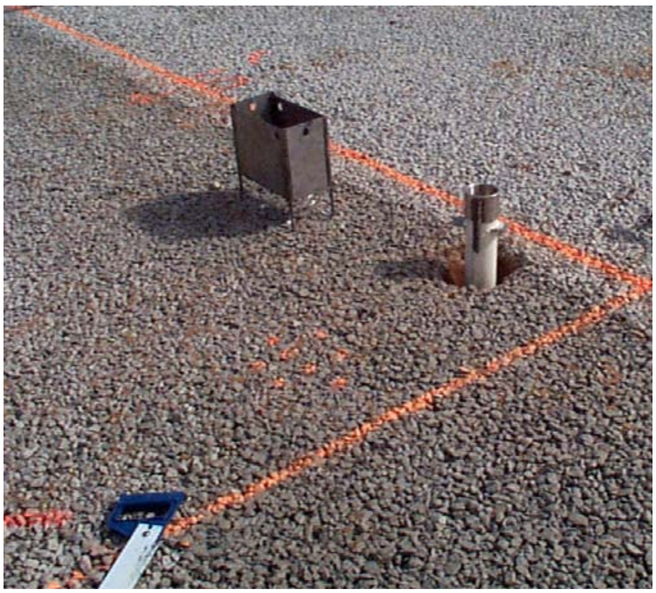
TRUCK/PAVEMENT/ECONOMIC MODELING AND IN-SITU FIELD TEST DATA ANALYSIS APPLICATIONS – VOLUME 1: INFLUENCE OF DRAINAGE ON SELECTION OF BASE

Shad Sargand, Shin Wu, J. Ludwig Figueroa



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16. Abstract
The primary objective of this study was to investigate how base materials should be properly selected for specific types of pavement, not only considering the performance of individual layers but also how they interact in the total pavement structure. Base types considered in this study included granular (GB), lean concrete (LCB), asphalt treated (ATB), cement treated (CTB), and permeable asphalt treated (PATB) bases as constructed under both asphalt concrete (AC) and Portland cement concrete (PCC) pavements. The Long Term Pavement Performance (LTPP) Seasonal Monitor Program (SMP) sites investigated for this report included four SMP sections in the North Carolina SPS-2 experiment on US52 and thirteen SMP sections in the SPS-1 and SPS-2 experiments on the Ohio SHRP Test Road on US23. The NC site contained two GB and two LCB sections, and the OH site contained eight GB, one ATB, two PATB, and two LCB sections. The NC sites are located in a wet-no-freeze zone and OH sites are located in a wet-freeze zone. Environmental data were collected via seasonal monitors and time domain reflectometry. The effects of service were measured by conducting surface profiles and falling weight deflectometer (FWD) measurements.

It was found that the type of base had little impact on subgrade moisture. The choice of base depends chiefly on three requirements: appropriate stiffness, sufficient permeability, and good constructability.

Guidelines for the selection of base under flexible and rigid pavements are given.

17. Key Words
Base, subgrade, moisture, pavement system, granular base, asphalt treated base, permeable asphalt treated base, lean concrete base, cement treated base, pavement system drainage

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

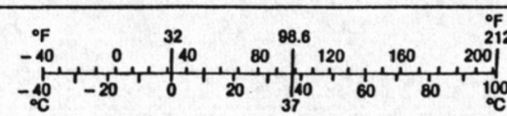
Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
		AREA		
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.093	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometres squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.028	metres cubed	m^3
yd^3	cubic yards	0.765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
		AREA		
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometres squared	0.386	square miles	mi^2
		VOLUME		
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F



* SI is the symbol for the International System of Measurement

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INTRODUCTION

Naturally occurring subgrade soil serves as the basic foundation for highway pavement structures. Layers of selected or modified soil and other materials, all carefully processed and placed in accordance with prevailing specifications, are constructed over the natural soil to provide a smooth surface capable of carrying traffic loads for a period of time. During pavement design and/or construction, materials "of equal strength" are often substituted to reduce costs or to take advantage of local availability. From an engineering point of view, the exchange of structurally similar materials would not seem to affect pavement performance. Observations from in-service pavements over the years, however, have called this assumption into question. Evidence now suggests that pavement layers which complement each other and interact harmoniously under traffic loading and environmental cycling provide better performance than layers which are less compatible.

Most pavement research is aimed at improving performance, with the ultimate goal of extending service life at the lowest possible construction and maintenance costs. The primary objective of this study was to investigate how base materials should be properly selected for specific types of pavement, not only considering the performance of individual layers but also how they interact in the total pavement structure. This implies that design procedures should not only consider material strength, but also the interaction between material layers. Base types considered in this study included granular (GB), lean concrete (LCB), asphalt treated (ATB), cement treated (CTB), and permeable asphalt treated (PATB) bases. For this study, data collected from the Ohio SHRP Test Road sections and from projects in North Carolina were combined with information gathered from the DataPave database and analyzed.

BACKGROUND

The provision of a safe, convenient, comfortable and long lasting pavement surface for vehicles to travel on during all weather conditions requires the accomplishment of several functional and structural goals. The periodic monitoring of three specific parameters, structure, smoothness, and skid resistance, provides incremental measures of condition; distress provides another measure of condition. Trends in condition over time are indicative of how well the pavement is performing and how well the design goals were met. Researchers continue to devise methods for improving the design, construction, and maintenance of highway pavements in order to extend service life and/or reduce user costs.

Pavements are traditionally designed as a series of independent material layers combined together to achieve a structure capacity capable of providing some expected level of service. For flexible pavements, the AASHTO Pavement Design Guide assigns a structural coefficient to each material, and a structural number is determined for each pavement layer by multiplying the material coefficient by the layer thickness. A total structural number is then calculated for the pavement by adding the individual layer numbers together. In the AASHTO procedure, layers of one material may be replaced with layers of another material as long as the desired structural number has been maintained. Recent studies have found, however, that there can be complex interactions between layers which affect performance. Thus, pavements need to be designed as an integral layered system with consideration given as to how the individual layers function together under traffic loading and environmental changes. Any deviation from the original design must be carefully evaluated for its effect on the total structure.

Because stresses generated by traffic loads are highest on the pavement surface, the top layer requires higher strength materials capable of withstanding stresses under and around the moving tires. As stresses decrease with depth in the pavement structure, material quality may be reduced accordingly. This progression of reduced material quality can continue until stresses are able to be sustained by the natural subgrade.

Flexible pavements show progressively increased permanent deformation under the application of repeated traffic loads when stresses exceed levels able to be sustained elastically by the material layers. This deformation can result from structural considerations within the layered structure and/or from various properties of the AC mix, including stability and density. While most deformation is recovered as the loads are removed, a small portion is permanently retained and added to previous residual deformations. Over time, these accumulated deformations affect the performance and rideability of the pavement surface. The total residual deformation on any pavement is affected by the number and level of applied stresses as well as the ability of the materials to carry that stress.

The magnitude of vertical strains on unbound materials determines the rate at which layer deformations accumulate to the point where ruts and cracks develop in flexible pavement surfaces. The stiffness of unbound granular materials is primarily affected by density and gradation characteristics. The stiffness of fine-grained soils, however, is primarily affected by moisture content or degree of saturation. Thus, the control of moisture in pavement systems leads to the preservation of subgrade strength, thereby, preventing premature damage to the system.

In bound materials, the number of load repetitions to develop fatigue cracking and failure depends upon the magnitude of tensile strains which develop at the bottom of the layer, although top down cracks have been observed in many in-service pavements. Distresses of either type are manifested into higher surface deflections, which may be used as an indicator of the integrity of the pavement.

PAVEMENT BASES

The “base” of a pavement structure is the layer that lies beneath the Portland Cement Concrete (PCC) or Asphalt Concrete (AC) surface layer and above the subbase or subgrade. Base courses under rigid and flexible pavements serve different purposes.

> “Base courses are used under rigid pavements for (1) prevention of pumping, (2) protection against frost action, (3) drainage, (4) prevention of volume change of the subgrade, (5) increased structural capacity, and (6) expedition of construction.” “Base courses…are used under flexible pavements to increase the load-supporting capacity of the pavement by providing added stiffness… resistance to fatigue… distribute the load… provide drainage… added protection against frost action…” (Yoder, 1975)

These fundamental differences make it necessary to use different approaches in designing rigid and flexible pavements.

DESIGN CONCEPT

The following two factors are considered fundamental for good pavement performance:

1. All material layers must be designed to maintain low stress-strength ratios under all load levels and all environmental conditions.
2. Pavement structures must be constructed to be as uniform as possible, with any variations in physical properties being minimal throughout the project.

Adequate strength insures that the pavement will carry traffic loads under all conditions without experiencing excessive damage to the structure, thus ensuring a long life. Uniform construction will minimize localized failures which prematurely decrease pavement serviceability. To attain adequate strength and uniformity in the pavement structure, it is necessary to:

1. Reduce vertical strain on the subgrade soil to the point where it will perform equally over the project length.
2. Minimize the effects of temperature and moisture cycling.
3. Construct pavement structures as uniformly as possible, with due consideration given to practicality, compaction issues, Quality Control/Quality Assurance (QC/QA), acceptance specifications, etc.

OBJECTIVES

The objectives of this study were as follows:

1. From subsurface moisture data obtained on pavement sections in the Ohio SPS-1 and SPS-2 LTPP experiments on the SHRP Test Road on US Route 23 in Delaware County and on experimental sections of US Route 52 in North Carolina, evaluate the effect of base type and drainage on subgrade moisture levels under flexible and rigid pavement. Particular attention is given to permeable bases and edge drainage systems.
2. From nondestructive and controlled vehicle test data obtain on the closely monitored experimental pavement sections, evaluate the effect of base type and drainage on the response of flexible and rigid pavement. Particular attention is given to permeable bases and edge drainage systems.
3. From visual distress and surface roughness data obtained on the closely monitored experimental pavement sections, evaluate the effect of base type and drainage on the performance of flexible and rigid pavement in terms of serviceability. Particular attention is given to permeable bases and edge drainage systems.
4. Select a currently available model for predicting subgrade moisture in pavement structures incorporating various types of subgrade soils, base materials and drainage systems. Calibrate this model using available data.
5. Provide design guidelines for reducing moisture in pavement structures.
6. Provide practical guidelines to identify under what physical and environmental conditions drainage is required to improve pavement performance.

DRAINABLE BASE USAGE IN THE UNITED STATES

A brief survey on the adoption and performance of drainable bases was sent to the departments of transportation of all 50 states. Responses were received from 24 states, for a 48% response rate. The questions are shown in Figure 1. Responses to Questions 1-4 are shown in Table 1.

Responses to Question 1 indicate that 20 of the 24 states (83.3%) states currently use drainable bases. One of these states (Illinois) indicated they had bad experiences with drainable bases on CRCP, but under flexible pavements they were good. Missouri indicated that they abandoned drainable bases in favor of alternative designs. Washington used drainable bases only under flexible pavements, two states specified use under rigid pavements, and three specified use under both types of pavements; the remainder of the states using drainable bases did not specify the types of pavements where they use drainable bases.

Regarding Question 2, of responding states, 10 (41.7%) have documented the performance of pavements on drainable bases. Three of these states indicated their research was in progress. One of the other states said that the data were there, while another was planning to document performance in the future. Question 3 asked states if they had compared the performance of pavements on drainable bases to those on dense graded bases. Only four states (16.7%) indicated they had.

Question 4 asked if states cleaned their drainable base underdrains. Seven states (29.2%) said they did, 16 (66.7%) did not, and one state (4.2%) did not answer the question. Two of the latter states indicated that crews will clean out drains when a problem is realized. One state indicated that there was no formal procedure in place, but money was set aside for cleaning drains.

Questions

1) Does your state use drainable bases?

2) Has your state documented the performance of pavements constructed on drainable bases?

3) Has your state compared the performance of pavements on drainable bases with pavements on dense graded bases?

4) Does your state clean the outlet to the underdrains? If so, could you send us your state's policy, procedure, equipment requirements or special drainage hardware used for routine underdrain cleanout?

5) If you answered yes to question 2, 3 or 4, Please provide a name, phone number, and email address of a person we can contact who could provide details (performance history, gradations, etc.)

Figure 1. Questions from Survey on Drainable Bases Sent to State Departments of Transportation.

Table 1. Responses to Nationwide Survey on Drainable Base Usage and Policies

State	Question 1	Question 2	Question 3	Question 4
Arizona	No	No	No	No
Florida	Yes	Yes	No	No
Georgia	No	No	No	Did use edgedrains at one time, but could not keep them cleaned out. Resulted in premature pavement failures
Idaho	Yes	No, but the data is there	Research in progress	No
Illinois	Tried open graded under several CRCP and on flexible pavement. CRCP sections performed very poorly, flexible is good so far	Yes – see TRB Record 1956 – report by Laura Heckel	No comparisons with dense graded, do have comparisons with other base types -- see TRB Record 1684 – report by Gharaibeh, et al.	Clean only as needed, no policy
Indiana	Yes	No – has documented some specific problems with random transverse midpanel cracking	No – did note some case of midpanel cracking under less permeable subbases	Yes
Iowa	Yes	Not documented, but Iowa has built pavements on drainable bases for 10 years – no problems experienced	No	No
Kentucky	Yes	Yes	Yes	Various – per SHD
Louisiana	Yes -- infrequently	Yes – have monitored several projects which are 5 years old – contact Gene Taylor for information on I-20 project	No	Yes
Maine	Yes, just started	Research in progress	No	No answer
Michigan	Yes – under JRCP since 1994, under JPCP since 1995, very limited use under flexible pavements	Yes	No	No formal procedure in place, but money is set aside to clean the drains
Missouri	Prior to 1993 – No, Since 1993 alternative drainable base designs have been used	No	No – under investigation	No

Table 1, continued.

State	Question 1	Question 2	Question 3	Question 4
Montana	Very rarely	No	No	No
Nebraska	Yes, just started	Research in progress	No	No
Nevada	Yes, but only under PCCP in high rainfall areas	No	No	Yes they clean them but they do not have a policy
New Jersey	Yes – non-stabilized open graded under both flexible and rigid	Yes – report "Improved Drainage and Frost Action Criteria for NJ Pavement Design	Yes – documented in report mentioned in Question 2	No, outlets are generally cleaned only when a problem is realized
New York	Yes, all new construction	No, not in the past, but will in the future	No	No
Oregon	Yes	No	No	No
Pennsylvania	Yes – use cement & asphalt treated permeable bases over dense graded granular bases. Has suspended the use of unstabilized open graded granular bases	Yes – the performance of pavements on unstabilized open graded bases has been good and bad. Its use has been suspended	No	Yes – Frequency and method of this maintenance is generally at the discretion of the county maintenance organization
Tennessee	Yes	No	No	No
Texas	No	No	No	No
Utah	Yes, for both ACC and PCC	No – but based on historical experience we know that good drainage provides better performance	No	No – If crews see a problem they can handle it.
Washington	Yes, but only under flexible	No	No	No
Wisconsin	Yes	Yes – Report "Performance Evaluation of Drained Pavement Structures"	Yes – documented in report mentioned in Question 2	Yes – they are maintained through contracts with county maintenance personnel
Total Yes	20 (83.3%)	10 (41.7%)	4 (16.7%)	7 (29.2%)
Total No	4 (16.7%)	14 (58.3%)	20 (83.3%)	16 (66.7%) (+1 No answer (4.2%))

EFFECT OF BASE TYPE ON SUBGRADE MOISTURE

It is well known that increased moisture will reduce the load bearing capacity of fine-grained subgrade soils. It is also common knowledge that surface water as well as ground water may influence base and subgrade moisture. Since one of the functions of the pavement structure is to prevent water intrusion, the selection of base type is critical to ease the effect of water intrusion from the surface and hence affect the pavement performance.

