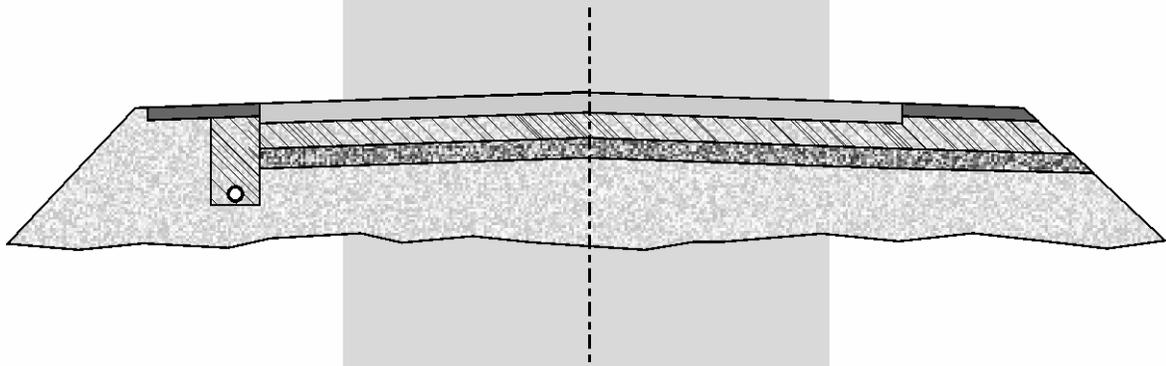


FINAL REPORT
VTRC 05-R35

EFFECT OF SUBSURFACE DRAINAGE ON THE STRUCTURAL CAPACITY OF FLEXIBLE PAVEMENT



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Supplementary Notes				
<p>Abstract:</p> <p>Following the recommendation of the Virginia Transportation Research Council's Pavement Research Advisory Committee, this project was initiated to determine the effectiveness of including subsurface drainage systems in pavements in Virginia. The researchers sought to determine the effectiveness of these systems by conducting a literature review and by comparing the strengths of pavement sections with and without a subsurface drainage layer in a limited field investigation involving two pavement structures in Virginia. The strength of the pavement structure was analyzed using the falling weight deflectometer.</p> <p>The researchers concluded that the drainage layer appears to affect positively the in-situ structural number for two projects investigated. Determination of the in-situ subgrade resilient modulus appeared to be positively influenced for only one of the two projects investigated. The researchers concluded that inclusion of a properly constructed drainage layer does not adversely affect the deflection of a pavement and therefore does not introduce a weakness into the pavement structure. However, the benefit of including a drainage layer may not be evident for all sites and conditions. Based on findings in the literature, maintaining a good working condition of the outlet pipes is of high importance.</p> <p>The researchers recommend that tests with additional sites be conducted in the spring when the subgrade moisture is expected to be highest; that the Virginia Department of Transportation (VDOT) develop a maintenance program to maintain functioning drainage outlet pipes; and that VDOT continue the practice of constructing subsurface drainage features on high-priority pavements where conditions suggest that proper drainage may be an issue.</p> <p>In 2005, VDOT anticipates spending approximately \$45 million on resurfacing interstate and primary roadways. According to the literature, the average service life of flexible pavements (time between successive rehabilitation efforts) is approximately 9 years. Based on findings from the literature, including subsurface drainage features offers a 4-year extension of service life (a 44% extension). Thus it can be approximated that the current practice of including subsurface drainage features is saving VDOT approximately \$20 million per year. However, this study shows that subsurface drainage features may not benefit all sites and conditions.</p> <p>The amount of this cost savings may not be fully realized if drainage outlet pipes are blocked or partially blocked. As reported in the literature, nonfunctioning drains accelerate pavement deterioration and thus may actually shorten the service life of pavement structures.</p>				

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ABSTRACT

Following the recommendation of the Virginia Transportation Research Council's Pavement Research Advisory Committee, this project was initiated to determine the effectiveness of including subsurface drainage systems in pavements in Virginia. The researchers sought to determine the effectiveness of these systems by conducting a literature review and by comparing the strengths of pavement sections with and without a subsurface drainage layer in a limited field investigation involving two pavement structures in Virginia. The strength of the pavement structure was analyzed using the falling weight deflectometer.