Analysis of Base Effect on Subgrade Moisture by Direct Comparison

The Long Term Pavement Performance (LTPP) Seasonal Monitor Program (SMP) test sections located in Specific Pavement Studies (SPS) and General Pavement Studies (GPS) experiments scattered around the country represent a variety of climatic conditions and design parameters. The majority of these sections were constructed with granular bases, with a few containing other base types. Due to the wide range of climatic and soil conditions, and the limited number of non-granular bases represented at these sites, it was not possible to establish a firm correlation between base type and subgrade moisture from these data. SMP sections with different design features within the same SPS project, however, offered an opportunity to compare the effects of base type on subgrade moisture directly. These sites were subjected to similar weather conditions, construction practices and subgrade properties.

Sites investigated for this report included four SMP sections in the North Carolina SPS-2 experiment on US52 and thirteen SMP sections in the SPS-1 and SPS-2 experiments on the Ohio SHRP Test Road on US23. The NC site contained two GB and two LCB sections, and the OH site contained eight GB, one ATB, two PATB, and two LCB sections. Table 1 shows all the SMP sites, where 370xxx are NC sites and 390xxx are Ohio sites. Unfortunately, one of the OH GB sections (390102) failed very early and did not yield sufficient data for analysis. The pavement in sections 390101 and 390110 also failed, but still provided some useful data for analysis. The NC sites are located in a wet-no-freeze zone while the OH sites are located in a wet-freeze zone.

Table 2. Seasonal Monitoring Sites

Site	Surface	Base	Subgrade	Location	Remark
370201	8" (20 cm) JCP	6" (15 cm) GB	A-6	NC	
370205	8" (20 cm) JCP	6" (15 cm) LCB	A-6	NC	
370208	11" (28 cm) JCP	6" (15 cm) LCB	A-6	NC	
370212	11" (28 cm) JCP	4" (10 cm) PATB /4" (10 cm) GB	A-6	NC	
390101	7" (18 cm) AC	8" (20 cm) GB		OH	Pavement Failed
390102	4" (10 cm) AC	12" (30 cm) GB		OH	Pavement Failed
390104	7" (10 cm) AC	12" (30 cm) ATB		OH	
390108	7" (18 cm) AC	4" (10 cm) ATB /4" (10 cm) GB		OH	
390110	7" (18 cm) AC	4" (10 cm) ATB /4" (10 cm) PATB	A-4	OH	Pavement Failed
390112	4" (10 cm) AC	12" (30 cm) ATB /4" (10 cm) PATB		OH	
390201	8" (20 cm) JCP	6" (15 cm) GB		OH	
390202	8" (20 cm) JCP	6" (15 cm) GB	A-6	OH	
390204	11" (28 cm) JCP	6" (15 cm) GB		OH	
390205	8" (20 cm) JCP	6" (15 cm) LCB	A-6	OH	
390208	11" (28 cm) JCP	6" (15 cm) LCB		OH	
390211	11" (28 cm) JCP	4" (10 cm) PATB /4" (10 cm) GB	A-6	OH	
390212	11" (28 cm) JCP	4" (10 cm) PATB /4" (10 cm) GB		OH	

Time domain reflectometry (TDR) probes were installed at different depths to monitor volumetric moisture content, which was determined from TDR traces by one of several established procedures. In turn, gravimetric moisture content can be calculated from volumetric moisture content using the dry density of the soil and the density of water. Figures 2 to 5 show typical yearly range, maximum, and minimum of gravimetric moisture contents recorded for four base types at Ohio sites (GB, ATB, LCB, and PATB) during the data collection periods. The zero of the vertical axis of each figure indicates the top of the subgrade. In the upper part of each graph, the notation “Year1” indicates measurements made the first year after construction of the road and installation of sensors, “Year2” indicates the second year, and so on. Similarly, in the legend in the bottom part, “Min1”/”Max1” means minimum/maximum moisture values recorded during the first year (“Year 1”), “Min2”/“Max2” refers to minimum/maximum values recorded during Year 2, and so on.

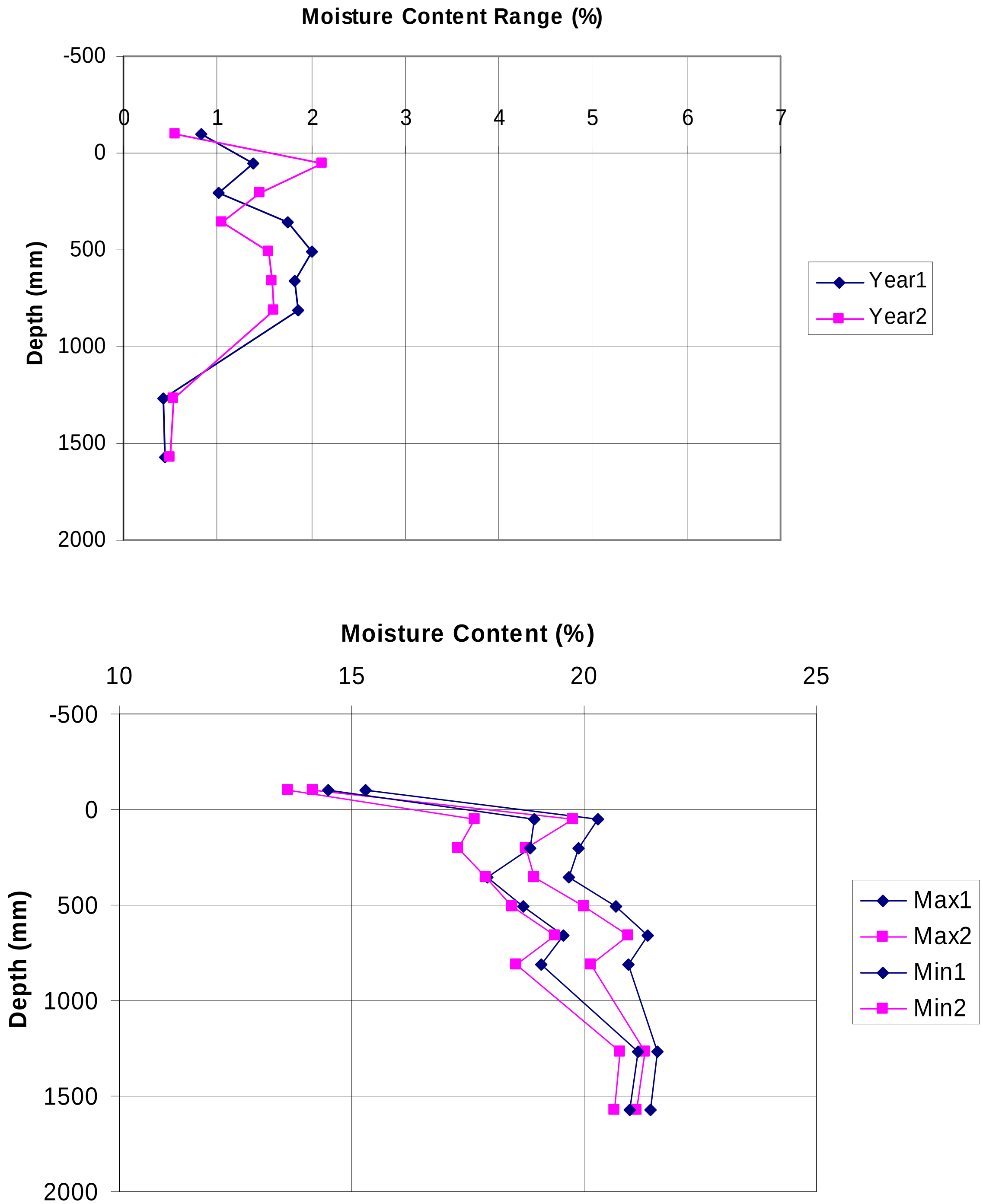


Figure 2. Range of Moisture Content Variation and Max/Min Moisture Content as a Function of Depth (Ohio Section 390101 GB) (100 mm = 3.94 in)

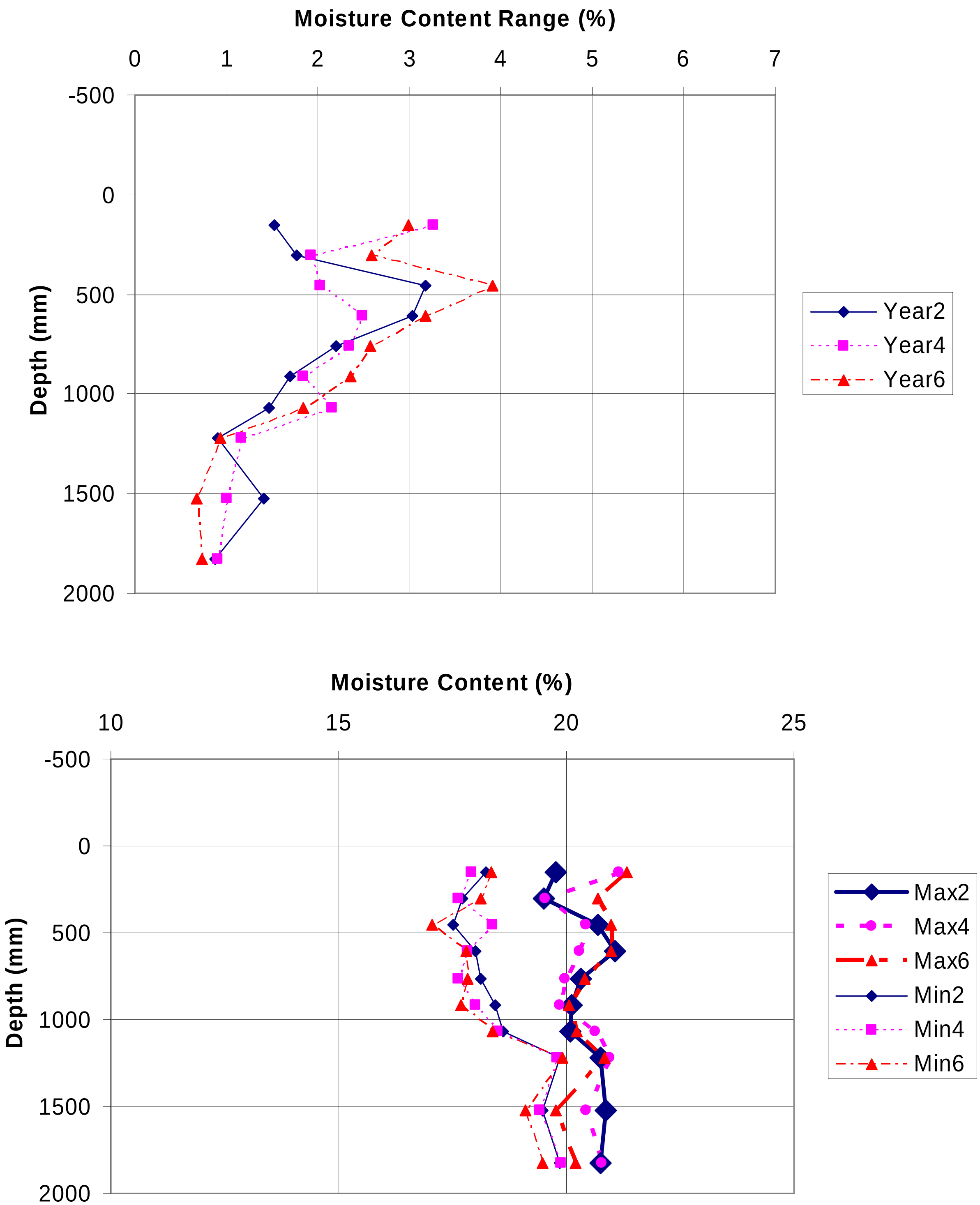
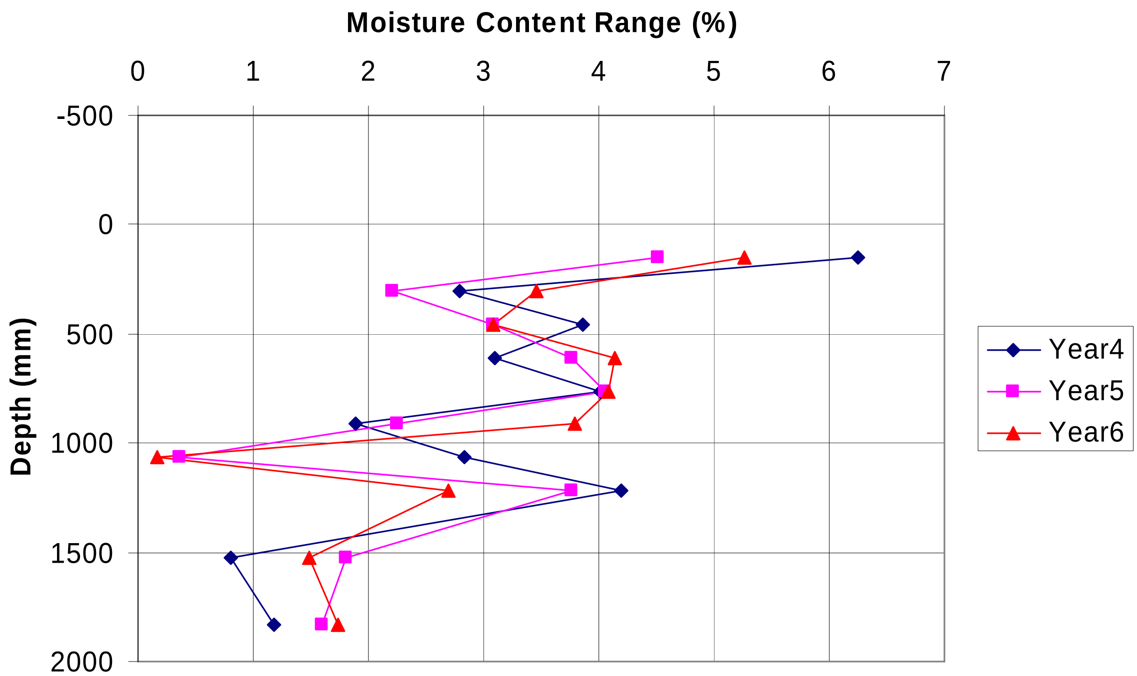


Figure 3. Range of Moisture Content Variation and Max/Min Moisture Content as a Function of Depth (Ohio Section 390104 ATB) (100 mm = 3.94 in)



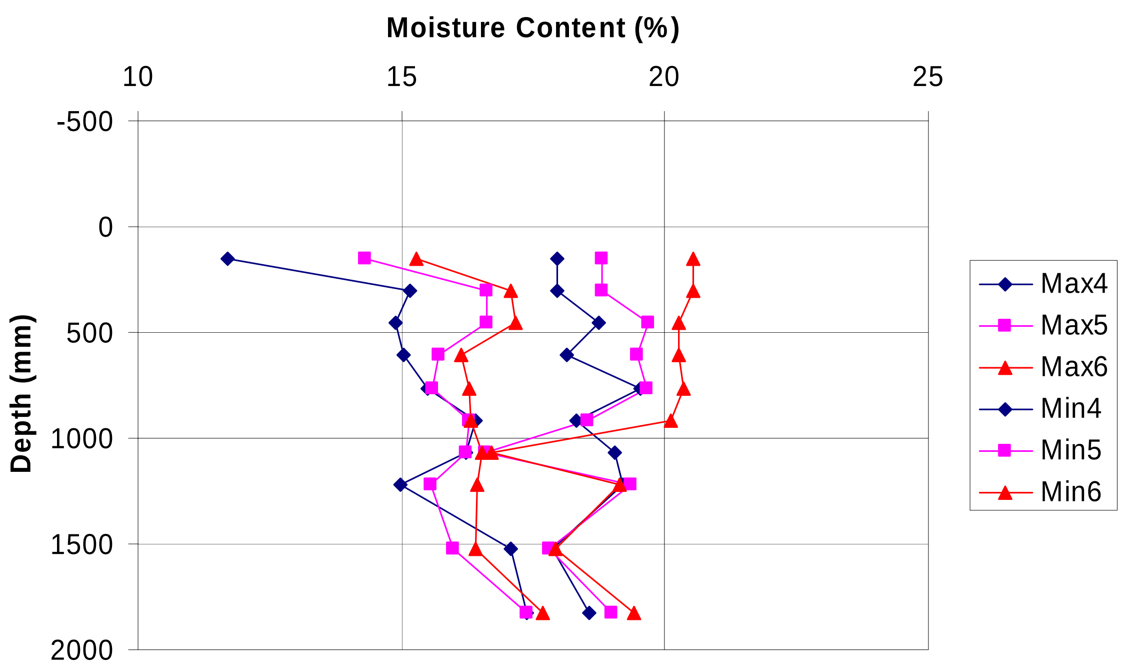


Figure 4. Range of Moisture Content Variation and Max/Min Moisture Content as a Function of Depth (Ohio Section 390208 LCB) (100 mm = 3.94 in)

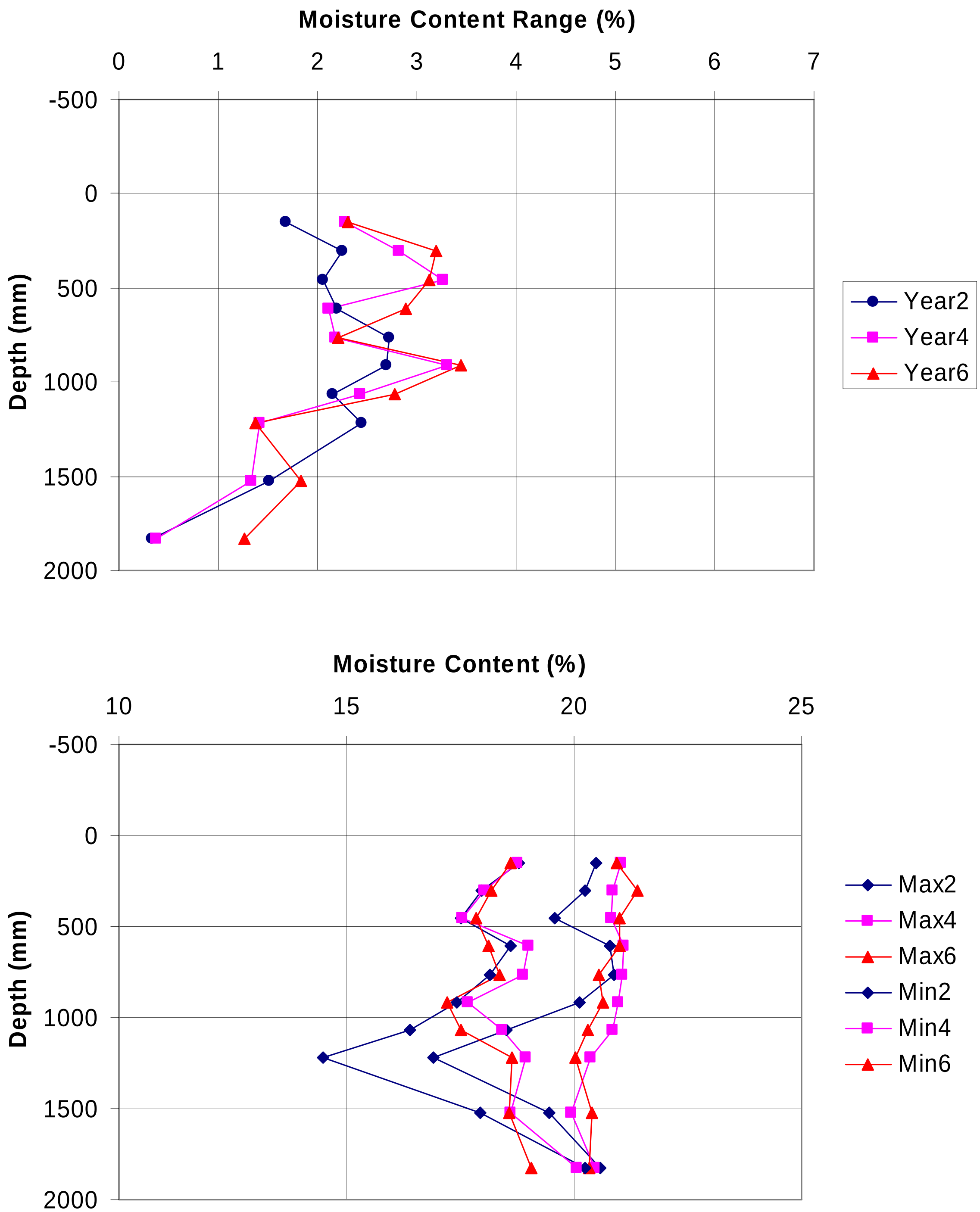


Figure 5. Range of Moisture Content Variation and Max/Min Moisture Content as a Function of Depth (Ohio Section 390110 PATB) (100 mm = 3.94 in)

Most of the recorded maximum moisture contents at any depths except within the GB layer were around 20%. This value may very well be near saturated moisture content of the in situ fine grained soil. Moisture content within the GB layer (section 390101), including both maximum moisture content (15%) and range of moisture content variation (< 1%), were lower than readings from inside the subgrade soil. From these plots, which are typical of the data recorded for all sites in the study – a complete set of graphs is included in Appendix A – it is observed that:

1. Maximum moisture contents were about the same at all depths.
2. Variation of moisture content near the subgrade surface is greater than or equal to 200 mm (7.9 in) to 300 mm (11.8 in) below.
3. Moisture content ranges at 2 meters (6.6 ft) deep were much smaller than that of near the surface of the subgrade.

This evidence implied that the moisture content near the subgrade surface is affected by the seasonal changes in surface water.

Variations in Long Term Moisture

Subgrade moisture content at different depths and locations is affected by:

1. Soil properties: saturated moisture content, permeability, and particle size.
2. Soil type.
3. Environmental conditions.
4. Topographical features.
5. Base permeability.
6. Regional factors as defined in Yoder & Witczak (1975, p. 511).
7. Pavement surface conditions

Subgrade soil properties inherently vary horizontally and vertically below the pavement surface. Since saturated moisture content varies with material type, measured moisture may be more indicative of soil properties than of the amount of water in the soil.

If base type affects subgrade moisture, moisture contents measured immediately beneath different bases should be different. High moisture implies poor subgrade protection, while low moisture suggests that the subgrade was protected from surface moisture penetration.

Three of the four SPS 2 sections constructed on fine-grained soil in NC showed moisture contents that were generally higher but with smaller variations throughout the monitoring depths than sections on fine-grained soil in Ohio. These differences were likely to be the result of site specific conditions. Long-term moisture data collected from the OH and NC sites can be summarized as follows:

1. All sites showed annual moisture cycles at all depths. Figure 6 is a typical example of these cycles in OH Section 390205, which oscillated around average values which remained relatively constant over the years. Figure 7 shows how moisture continued to increase with time near the top of the subgrade in OH Section 390208.

2. The amplitudes of annual moisture cycles at a depth of about 1.8 meters (6 ft) below the subgrade surface were very small at all sites. In general, moisture content (MC) levels at 1.8 meters (6 ft) were higher than or at least the same as those at shallower depths, as shown in Table 3. This may indicate that the soil was near saturation at that depth. Exact depths to TDRs in the various sections will vary according to build up.
3. The amplitudes of annual moisture cycles at different depths were not the same for all sections.
4. Lower moisture variations with depth suggested that water infiltrated from the pavement surface. Since the amplitudes were small and the median remained about the same during the year, the effect of moisture variations on subgrade resilient modulus were minor.
5. The range of moisture contents measured between 0.07 to 0.23 meter (3 and 9 inches) below the top of the subgrade were as follows under different surface types and bases: AC on GB (1.5 to 2.1%), AC on PATB (2.4 to 2.7%), AC on ATB (3.4%), JCP on LCB (1.9 to 5%), JCP on GB (1.7 to 4.5%) and JCP on PATB/GB (1.1 to 2.4%). This range of depths is provided to cover TDR locations in the various sections.
6. TDRs installed at mid-depth in the GB layer showed that median moisture contents and variations in moisture were very low within this layer. Figure 7 is a plot of moisture recorded in the middle of GB layers on the Ohio SHRP Test Road.

Appendix A shows plots of annual moisture cycles at different depths for all monitoring sites.

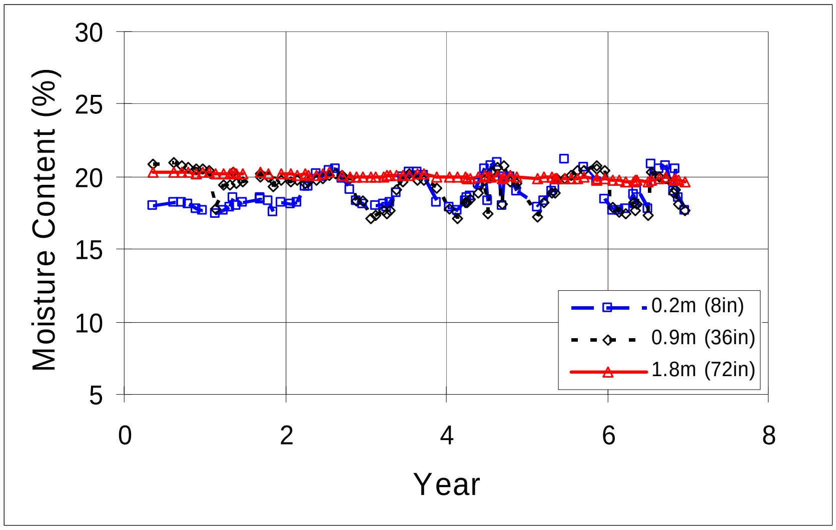


Figure 6. Annual Moisture Cycles at Different Depths in Ohio Section 390205 with LCB

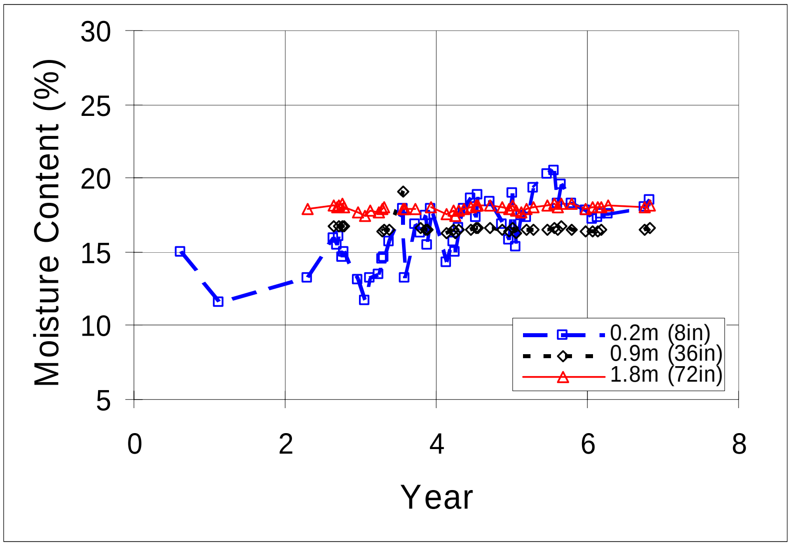


Figure 7. Annual Moisture Cycles at Different Depths in Ohio Section 390208 with LCB

Table 3. Annual Moisture Cycles at Different Depths by Section (390xxx sections are in Ohio, 370xxx sections are in North Carolina)

Moisture Parameter		Median (%)			Amplitude (%)		
Depth below subgrade surface (m)		0.2	0.9	1.8	0.2	0.9	1.8
Depth below subgrade surface (ft)		0.66	3.0	5.9	0.66	3.0	5.9
Section	Base Type						
390101	GB	18.7	19.3	20.9	2.1	1.6	0.5
390104	ATB	19.3	19.2	20.1	3.4	2.5	1.5
390108	PATB-GB	19.2	15.6	19.1	1.5	2.3	0.4
390110	ATB-PATB	19.8	19.1	20.2	2.4	3.8	0.5
390112	ATB-PATB	18.5	17.7	17.8	2.7	1.4	0.4
370201	GB	30.5	26.1	25.2	4.5	0.8	1.7
390201	GB	18.1	19.1	18.1	4.0	2.1	1.5
390202	GB	17.6	16.7	18.6	4.2	3.1	0.8
390204	GB	17.9	19.2	20.1	1.7	2.2	0.9
370205	LCB	25.0	25.7	21.9	5.0	0.9	2.6
370208	LCB	10.2	13.6	16.5	1.9	1.7	1.3
390205	LCB	19.4	19.0	19.8	3.5	2.2	0.3
390208	LCB	18.9	16.5	18.1	3.4	0.4	0.4
370212	PATB-GB	26.9	23.9	21.2	1.1	1.4	1.5
390211	PATB-GB	16.8	19.2	18.8	2.4	2.8	1.5
390212	PATB-GB	17.9	18.7	20.7	1.9	1.2	0.7

Figure 7 above shows minimal annual moisture cycling in OH Section 390208 with lean concrete base. Figure 8 is a plot of moisture variations found in all OH AC and JCP sections on granular bases. Figure 9 is a plot of moisture contents recorded at different depths in OH Section 390108 with PATB and GB. Figure 10 is a plot of moisture contents in the top soil layer (150mm below subgrade) in two NC LCB sections. Differences in the level and amplitude of the moisture cycles indicated that surface water may play a greater role on NC Section 370205 than on NC Section 370208.