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The researchers recommend that tests with additional sites be conducted in the spring when the subgrade moisture is expected to be highest; that the Virginia Department of Transportation (VDOT) develop a maintenance program to maintain functioning drainage outlet pipes; and that VDOT continue the practice of constructing subsurface drainage features on high-priority pavements where conditions suggest that proper drainage may be an issue.

In 2005, VDOT anticipates spending approximately \$45 million on resurfacing interstate and primary roadways. According to the literature, the average service life of flexible pavements (time between successive rehabilitation efforts) is approximately 9 years. Based on findings from the literature, including subsurface drainage features offers a 4-year extension of service life (a 44% extension). Thus it can be approximated that the current practice of including subsurface drainage features is saving VDOT approximately \$20 million per year. However, this study shows that subsurface drainage features may not benefit all sites and conditions.

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FINAL REPORT

EFFECT OF SUBSURFACE DRAINAGE ON THE STRUCTURAL CAPACITY OF FLEXIBLE PAVEMENTS

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INTRODUCTION

Pavement deterioration and/or premature failure can result from the presence of water in the pavement structure. Following the recommendation of the Virginia Transportation Research Council's (VTRC) Pavement Research Advisory Committee, a project was initiated to determine the effectiveness of including subsurface drainage in pavements in Virginia and to investigate the theory that an open-graded drainage layer (OGDL) introduces a weakness in a pavement structure that typically consists of dense-graded layers.

Early full-scale pavement tests in the United States, including the Maryland Road Test (Highway Research Board, 1952), the WASHO Road Test (Highway Research Board, 1955), and the AASHO Road Test (Highway Research Board, 1962), indicated that rates of pavement damage attributable to traffic were significantly higher when the pavement structure was saturated. In 1973, the Federal Highway Administration (FHWA) published *Guidelines for the Design of Subsurface Drainage Systems for Highway Structural Sections* (Cedergreen, Arman, and O'Brien, 1973). In this report, the FHWA concluded that poor drainage was a major contributing factor to the premature failure of heavy-duty pavements. In 1993, the American Association of State Highway and Transportation Officials (AASHTO) incorporated this idea into the *Guide for Design of Pavement Structures* by including a modification to the layer coefficient value. This modification effectively increased the structural coefficient for unbound materials if the quality of drainage improves and the time a pavement structure is exposed to moisture levels approaching saturation decreases.

The Virginia Department of Transportation (VDOT) typically incorporates an OGDL, and accompanying longitudinal underdrain collector pipes, in designs for high-priority pavements. In addition, it has been a historical practice to retrofit longitudinal edgedrain collector pipes in high-priority roadways that were designed and constructed without subsurface drainage features. It is hypothesized that inclusion of subsurface drainage features increases the average in-situ subgrade resilient modulus, as it is known that the resilient modulus of the subgrade can significantly decrease during periods of increased moisture. However, questions

are still raised as to whether the OGD represents a weakened layer within the pavement as compared to a dense-graded base layer because of its lower modulus value and its higher void content. It has also been suggested that OGDs weaken the pavement structure. The weak effect can also take place if the drainage layer fails to maintain an effective drainage outflow and traps water within the pavement structure. In fact, some research has pointed out that having a drainage system that is not properly maintained can actually be more detrimental to the strength of a pavement than having no drainage system at all (Bejarno and Harvey, 2004; Mallela, Titus-Glover, and Darter, 2000; Hassan et al., 1996; Fleckenstein and Allen, 1996).

VDOT uses drainable and undrainable bases in the construction of its flexible pavements. Several questions have been raised as to (1) whether the drainable bases in flexible pavements contribute to a weaker pavement structure compared to pavements constructed using undrainable bases, (2) whether the drainage layer contributes to a higher in-situ subgrade resilient modulus by protecting the subgrade from water that otherwise infiltrates the pavement structure, and (3) whether it is a good practice/cost-effective to recommend that drainable bases be constructed as a part of future flexible pavement designs.

PURPOSE AND SCOPE

The purpose of this research was to study the effect of a drainage layer on the overall pavement structure and determine its contribution in protecting the subgrade. The objectives were to answer the following questions:

- Does the incorporation of a subsurface drainage system introduce a weakened area within the pavement structure?
- Does the incorporation of a subsurface drainage system reduce moisture-related damage or introduce other types of distress?
- Does a subsurface drainage system effectively transport water out of a pavement or does it tend to collect subsurface water?

To achieve the objectives of this study, two pavements, having similar pavement structural numbers (SNs), were tested with the falling weight deflectometer (FWD); both pavement structures contained drained and undrained sections. The study was confined to high-priority routes in Virginia.

METHODS

To achieve the study objectives, the methods consisted of a two-phase effort: a detailed literature review and a series of field tests involving a visual survey, coring, and VDOT's FWD. Use of the FWD allowed for a comparison of in-service pavement sections with subsurface drainage systems with adjacent sections without subsurface drainage layers. Field investigations

using the FWD occurred in September 2004 in two structurally similar pavements: one was in the northbound lane of Route 19 in Russell County, Virginia (milepost 7.70 to 10.01), and the other was in the outside lane of northbound Route 29 in Pittsylvania County, Virginia (milepost 3.93 to 5.78). Although it was desired that the FWD tests and analysis lead to valid conclusions for the objectives of this study, because a comparison was made between two slightly different, although similar, structures with more than one variable (such as material type and layer thickness), this may not have been the case. Ideally, the only variable that should have varied was the presence of the drainage layer.

Each pavement test site consisted of two pavement sections: one drained section containing an OGDL and an adjacent undrained section of a similar pavement design that did not contain an OGDL. To evaluate the effect of the drainage layer on the pavement structure for the two pavements, the difference in the SN and the subgrade resilient modulus (M_r) between drained and undrained sections was compared. Tables 1 and 2 provide the pavement design of each section as given in VDOT's Highway Traffic Record Information System (HTRIS) database.

Table 1. Pavement Layer Details: Northbound Lane, Route 19, Russell County

Layer	Undrained Section (MP 7.7-8.2)			Drained Section (MP 8.2-10.0)		
	Layer Material	Depth, in	Date Placed	Layer Material	Depth, in	Date Placed
1	SM-9.5A	1.5	1998	SM-9.5A	1.5	1998
2	S-5	1.2	1986	IM-1A	2.0	1998
3	I-2	1.5	1986	B-3	6.0	1998
4	B-3	6.0	1986	OGDL – Type 1	3.0	1998
5	21A Subbase	6.0	1985	21B Subbase	8.0	1998

Table 2. Pavement Layer Details: Outside Lane, Route 29, Pittsylvania County

Layer	Undrained Section (MP 3.56-4.17)			Drained Section (MP 4.17-7.32)		
	Layer Material	Depth, in	Date Placed	Layer Material	Depth, in	Date Placed
1	SM-2A	1.5	1986	SM-9.5D	1.5	2000
2	S-5	1.4	1985	SM-2B	1.6	1992
3	B-3	6.0	1985	IM-1A	2.0	1991
4	21A Base (w/cement)	6.5	1985	BM-2	5.5	1991
5	21A Subbase	6.0	1980	OGDL, Type III	4.0	1991
6				21A Subbase	8.0	1991

Literature Review

A literature review was conducted to explore subsurface drainage systems and their effect on pavement structures. This included benefits, location, types, effectiveness, and maintenance of drainage systems.