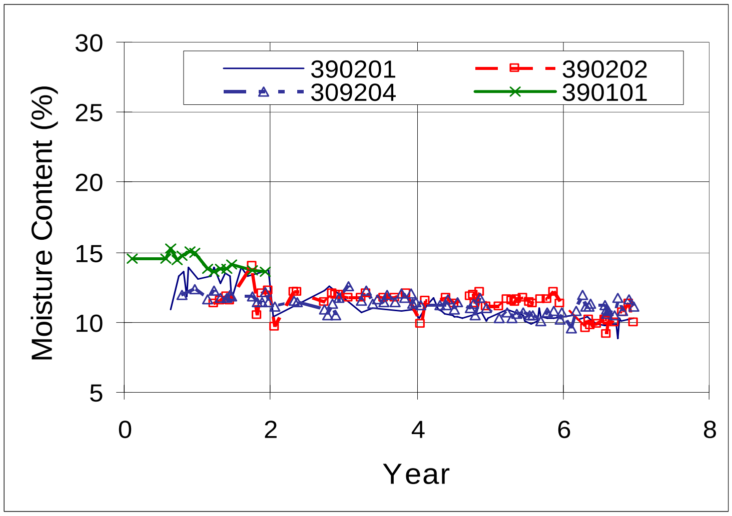


Figure 8. Moisture Variations in OH AC Section (390101) and JCP Sections (390201, 390202 and 390204) on GB

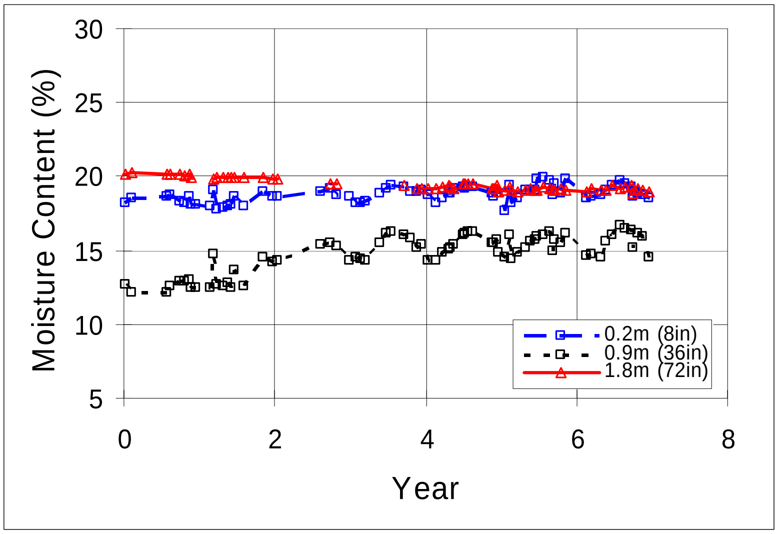


Figure 9. Moisture Variations in OH Section 390108 with PATB and GB

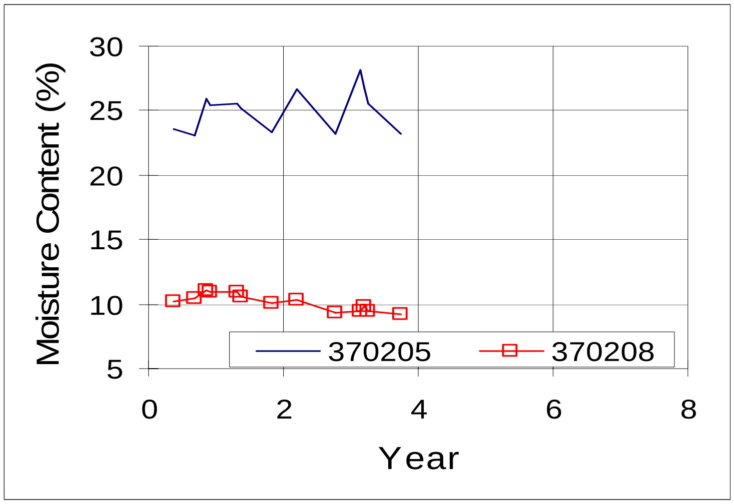


Figure 10. Moisture Variations in NC Sections 370205 and 370208 with LCB

Range of Moisture Content Deviations from Mean

Tables 4 to 6 show how the moisture content 0.07 to 0.23 meter (3 to 9 inches) below the subgrade surface deviated from the section mean for different base types.

Table 4. Range of Moisture Content Deviations from the Mean under Granular Base

Section	NC 370201	NC 370212	OH 390101	OH 390108	OH 390201	OH 390202	OH 390204	OH 390211	OH 390212
Max. Positive Dev. (%)	0.37	0.57	1.45	1.86	1.55	1.47	1.09	2.06	1.47
Max. Negative Dev. (%)	-0.73	-0.53	-1.20	-1.73	-2.45	-1.83	-1.53	-1.96	-1.52

Table 5. Range of Moisture Content Deviations from the Mean under LCB

Section	NC 370205	NC 370208	OH 390208	OH 390205
Max. Positive Dev. (%)	3.07	0.95	2.30	4.14
Max. Negative Dev. (%)	-1.93	-0.95	-1.38	-4.78

Table 6. Range of Moisture Content under Asphalt Stabilized Base

Ohio Section/Base Type	390104 ATB	390110 PATB	390112 PATB
Max. Positive Dev. (%)	2.00	1.22	1.55
Max. Negative Dev. (%)	-1.43	-1.19	-1.18

Figures 11 to 13 are plots of the subgrade moisture content deviation from the mean beneath pavements containing GB, LCB and PATB or ATB, respectively. Moisture variations from the mean for all sections with GB were similar except one section (370201) that was different from others (Figure 11). Also, all LCB sections were similar except one site (370208), which was very different from others (Figure 12). All PATB and ATB data were from Ohio. Moisture variations from the mean were also similar (Figure 13).

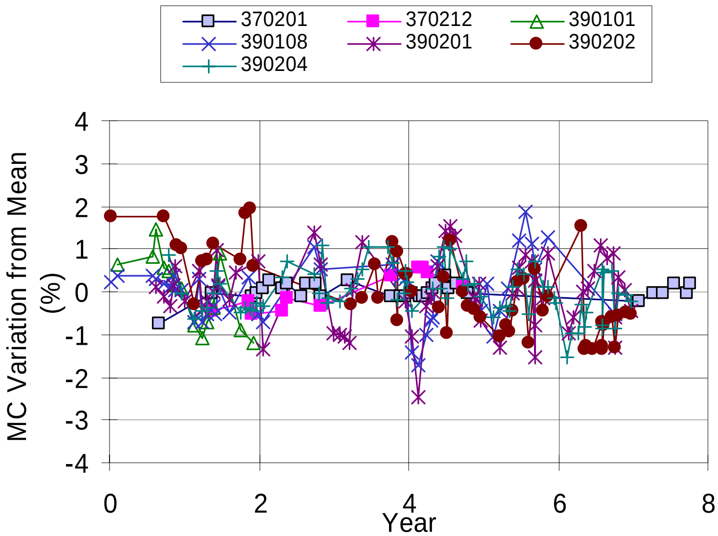


Figure 11. Moisture Deviations from the Mean on NC and OH GB Sections

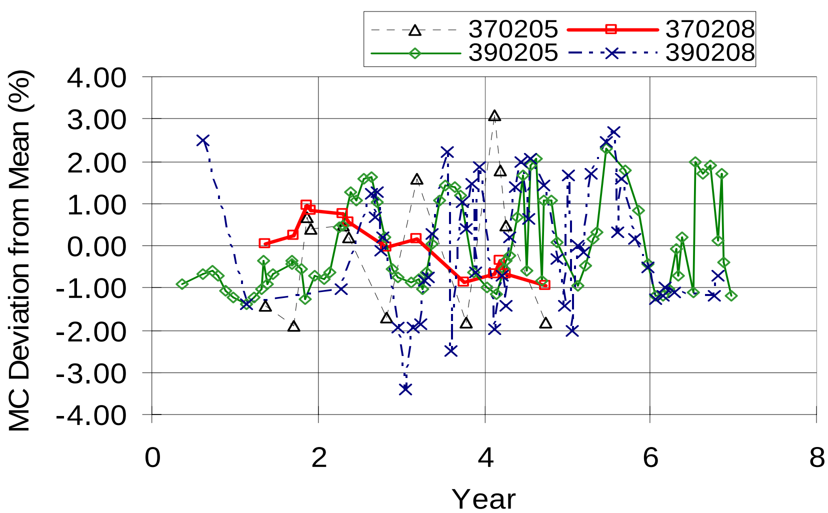


Figure 12. Moisture Deviations from the Mean on NC and OH LCB Sections

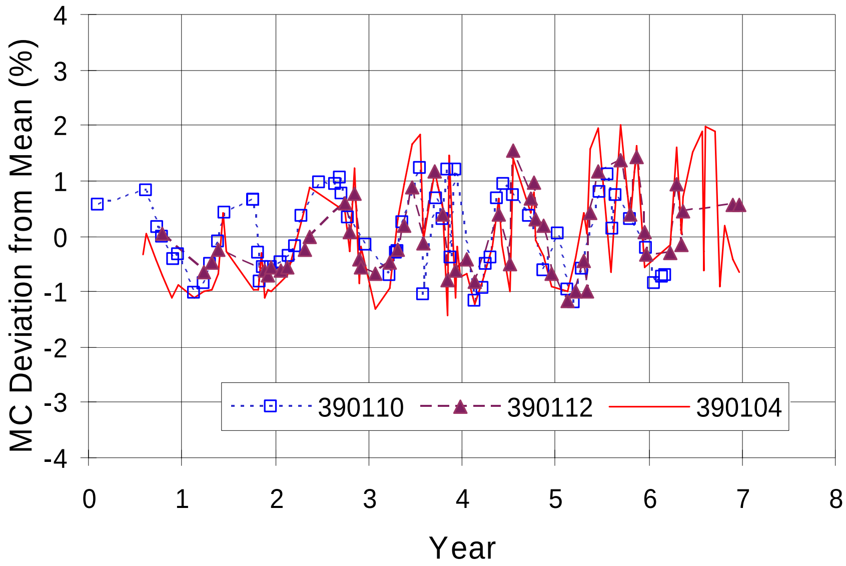


Figure 13. Moisture Deviations from the Mean on OH Sections
with PATB (390110 and 390112) and ATB (390104)

Variations in long-term subgrade moisture can be summarized by the following:

1. Subgrade moisture variations under GB, ATB, and PATB were nearly the same, indicating that the effects of these base types on subgrade moisture were similar.
2. Subgrade moisture content under LCB varied widely from site to site, which may be attributed to the relative location of the TDRs and any possible LCB cracks. The NC field investigation indicated that the interface between the concrete slab and the LCB essentially becomes a channel for water to flow. It is thus expected that subgrade moisture will change substantially as water enters the LCB cracks. If this hypothesis is true, then the performance of LCB is questionable since areas near an LCB crack will be weakened further by higher subgrade moisture under the crack.
3. While SMP data from the LTPP database provided some insights into long-term moisture variations, most bases in LTPP SMP sections were GB with a few ATB and no LCB. With this limitation, the LTPP SMP database can not be used alone to determine the effect of base type on subgrade moisture.
4. LTPP SMP data alone can not support the hypothesis that base type affects subgrade moisture content.

The analysis of moisture data presented above did not prove that base type has a significant effect on subgrade moisture. Soil moisture under LCB may be affected by contraction cracks in the LCB which provide a path for water to infiltrate the subgrade and eventually have a negative effect on pavement performance.

It is important to point out that the data used for this analysis were collected from relatively new pavement sections with minimal surface cracking. These good surfaces reduced any negative effects of surface cracks in the LCB had on subgrade moisture.

EFFECTS OF BASE TYPE ON DEFLECTION

FWD Data Collection

Layer Deflection

Falling Weight Deflectometer (FWD) tests were performed on individual material layers as the Ohio SHRP Test Road was being constructed. Deflection data were taken along the centerline of the lane and in the right wheel path at 15.2m (50') intervals. Multiple load levels were applied, including 8.9, 13.4, 17.8, and 22.3kN (2, 3, 4, and 5 kip) on the subgrade and 26.7, 40, 53.4, and 66.7kN (6, 9, 12, and 15 kip) on the base and pavement layers. Two drops were applied at each load level for a total of eight drops per test location.

Curling Effect on Deflection

In order to understand how curling affects slab deflection, the FWD was used to obtain deflection data on the NC US-52 test sections at different times of the day and at different locations on the slabs. FWD tests were performed at the quarter points of the slab along the center and outside edge of the slabs. Target loads were 26.7, 40, and 53.4kN (6, 9 and 12 kips). Tests were performed at dawn, mid-morning, noon and mid-afternoon. These times represented conditions with the maximum negative, zero and maximum positive temperature gradients.

Data Analysis

Layer Deflection

Since FWD data were collected at different times of the year and at different times of the day, highly dissimilar temperatures and moisture contents would be expected to affect the measured deflections. Unbound material was tested soon after construction when moisture would be expected to be close to optimum. No attempt was made to normalize deflections on the asphalt treated base (ATB) to a reference temperature.

Deflections obtained during multiple drops at the same load level were averaged together. Subgrade deflections near the 20kN (4.5 kips) load level were normalized to 20kN (4.5 kips) and then extrapolated to a 40kN (9 kips) load. With the exception of a few test locations, the extrapolated load-deflection relationships were linear (R2 = 0.99), which implied that the error induced by this extrapolation was not significant. For all other layers, deflections near the 40kN (9 kips) load level were also normalized to 40kN.

Maximum FWD deflections at the center of the loaded plate (D0) on the subgrade and base layers were normalized to 40kN (9 kips), as shown in Table 7. Numbers after the base symbol represent the layer thicknesses in millimeters.

Subgrade

Normalized subgrade deflections on the Ohio SHRP Test Road ranged between 0.28 mm (0.011 in) and 7.06 mm (0.278 in), with the average deflection being 1.37 mm (0.054 in), the standard deviation being 0.98 mm (0.039 in), and the Coefficient of Variation (COV) being 0.71.

COV is standard deviation divided by the average and is an indicator of variability within a set of data. Figure 14 is a plot of the subgrade deflection distribution showing a long tail to the right. Ninety percent of these data points fell within 0 to 3 mm (0.12 in), with only 10% falling above 3 mm (0.12 in).

Table 7. Normalized FWD Deflection Data in mm (1 mm = 39.37 mil)

Layer Type	Deflection D0 (mm/9 kips)			Std. Dev.	Coefficient of Variation	No. of Data Points
	Average	Max	Min			
Subgrade	1.37	7.06	0.28	0.98	0.71	357
GB100	1.55	3.11	0.71	0.56	0.36	139
GB150	1.22	2.67	0.58	0.44	0.36	56
GB200	1.04	2.25	0.62	0.35	0.34	41
GB300	0.85	1.41	0.50	0.17	0.20	31
LCB	0.17	0.39	0.11	0.05	0.29	79
PATB	1.05	1.82	0.68	0.26	0.25	62
PATB(G)	0.90	1.76	0.60	0.20	0.22	82
ATB100(B)	0.59	0.80	0.35	0.08	0.14	21
ATB200	0.30	0.44	0.24	0.05	0.17	20
ATB200(B)	0.17	0.21	0.12	0.02	0.12	21
ATB300	0.12	0.15	0.10	0.01	0.08	32
AC100(G)	0.74	0.96	0.56	0.10	0.13	21
AC175(G)	0.35	0.47	0.30	0.04	0.12	21
AC100 (A)	0.21	0.37	0.10	0.08	0.38	84
AC175(A)	0.18	0.25	0.09	0.05	0.28	94

All materials on subgrade, except: (G) on GB, (B) on GB or PATB, and (A) on ATB

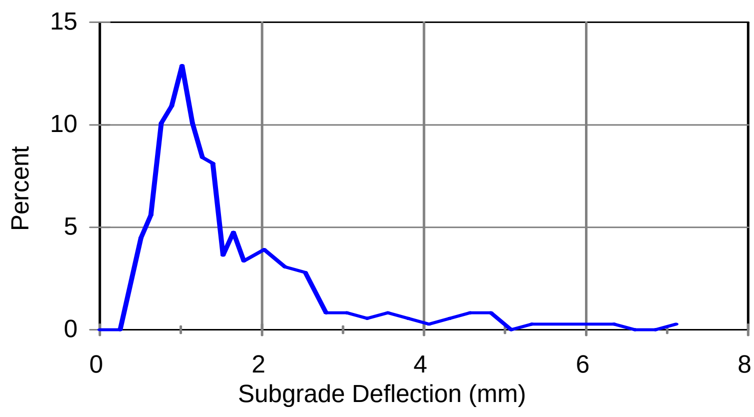


Figure 14. Subgrade Deflection Distribution for Ohio sections. (1 mm = 39.37 mil)

Current subgrade acceptance specifications are based on density test results which, on the Ohio project, showed the average nuclear gauge dry density to be 1.812 g/cm3 (113.15 pcf) with a standard deviation of 0.0916 g/cm3 (5.72 pcf) and a COV of 0.05. Although the subgrade density test results were quite uniform (COV = 0.05), deflection tests, which are a better indicator of subgrade strength, showed the subgrade to be highly variable (COV = 0.71). This raises concern regarding the validity of using of density measurements to control subgrade construction. Density can be used as an indicator of construction quality, but it is not a reliable gauge of subgrade strength.

Granular Aggregate Base (GB)

Figures 15 and 16, showing plots of granular base deflection versus subgrade deflection for the first FWD sensor D0, did not show any obvious trends. Figure 15 indicates that most of the data points for the 100 mm (4 in) GB were left of the line of equality, indicating that the 100 mm (4 in) GB did not improve subgrade stiffness. Table 8 summarizes average deflection, standard deviation, COV, maximum and minimum deflection of the subgrade and the GB with 100 mm (4 in), 150 mm (6 in), 200 mm (8 in), or 300 mm (12 in) thickness. It is interesting to note that, although the average deflection of the 100 mm (4 in) GB (GB100) sections was greater than that of the finished subgrade, the standard deviation of the GB100 section was smaller than that of the subgrade. The lower standard deviation held true for all sections with different GB thicknesses. These results indicate that the addition of GB improves uniformity.

Table 8. Granular Base Deflections (1 mm = 39.37 mil)

	SG	GB100	SG	GB150	SG	GB200	SG	GB300
Average	1.49	1.55	1.35	1.22	1.80	1.04	1.13	0.85
Std. Dev	1.16	0.56	1.12	0.44	0.83	0.35	0.72	0.17
COV	0.78	0.36	0.83	0.36	0.46	0.34	0.64	0.20
Max	7.06	3.11	5.51	2.67	4.07	2.25	4.39	1.41
Min	0.47	0.71	0.28	0.58	0.73	0.62	0.49	0.50

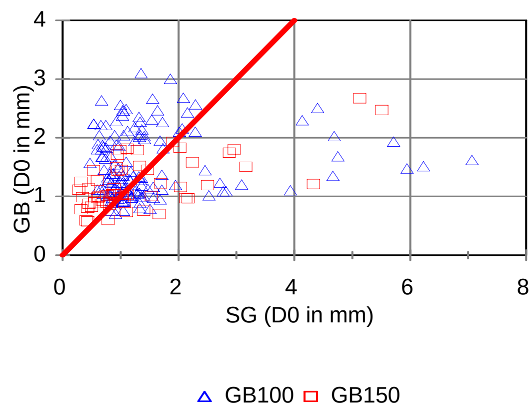


Figure 15. Thin Granular Base Deflection Comparison (1 mm = 39.37 mil)

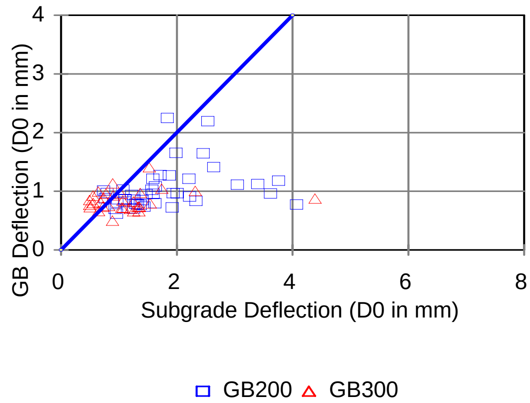


Figure 16. Thick Granular Base Deflection Comparison (1 mm = 39.37 mil)

GB deflection variability decreased as layer thickness increased. Figure 17 shows the relationship between the GB thickness and the average deflection. The effect of layer thickness on deflection and its standard deviation, which can be considered as indices of uniformity, is clearly shown.

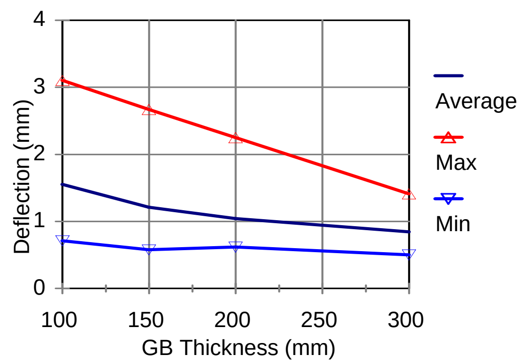


Figure 17. Average Deflection of GB with Different Thicknesses (1 mm = 39.37 mil)

Lean Concrete Base (LCB)

The analyzed sections included a 150 mm (6 in) thick lean concrete base placed on top of the finished subgrade. Figure 18 shows the distribution of LCB deflections, as well as the corresponding regression line, with respect to subgrade deflection. LCB deflections were concentrated within a narrow range from 0.11 mm (0.0043 in) to 0.39 mm (0.015 in), and it was found that subgrade deflection had very little effect on LCB deflection. A regression analysis provided the following equation with a low Coefficient of Determination (R^2):

$$D_{LCB} = 0.15 + 0.014 * D_{SG} \qquad (R^2 = 0.14)$$

Where: D_{LCB} = LCB Deflection
D_{SG} = Subgrade Deflection

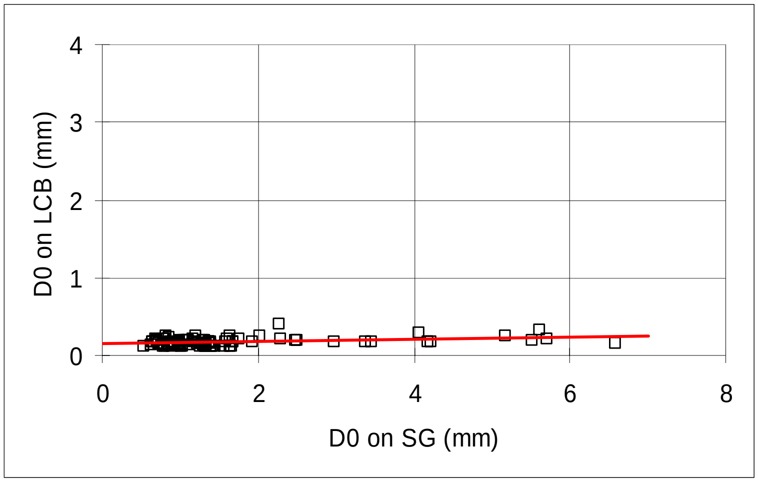


Figure 18. Lean Concrete Base Deflection Comparison (1 mm = 39.37 mil)

Permeable Asphalt Treated Base (PATB)

Four test sections were constructed with 100 mm (4 in.) PATB placed on the finished subgrade, while three other sections were constructed with 100 mm (4 in.) PATB on GB. Plots of PATB deflection on SG and on GB are presented in Figure 19. Ranges of deflection in both cases were about the same; however, the overall deflection of PATB on GB was less than that for PATB on SG, as would be expected.

The traditional approach to flexible pavement design is to build up material layers to strengthen the structure and reduce deflection. The amount PATB strengthens or stiffens the pavement system can be represented by the reduction in deflection after placement of the PATB. Since FWD tests were performed at the same locations on each layer, the changes in deflection reduction can be simply defined as the difference between deflection on the PATB and deflection on the subgrade or GB. Figure 20 is a plot of the changes in deflection with regression lines corresponding to the following deflection reduction regression equations for PATB on SG and on GB:

$$D_{PATB} = 0.82 * D_{SG} - 0.81 \qquad (R^2 = 0.84)$$
$$D_{PATB} = 0.94 * D_{GB} - 0.78 \qquad (R^2 = 0.84)$$

Where: D_{PATB} = PATB Deflection
D_{SG} = Subgrade Deflection
D_{GB} = GB Deflection

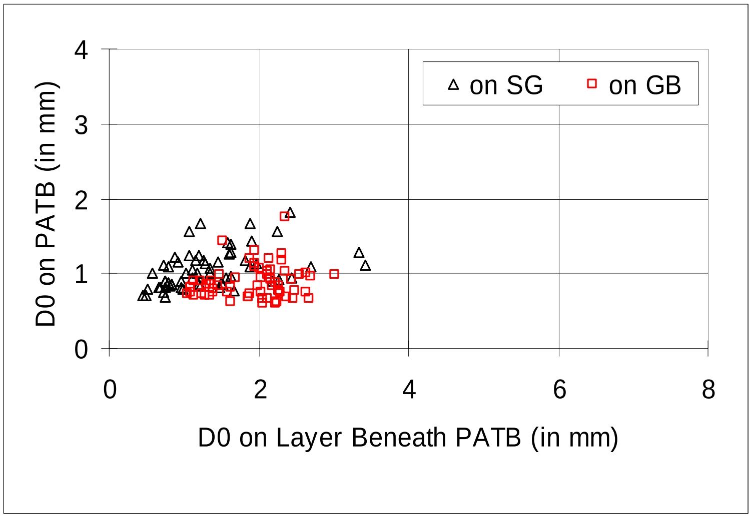


Figure 19. PATB Deflection Comparison (1 mm = 39.37 mil)

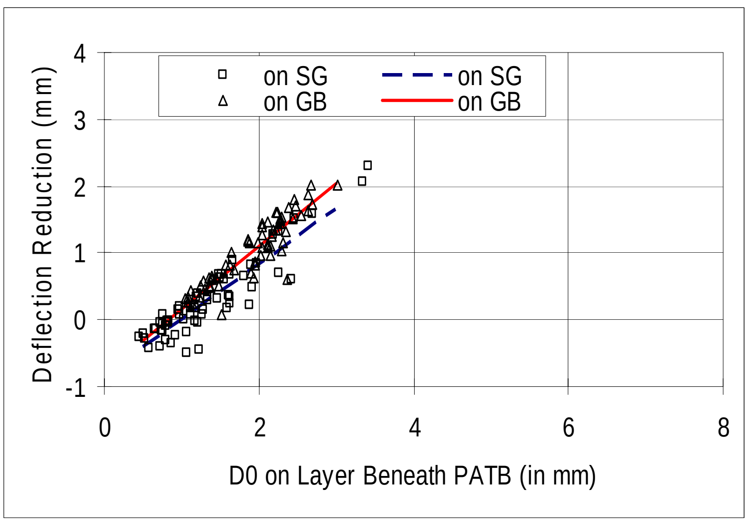


Figure 20. PATB Deflection Reduction (1 mm = 39.37 mil)

Once again, GB helped decrease the overall deflection on the SG. It is interesting to note that, when the deflection on the layer beneath the PATB was less than about 1 mm (0.04 in), a higher deflection was measured on the PATB than on the underlying layer, thereby indicating lower stiffness. This result indicated that the open graded PATB was not as stiff as the GB.

Asphalt Treated Base (ATB)

A total of seven ATB sections were constructed on the Ohio SHRP Test Road; two of which (200 mm (8 in) and 300 mm (12 in)) were placed directly on the subgrade, while the remaining five were placed on either GB or PATB. Figure 21 shows that readings for all sections with 300 mm (12 in) ATB on subgrade and GB fell along the same line. However, deflections from the

100 mm (4 in) ATB on SG were different than 200 mm (8 in) ATB deflections on GB or PATB. A regression line for the 300 mm (12 in) ATB deflection yields:

$$D_{ATB} = 0.1 + 0.017 * D_{BASE} \qquad (R^2 = 0.30)$$

The low Coefficient of Determination is due to the minimal effect of base or subgrade deflection on ATB deflection, not the predictive ability of the equation.

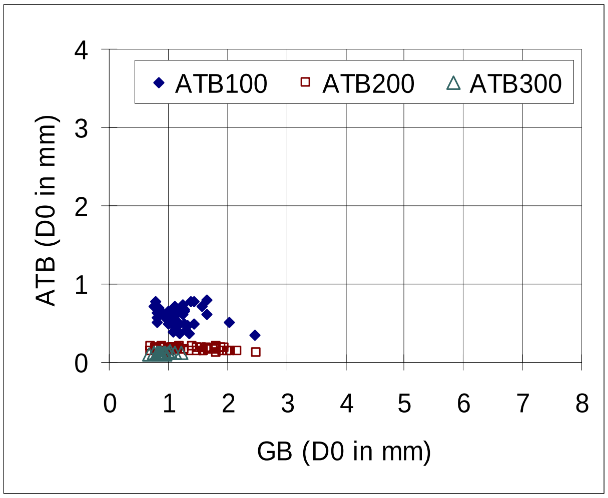


Figure 21. ATB Deflection Comparison (1 mm = 39.37 mil)

Effective Thickness

Plots of deflection data suggest that there exists an effective minimum threshold thickness for each base type at which total pavement stiffness begins to increase. Thicknesses less than the minimum threshold thickness did not effectively increase the total stiffness.

In addition, the base must be thick enough to sustain high traffic loads and have a reasonably long fatigue life. NCDOT constructed a flexible pavement experimental project on US 421 in Siler City that included some sections with 140 mm (5.5 in.) thick CTB and asphalt concrete thicknesses ranging from 50 mm (2 in) to 125 mm (5 in). These sections all had a significantly shorter service life than predicted by the AASHTO design procedures. Premature failure was caused by severe cracking of the CTB, with cracks reflecting to the surface and leading to the complete failure of these sections shortly after opening to traffic. Other projects in NC constructed with 175 mm (7 in) to 200 mm (8 in) CTB have performed satisfactorily. These results led to the hypothesis that an effective minimum thickness for CTB would be between 140 mm (5.5 in) and 200 mm (8 in). While CTB strength is a consideration, 200 mm (8 in) probably should be considered as a minimum thickness.

A large portion of deflections measured on 100 mm (4 in) and 150 mm (6 in) thick GB were greater than subgrade deflection (Figure 15). This indicated that the addition of 100 mm (4 in) or 150 mm (6 in) of GB did not improve subgrade stiffness and there is an absolute minimum deflection the GB can achieve. However, the standard deviation of GB is considerable lower than that of the subgrade. This result indicates that, while adding a GB does not improve overall stiffness, it does improve uniformity of the pavement structure.

Table 8 above summarizes the average and the standard deviation of FWD deflections on different thicknesses of GB on subgrade. It is clear that layer stiffness and uniformity improved when the GB thickness was 200 mm (8 in) or greater. This table also shows that the 100 mm (4 in) and the 150 mm (6 in) GB did not effectively improve the “apparent” stiffness of the subgrade. It is suggested, therefore, that 200 mm (8 in) be used as the minimum effective thickness for granular bases.

Figure 21 indicates that deflections on a 100 mm (4 in) ATB were widely scattered, while deflections on a 200 mm (8 in) ATB fell along a narrow band. It is thus expected that the minimum effective thickness of an ATB would be around 150 mm (6 in). Further FWD tests on 150 mm (6 in) ATB projects should help resolve this issue.

Since there was only one design thickness for LCB and PATB sections, an effective minimum thickness can not be established for these two base types. It was noted however, that the 150 mm (6 in) LCB deflection range was the same as that for the 200 mm (8 in) ATB; while the 150 mm (6 in) PATB deflection range was the same as that for the 200 mm (8 in) GB.

Curling Effect on Deflection

One goal of the North Carolina US 52 field test was to understand the effect of slab curling on base support. FWD tests were performed at different times of the day and at different locations on the slabs. Test results indicated that deflection under the load plate (D0) varied significantly with both parameters. D0s were normalized by subtracting the minimum D0 of that slab at that time period (dawn or PM). Plots of centerline and edge deflection at extreme temperature gradients in Figures 22 to 25 show that:

1. Slabs constructed on LCB had the largest deflection variation at different times of the day and at different locations on the slab and, at some locations and times, LCB provides very poor support.
2. Slabs constructed on ATB showed the least variation in deflection and, therefore, the most uniform support at all locations and all times.
3. Slabs constructed on GB and PATB showed deflection variations measured somewhere between LCB and ATB.

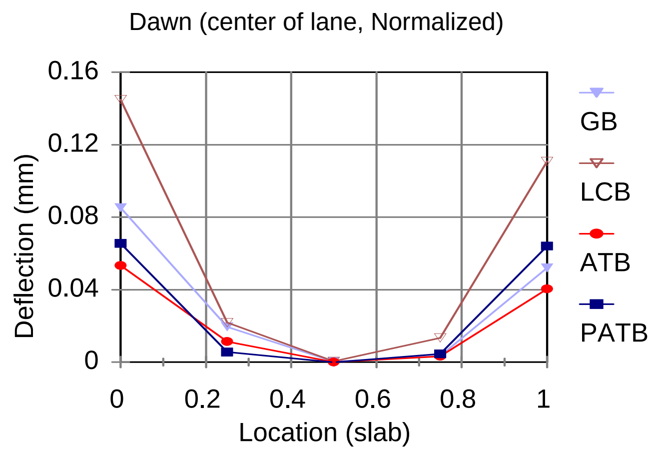


Figure 22. Center of Lane Deflection, Dawn (1 mm = 39.37 mil)

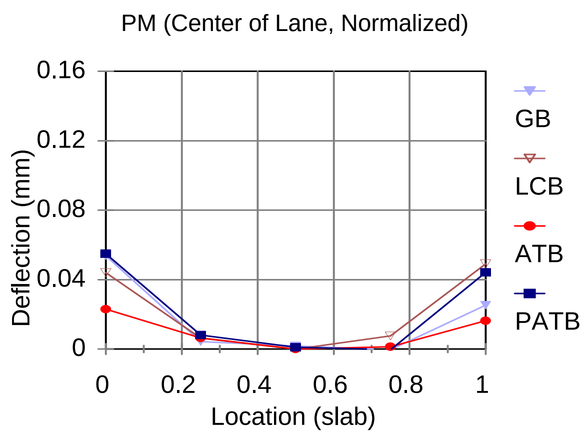


Figure 23. Center of Lane Deflection, Mid Afternoon (1 mm = 39.37 mil)

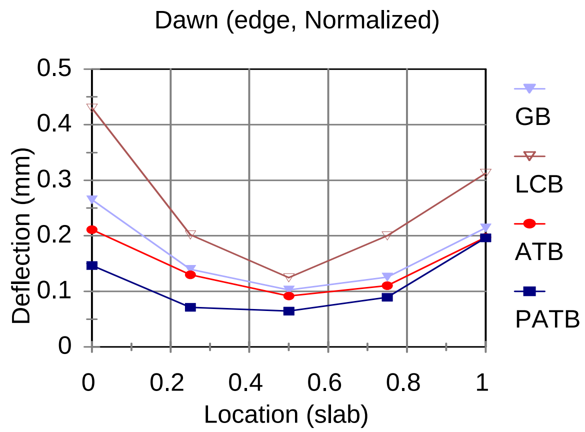


Figure 24. Edge of Slab Deflection, Dawn (1 mm = 39.37 mil)

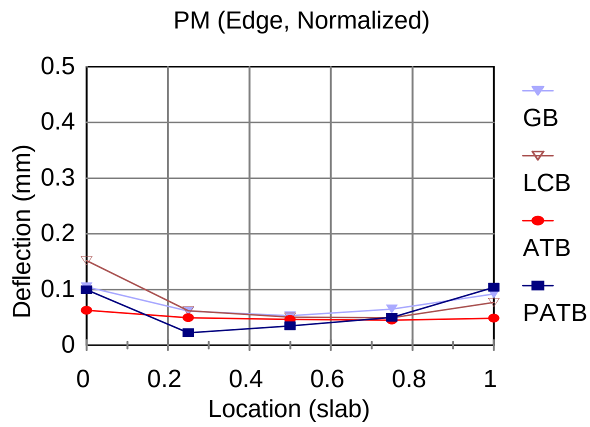


Figure 25. Edge of Slab Deflection, Mid Afternoon (1 mm = 39.37 mil)

These FWD test results indicated that curling significantly affected base support. The effect of curling is greater on stiffer bases when a smaller portion of the curled slab is in contact with the base. In this situation, curling induced dead load stresses are superimposed on higher than normal live load stresses to greatly affect slab fatigue life (Wu, 1998). FWD test results showed that base type plays a significant role in determining the effect of curling on deflection and, further, the relative stiffness of the base and slab plays a key role in the curling effect. Ultimately, stiffer bases magnify the negative effects of slab curling.

When LCB was introduced in the 1970s, the design concept was that a stiffer base would increase the overall stiffness of the pavement structure and, therefore, lower bending stresses would extend the fatigue life of concrete slabs. The catastrophic premature failure of an LCB project set off a joint study in 1985. This study included a few neighboring states with performance records on jointed concrete pavement (JCP) projects with LCB. The study found that JCP on weaker LCB (greater relative strength) performed fairly well, while JCP on strong LCB (lower relative strength) performed poorly. Field measurements indicated that concrete slabs separate from the LCB and lift up during curling (Wu and Hearne). These findings lead to the conclusion that stiffer bases increased the curling effect and caused a greater loss of slab support, thus resulting in higher stresses in the cantilevered slabs. This may be the reason for poor performance on some LCB projects. Similarly, it is hypothesized that the relative stiffness between the slabs and the base affects the fatigue life of the slabs.

There are several well-adopted stress-strength performance models (Yu, etc. 1998), with all but one being nonlinear models. It is expected, therefore, that with the same average loading, high variations in deflection will lead to poor performance. Based on this concept, concrete slabs on LCB will perform the poorest, while concrete slabs on ATB will perform the best. Surface distress surveys widely support this concept.

BASE TYPE EFFECT ON SURFACE DISTRESS

An FHWA research project used the LTPP database to compare good and poorly performing PCC pavements (Khazanovich, etc. 1998). Researchers found that, for non-doweled sections, 59% of good sections had stabilized bases and 62% of poor sections had granular bases. The results for doweled sections were about the same, but slightly less significant (54% and 59% respectively). An obvious effect of base type on JCP performance was also found by comparing slab cracking in sections with different types of base, as shown in Table 9 (after Khazanovich).

Table 9. Percent JPC Sections with at Least One Transverse Crack

Base Type	LTPP	RIPPER
ATB	8	28
GB	22	38
SCB *	38	100
CTB *	42	68
LCB	56	38

* SCB: Soil cement base   CTB: Cement treated base
RIPPER is a database maintained by ERES

The LTPP SPS 2 test plan was designed to compare the effects of different design features on JCP performance. One of these features was different types of base material; namely GB, LCB, and PATB. Although the SPS 2 projects are of different ages, all included basically the same feature combinations (half factorial design) and all sections were 152.4 m (500 ft) long. Average distress per section from all SPS 2 projects was a good indication of the overall performance of these different base types.

Performance results from the LTPP DataPave SPS 2 data (2003 or the most recent data) are presented on Table 10. It is clear that LCB sections had the highest occurrence of cracking and spalling; followed by GB sections. Of these three types of bases, PATB performed the best. Joint faulting for all sections was very low. Joint spalling on LCB sections was significantly greater than that on GB and PATB sections. The same trends were observed on all individual SPS 2 projects.

The NC SPS 2 project included a supplemental section with a 280 mm (11 in.) slab on ATB. The 2003 surface distress survey record showed very minor surface distress for this 10 year old project. Table 11 shows the surface distress of 280 mm (11 in.) slab sections containing different bases. Results indicated that the section with ATB has performed better than the section with PATB, which had considerable spalling.

Table 10. Average JCP Surface Distress per Section (1 m = 3.28 ft)

Base Type	Cracking (m)	Spalling (m)	Corner Breaks (number)	Patching (m^2)	Pumping (m)	Average Faulting
LCB	47.43	9.08	0.07	8.86	0.71	0.28
GB	15.60	7.20	0.09	0.68	17.76	0.16
PATB	5.54	6.34	0.02	0.91	1.83	0.16

Table 11. NC SPS 2 - 11” (280 mm) Slab Surface Distress (1 m = 3.28 ft)

Base Type	Cracking (m)	Spalling (m)	Pumping (m)	Average Faulting (mm)
PATB	0.00	62.30	0.00	0.10
ATB	0.00	3.10	0.00	0.20
GB	0.00	2.80	0.00	0.60
LCB	0.00	4.00	0.00	0.30

The data presented in Tables 9 to 11 support the hypothesis that relative strength (stiffness) of slabs and base is an important factor in JCP fatigue life. SPS 1 data from DataPave, including the 2000 data, did not show the same effects of base type on flexible pavement performance. Table 12 shows average distress per section.

Table 12. Average Flexible Pavement Surface Distress per Section (1 m = 3.28 ft)

Section	Longitudinal Cracking (wp)	Longitudinal Cracking (nwp)	Transverse Cracking	Pumping	Alligator Cracking	Block Cracking	Patching
	(m)				(m^2)		
101	6.74	19.97	3.90	0.14	23.19	0.00	39.06
102	9.59	9.26	11.16	8.64	47.17	0.00	93.87
103	25.44	42.30	4.79	0.34	26.29	15.16	29.59
104	10.70	80.71	3.27	0.31	18.43	1.97	28.37
105	7.80	75.14	9.53	0.39	45.59	0.00	39.06
106	47.96	41.51	4.79	0.00	27.12	7.30	30.29
107	7.50	43.93	3.56	0.14	16.67	0.00	48.36
108	25.86	22.56	2.89	0.00	38.35	39.53	36.30
109	30.51	62.45	1.94	3.55	19.91	62.55	35.83
110	27.29	40.88	2.96	0.00	39.39	23.56	33.73
111	13.22	22.40	1.02	0.00	17.91	61.78	28.51
112	16.99	35.60	1.06	0.00	9.63	44.26	30.02
113	20.84	60.09	12.98	3.09	28.65	0.00	0.00
114	1.08	93.79	8.38	0.00	18.79	0.00	0.00
115	10.98	86.88	2.86	9.69	10.17	0.00	6.88
116	0.76	68.86	2.00	0.00	5.52	0.00	0.02
117	12.00	60.61	2.84	1.99	10.71	0.00	0.00
118	17.18	69.60	2.14	0.00	3.98	0.00	0.03
119	11.24	94.29	9.64	0.00	28.85	0.00	6.55
120	0.90	81.96	8.33	0.11	22.12	0.00	4.31
121	16.91	75.01	9.20	0.00	25.06	0.00	0.00
122	0.19	81.40	1.96	0.00	18.28	0.00	0.00
123	16.36	86.86	2.06	6.32	4.68	0.00	0.00
124	13.12	63.01	1.81	0.00	5.62	0.00	0.10

Findings

Based on data collected from the Ohio SHRP Test Road and the NC US 52 project, as well as the DataPave database and related studies, researchers found that:

1. Concrete pavement performance was highly dependent upon base type. JCP pavements performed best with ATB and worst with LCB.
2. The 150 mm (6 in) LCB was stiffer than the 200 mm (8 in) GB and about the same as the 200 mm (8 in) ATB.
3. GB thicknesses less than 200 mm (8 in) did not increase overall system stiffness, although it did improve uniformity.
4. GB, 200 mm (8 in) or thicker, increased the stiffness and uniformity of the subgrade.

5. Increased GB thickness resulted in a stiffer and more uniform support.
6. An increase in ATB thickness from 100 mm (4 in) to 200 mm (8 in) greatly increased structural uniformity.
7. SMP data did not prove that base type significantly affected subgrade moisture.
8. Subgrade soil around LCB contraction cracks was susceptible to surface water intrusion.
9. The amplitude of annual moisture cycles and the median moisture content of the subgrade remained relatively constant over the years, except on the LCB sites. The effect of base type on subgrade moisture contents was negligible.
10. Subgrade deflections measured with the FWD were highly variable, even though subgrade density test results met specification requirements.
11. Deflection data indicated that slabs on LCB were most affected by curling, while slabs on asphalt stabilized bases were least affected by this temperature-related phenomenon.

BASE REQUIREMENTS

The mechanisms by which rigid and flexible pavements carry loads are different and the bases under these pavements serve different functions. Hence, approaches for the selection of bases for these two types of pavement must be different.

Subgrade

Because subgrade is the one pavement component over which designers and contractors have the least control, adequate testing must be performed to characterize this layer over the entire project length. If all or a portion of the subgrade is deemed unsuitable to support the pavement, it must be modified to improve strength and uniformity. There are several methods available to improve the quality of subgrade support; namely: undercut and replacement with better material, geo-textile reinforcement, mechanical and chemical modification, etc.

Chemical and mechanical modification provides a stronger and more stable platform for subsequent construction operations, improves the overall uniformity of the subgrade, and enhances pavement performance. The selection of the type of subgrade improvement depends upon several factors, including: mechanical properties and chemical reactivity of the natural soil, material availability, quantity, cost, and pavement type. Chemical modification of the subgrade results in a stiff, non-erosive layer that acts as a moisture barrier.

Among the most critical characteristics of subgrade soil are variations in moisture experienced during the service life of the pavement and the effect these variations have on strength. Increased moisture can have a dramatic effect on the strength of fine-grained soils. Water may migrate down into the pavement structure from the surface, laterally from the sides, or up from the ground water table. Good maintenance will minimize the intrusion of water through joints, cracks and other openings in the surface. A lower ground water table will lessen its effect and the provision of longitudinal drains will control moisture directly beneath the pavement to a certain extent. These factors should all be considered during design to minimize the intrusion of water.

Rigid Pavement Base Type Selection Considerations

The purposes of the base under a rigid pavement slab are to provide:

1. Uniform support for the slab at all times (i.e., minimize the loss of support due to curling and warping.)
2. A non-erosive and drainable layer to prevent pumping.
3. A platform to support construction equipment and traffic.

According to the AASHTO design guide, slab thickness is not particularly sensitive to the modulus of subgrade reaction (k) value. Therefore, increasing the k-value by improving base strength is not a cost-effective approach.

Curling Effect

Concrete slabs curl and warp constantly under the influence of temperature and moisture gradients, and stiffer bases do not necessary provide better support for the slabs at all times. FWD tests showed that, when slab edges are curled upward, much of the slab is not supported by LCB. Poor performance of JCP on LCB is the result of this loss of support. Thus, base stiffness must be considered when selecting base materials for a rigid pavement.

Permeability

Factors contributing to rigid pavement pumping include free water, differential slab movement, erodable material, and loading. Modern JCP design encourages the use of load transfer devices to eliminate differential slab movement, stabilized base material for support, drainable bases to remove water quickly, and sealed joints and cracks to minimize water intrusion. These preventative measures will all help reduce pumping.

PATB is an open graded layer that allows the percolation of large quantities of water. In one field demonstration, water poured from a water truck on PATB disappeared immediately. Due to its openness, however, stripping and secondary consolidation are major concerns. Cores taken from a project on I-40 in Johnston County, North Carolina with well sealed slabs in a wet, non-freeze zone, showed PATB to be in good, solid, dry, clean condition after 10 years. No stripping was observed on this project. On the other hand, PATB on the Ohio SHRP Test Road was unstable; it rutted under construction traffic and some stripping was noted. This leads to the following questions:

1. How much water is expected in the base of a rigid pavement with sealed joints?
2. How much permeability is sufficient?
3. What is the long-term effect of stability and stripping on performance?

The quantity of water running through a base is determined largely by how much water infiltrates through joints and cracks in the pavement surface and the permeability of the base material. Excess water runs off to the edges of the pavement. More water can permeate through pavement systems constructed with open bases, such as PATB.

Should subsurface water channels be provided for water to flow freely? Is the permeability that PATB offers really necessary? Should stability be sacrificed for high permeability? The obvious answer to these questions is “no”. Under most circumstances, PATB permeability is excessive and the resulting risks outweigh the potential benefits.

Constructability

Two issues must be addressed regarding base constructability. First, the base material must be sufficiently stable to support construction equipment during subsequent paving operations. Any instability can lead to deformation or rutting of the surface prior to paving. Second, the base must provide uniform support for the pavement. Areas of weakness in the base or subgrade can result in localized failures and poorly performing pavements.

While LCB is a good, strong base that can carry construction vehicles, contraction cracks often cause reflective cracks in JCP slabs. . In NC, reflective cracking was reduced significantly when roofing felt was placed on top of the LCB cracks. But LCB contraction cracks are unavoidable and can serve as expedient channels for surface water to reach the subgrade and reduce support

GB is sufficiently stable to carry construction vehicles with minimal deformation in the finished surface. It also provides a solid, smooth platform for pavers. LTPP data indicated that pumping can be a problem in sections with granular base.

PATB is relatively stable at cool temperatures. On hot days, however, haul trucks can leave deep tracks in the PATB as it shoves under load. Uneven base surfaces may result in nonuniform pavement thickness and poor pavement performance. Yet, with proper equipment and reasonable care, PATB can provide an adequate support perform for paving equipment and for the overlying pavement.

ATB provides a stable base layer that adequately supports construction equipment. NC and OH have successfully constructed ATB for many years.

Surface Distress

Surface distresses are generally associated with particular defects. For example, joint faulting indicates pumping, transverse cracking in rigid pavements are load-induced, joint spalling may be a sign of poor joint seals or defective concrete, and D - cracking suggests poor aggregate quality. Surface distresses associated with bases include faulting and transverse cracking. Non-erosive base materials and load transfer devices can reduce faulting. Base materials that maximize slab support under all environmental conditions will reduce transverse cracking.

Flexible Pavement Base Type Selection Considerations

Flexible pavement bases need to provide:

1. Improved uniformity over nonuniform subgrades.
2. Increased stiffness to minimize radial strain at the bottom of AC pavements.

3. Distributed loads to minimize vertical strain on the subgrade.
4. Drainability or insulation to protect the subgrade from surface moisture.
5. Support for construction operations (i.e., hauling, equipment operation, and compaction).

Deflection Reduction

FWD deflection is a measurement of pavement stiffness. From a mechanistic point of view, pavements are designed by building up layers and reducing deflection until an acceptable stiffness is attained. Changes in deflection after a new layer of material has been added are a measure of the strength of that layer and the composite interaction of that layer with underlying layers.

Surface Distress

Surface distresses in flexible pavement point to specific pavement defects. For example, stripping and raveling indicate material defects, rutting can suggest either an unstable AC mix or excessive base/subgrade deformation, longitudinal and alligator cracking results from fatigue failures, and transverse cracking is caused by thermal effects. Proper base selection and design can minimize fatigue failures and subgrade deformation.

Subgrade Moisture Intrusion

In this analysis, data collected from LTPP SMP sites did not show a significant effect of base type (GB, ATB and PATB) on subgrade moisture content.

CONCLUSIONS

Based on findings from this study, researchers concluded that:

1. Since soil properties are inherent to soil type and soils are non-isotropic, sufficient data must be gathered to evaluate the range of conditions existing on each project. During design, relatively few soil samples have traditionally been collected and tested in the laboratory to describe soil conditions over an entire project length. Limited testing can lead to unreliable results and poor pavement performance. Extensive FWD tests performed at the Ohio SHRP Test Road indicated that, even when the finished subgrade was accepted by QC/QA density tests, FWD deflections, which measure in-situ stiffness and are indicative of in-situ strength, were highly variable.
2. Because of differences in the stiffness of asphalt concrete and Portland cement concrete, rigid pavement performance is less sensitive to subgrade stiffness than flexible pavement performance. LTPP data support the hypothesis that the relative stiffness between the pavement and the underlying layers affects fatigue life. Therefore, it is important to consider slab-base interactions when selecting appropriate bases for rigid pavement.
3. ATB provides the most uniform slab support because of its ability to adapt to slab deformations. FWD data indicated that this adaptability minimizes the adverse effects of curling and warping.

4. Because of the rigidity of LCB, the level of support it provides is highly dependent upon slab shape, which can vary with environmental conditions, location on the slab and time of day. When slabs deform upward, voids are formed under the slab, support is lost, and particles can enter the voids. Although the k-value of LCB is very high, the loss of support caused by slab deformation results in poor performance.
5. JCP sections with GB performed fairly well. This type of base provides reasonably good support under deformed slabs, with the advantage that it is the least expensive of all base materials in the study. It is important to keep in mind that GB is an erodable base but, with proper joint seals and load transfer devices, pumping may not be a serious problem. However, poor pavement maintenance may eventually lead to pumping.
6. LTPP DataPave data indicated that JCP sections with PATB performed better than those with GB and LCB. PATB base provided more uniform support for deformed slabs and faster drainage capability. FWD results indicated that pavement with PATB experienced greater deflection, or lower stiffness, and the open graded hot mix may also lead to long-term stripping and loss of stability.
7. While ATB was not included in the basic SPS-2 experiment, one ATB section was added as a supplemental SPS-2 section in NC. Performance data indicated that JCP on ATB performed better than JCP on PATB. ATB was stiffer, less permeable, and more stable than PATB. PATB, which provides excessive permeability and encourages the creation of water channels under the pavement, may lead to subgrade erosion and a loss of support as surface water infiltrates through cracks and deteriorated joint seals in the pavement.
8. The selection of base material for flexible pavements is dependent upon subgrade stiffness and uniformity. To select the appropriate type of base, it is necessary to have well covered subgrade stiffness data. The current density-based acceptance specification can not confirm these qualities.
9. Of the four types of base studied, LCB (CTB) is the stiffest base and the PATB is the softest.
10. FWD test results indicated that a GB of 200 mm (8 in) and thicker increases both stiffness and uniformity. Also deflection on 200 mm (8 in) thick ATB is much more uniform than that on 100 mm (4 in) thick ATB. These results suggest that to effectively improve support of the surface course, there may be a minimum thickness for different types of base.
11. Moisture data and field observation suggested that contraction crack in LCB can be a direct channel for surface water to reach the subgrade. A CTB contraction crack will reflect to an AC surface and create a direct access path for surface water to reach subgrade soil.

RECOMMENDATIONS

In-situ soil stiffness can be measured with the FWD, the Dynamic Cone Penetrometer (DCP) and the soil stiffness gauge. Current density-based acceptance specifications do not ensure that the in-situ stiffness of the subgrade will be sufficient to support the expected performance. It is recommended that an acceptance specification to properly monitor subgrade stiffness and uniformity during construction be developed. A construction contract that allows agencies to adjust pavement designs to achieve the expected level of performance after the subgrade has been completed should be developed.

Mechanical and/or chemical stabilization techniques can be used to improve both subgrade stiffness and uniformity. These options should be considered when subgrade soils in their natural state are questionable.

It is hypothesized that there is a minimum thickness requirement for different types of bases to function and effectively improve subgrade support. Further research is needed to identify what these minimum thicknesses are.

Thinner CTB does not have the structural strength to support heavy axle loads. Enough thickness must be constructed to prevent damage by occasional heavy loads. Base thickness is a function of subgrade stiffness, strength of CTB and thickness of AC layers. An in-depth analysis needs to be performed to verify the minimum thickness requirement.

LTPP data indicated that performances of JCP on LCB were very poor. This stiff base shall be avoided by all means.

ATB is by far the best base material for JCP. An optimal choice for rigid pavement base may be a modified ATB that can provide some drainage capability. Further study is needed to modify ATB mix design to make it more permeable.

GB is a low cost base material. It performed reasonably well and can be a viable base for lower traffic facilities.

The selection of base material for flexible pavements is dependent upon subgrade strength. To select the appropriate type of base, it is necessary to have complete subgrade stiffness data and the following guidelines are recommended:

1. For uniformly weak or highly variable subgrades, bases with high stiffness, such as CTB, ATB, or very thick (> 300 mm (12 in)) GB are recommended. Soil stabilization with lime or cement may be used to improve subgrade stiffness and uniformity. CTB must be covered with AC layers thick enough (> 150 mm (6 in)) to retard reflective cracking.
2. For strong, uniform subgrades, GB and ATB are suitable choices.
3. CTB must be constructed with sufficient thickness (greater than 150 mm (6 in)) to prevent damage by occasional heavy loads. Base thickness is a function of subgrade stiffness, strength of CTB and thickness of AC layers. An in-depth analysis needs to be performed to verify the minimum thickness requirement.
4. A 200 mm (8 in) or thicker GB increases both stiffness and uniformity of the subgrade. The use of granular bases less than 200 mm (8 in) in thickness should be limited to low volume roads.
5. Uniformity provided by a 200 mm (8 in) thick ATB is much greater than that of the 100 mm (4 in) thick ATB. For high traffic conditions, a 200 mm (8 in) ATB in thickness should be considered as the minimum thickness.

Although most of these recommendations may not significantly impact construction costs, further research is needed to evaluate their cost-effectiveness.

IMPLEMENTATION

Implementation is already underway. Memoranda have been sent to all districts recommending the measures outlined above, specifically the discontinuation of the use of stiff bases such as LCB underneath rigid pavements. These recommendations will also be incorporated into the specifications. It is expected that the appropriate matching of bases to pavement types will allow the state to obtain the expected life of the pavement system, ultimately saving resources on unplanned pavement repairs.

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APPENDIX A: MOISTURE CONTENT VARIATION OVER THE YEARS

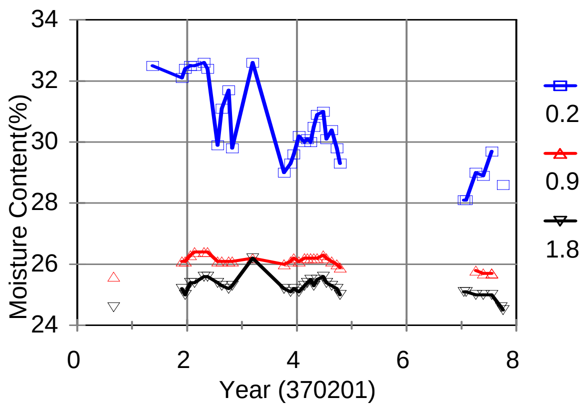
Section number

3702xx: North Carolina Sites (JCP Surface)
3902xx: Ohio Sites (JCP Surface)
3901xx: Ohio Sites (AC Surface)

MOISTURE CONTENT AT DIFFERENT DEPTHS

This section presents moisture contents variations at depths 0.2, 0.9, and 1.8 meters (8, 36, and 72 inches) from the top of the subgrade. Noted that vertical axles may have different values but the scales are the same. Figures are grouped by base types.

Granular Base



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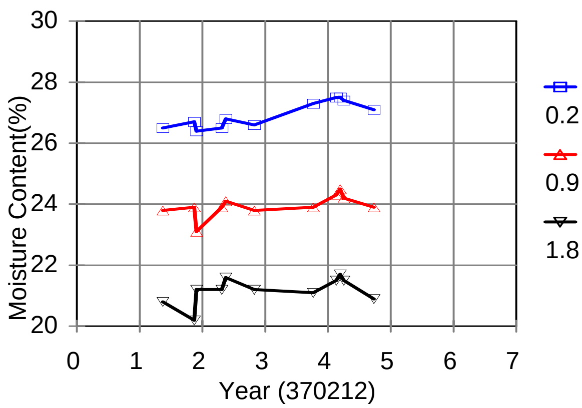

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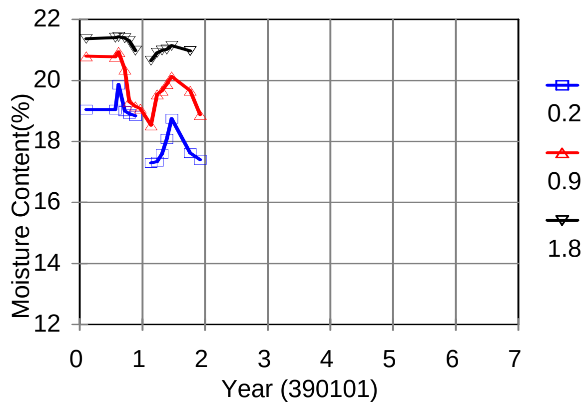

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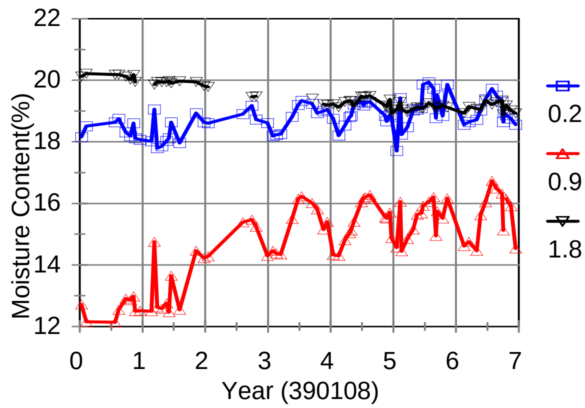

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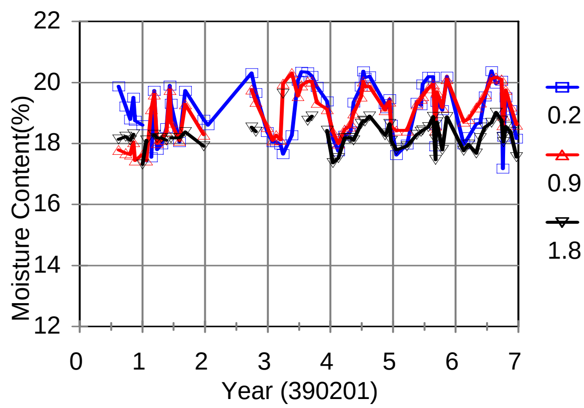

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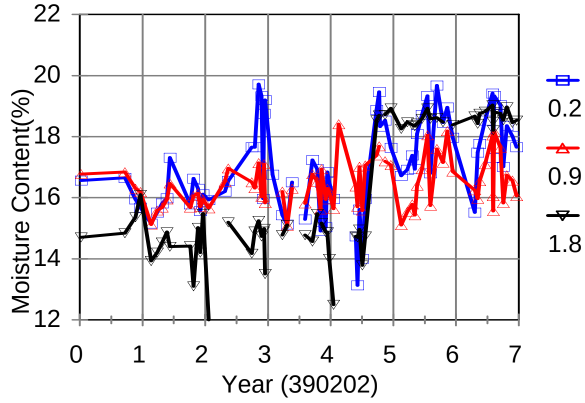

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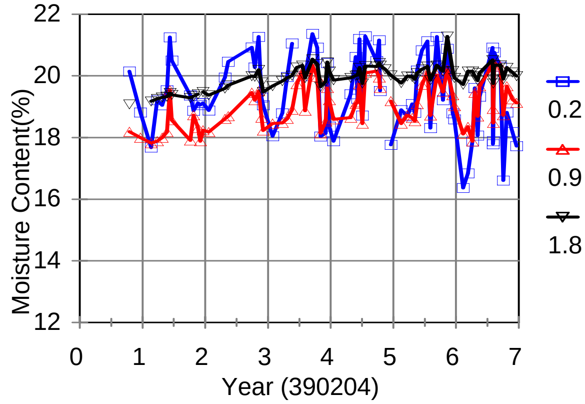

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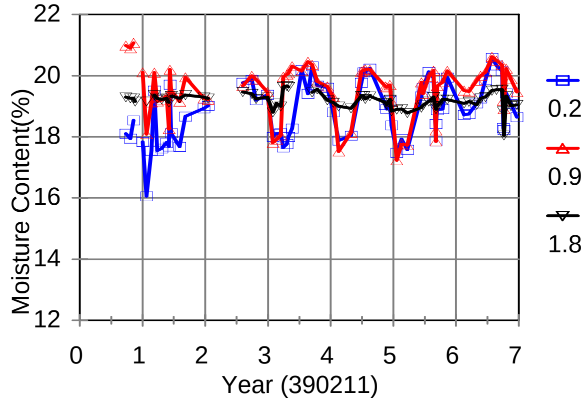

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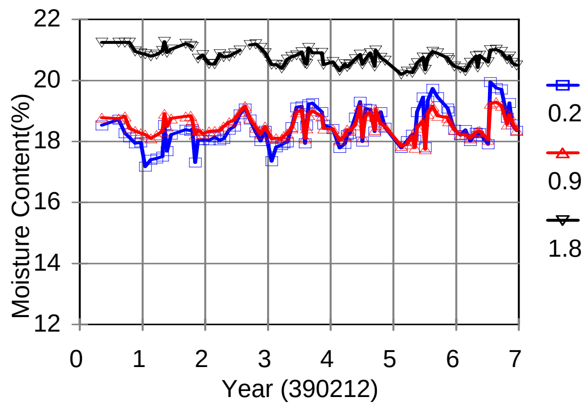
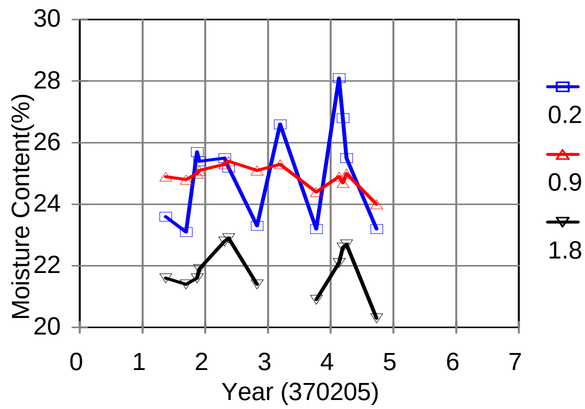


Figure A9

Lean Concrete Base



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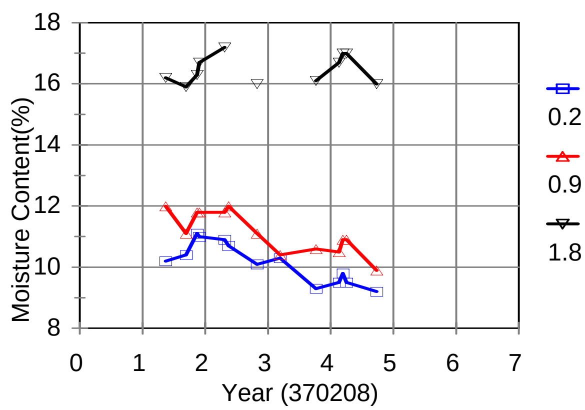

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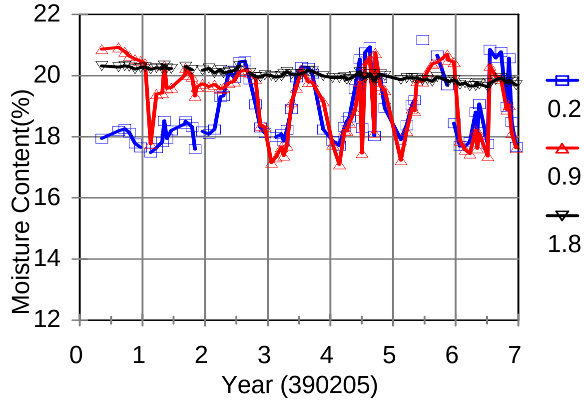

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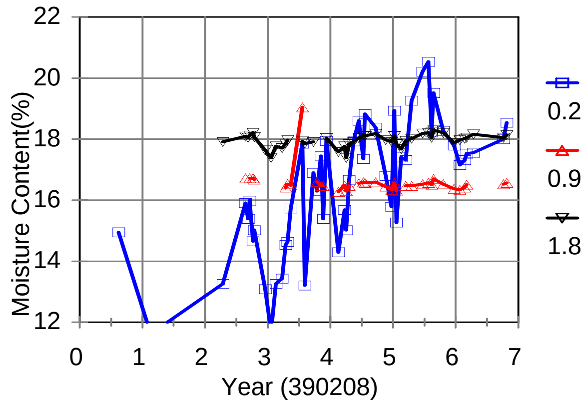

Figure A13

Permeable Asphalt Treated Base

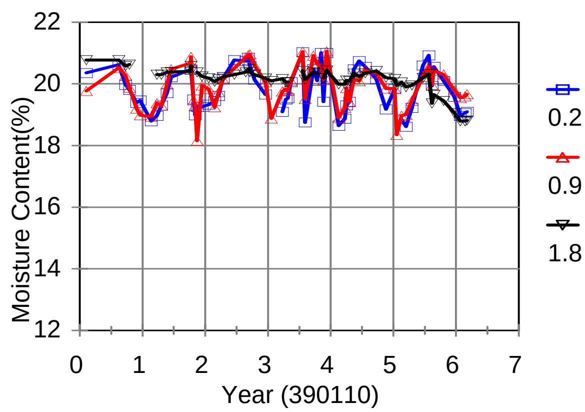

Figure A14

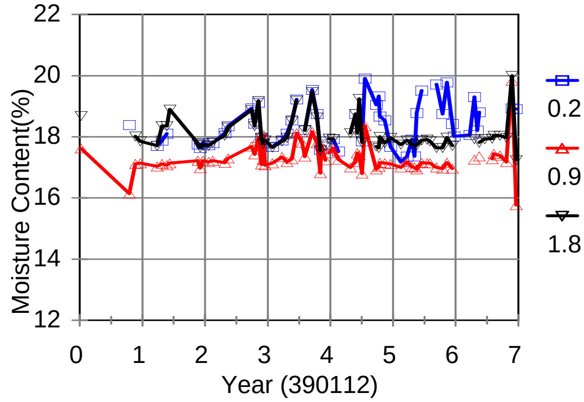

Figure A15

Asphalt Treated Base

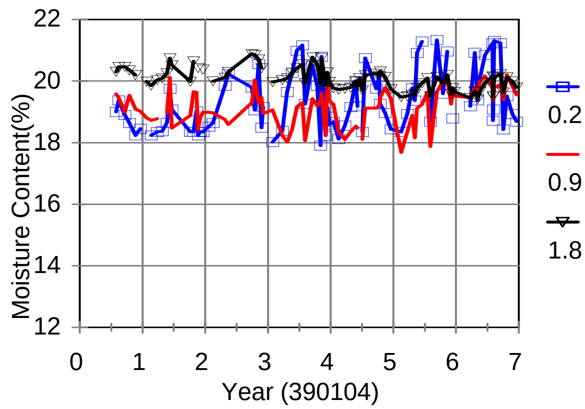

Figure A16

MOISTURE CONTENT AT MID-DEPTH OF GRANGULAR BASE LAYER

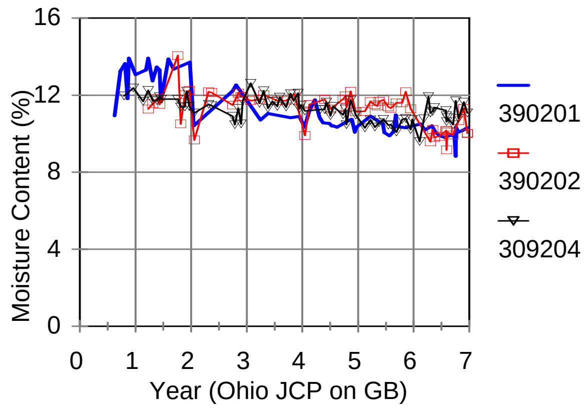

Figure A17

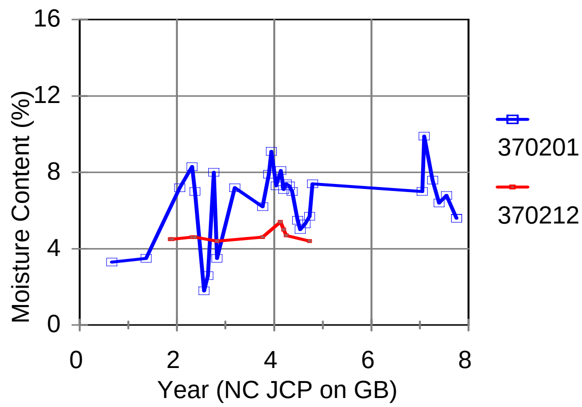

Figure A18

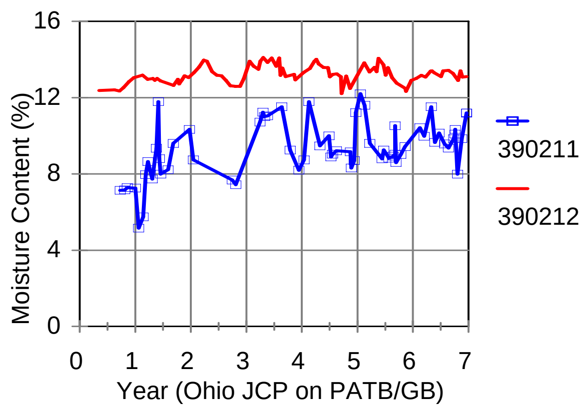

Figure A19

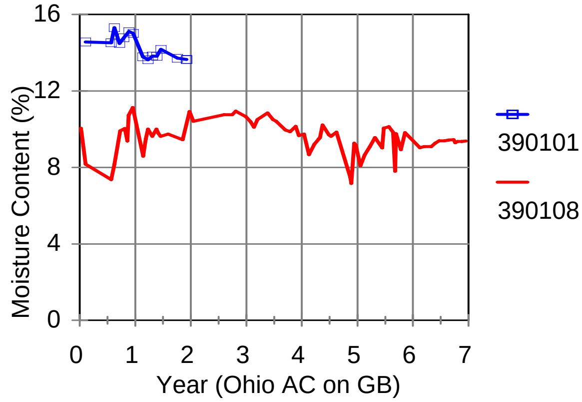
16
12
8
4
0
Moisture Content (%)
0
1
2
3
4
5
6
7
Year (Ohio AC on GB)
390101
390108

Figure A20

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