Visual Survey and Coring

A visual survey of the pavement surface was conducted at both sites. The survey consisted of noting the major distresses that were evident on the pavement surface; the purpose was to document any anomalies that might be reflected in the coring or FWD analysis. In addition, a cursory review of the drainage outlet pipes was performed. This review consisted of locating the outlet pipes and visually observing their condition.

Cores were collected from the drained and undrained sections of both Route 19 and Route 29. The cores were analyzed with respect to the condition and thickness of each paved layer. The condition of each layer was analyzed for signs of crushed aggregate or aggregate stripping. The total thickness of all hot-mix asphalt (HMA) layers and the thickness of the drainage layer (where present) were measured and compared to the information provided in the HTRIS database.

Field Testing Using the Falling Weight Deflectometer

FWD testing is a common tool used by many state departments of transportation to measure the structural capacity of in-service pavements nondestructively. The FWD operates by applying an impulse load on an 11.8-in-diameter loading plate. Using a series of geophones located at known radial distances from the center of the loading plate, the deflection attributable to the applied load is measured. Through a series of calculations, the resilient modulus of the different pavement layers may be determined (provided that the thickness is known beforehand). During this study, the area of the pavement deflected beneath the load cells, or *deflection basin*, was calculated. The FWD used by VDOT is a Dynatest model 8000. This FWD is trailer mounted and is towed behind a van that includes an on-board data storage and processing computer. Loads, ranging from 1,500 to 24,000 lb, are applied to the pavement by dropping known loads (110, 220, 440, or 660 lb) from heights ranging from 0.8 to 15 in.

FWD testing was conducted at four load levels (6,000; 9,000; 12,000 and 16,000 lb). At each load level, three deflection basins were collected. This process resulted in a total of 12 deflection basins collected at each testing location. Two seating drops at 12,000 lb preceded the recorded FWD measurement as specified by VDOT's deflection basin testing protocol. Testing spacing was set at 75-ft (25-m) intervals to ensure a representative statistical sample for the pavement sections. MODTAG software was used to process the FWD data.

In this study, field testing using the FWD allowed for the following three comparisons to be made.

1. *Compare the variability in backcalculated subgrade resilient modulus and subgrade resilient modulus between drained and undrained sections.* It was hypothesized that lower variability and a higher in-situ subgrade resilient modulus may be associated with the presence of the drainage layer.

2. *Compare the effective pavement modulus (the modulus of all combined layers on top of the subgrade) between drained and undrained sections.* It was hypothesized that a similar effective pavement modulus between drained and undrained sections demonstrated that the drainage layer does not weaken the pavement structure.
3. *Compare the in-situ SN between drained and undrained sections.* It was hypothesized that a similar in-situ SN between drained and undrained sections demonstrated that the drainage layer does not weaken the pavement structure.

For comparisons between drained and undrained pavements using the FWD, the AASHTO 1993 pavement design guide was used for the calculation of the subgrade resilient modulus, the effective pavement modulus, and the effective SN.

Subgrade Resilient Modulus

The subgrade resilient modulus, M_r , is calculated using Equation 1:

$$M_r = \frac{P * (1 - \mu^2)}{\pi * r * d_r} \quad [\text{Eq. 1}]$$

where

M_r = subgrade resilient modulus

P = applied load

r = radial distance at which the deflection is measured

d_r = measured deflection at a radial distance, r .

Typically, the backcalculated subgrade resilient modulus is based on the fact that at a point far away from the center of the load plate, the measured deflection is almost entirely due to the deformation in the subgrade and is independent of the radius of the load plate (AASHTO, 1993).

Effective Pavement Modulus

The effective pavement modulus, E_p , is calculated using Equation 2. Knowing the pavement thickness and calculating or assuming the subgrade resilient modulus, the only unknown in Equation 2 is the effective pavement modulus, which can be calculated using an iterative process (AASHTO, 1993).

$$d_0 = 1.5 * P * a \left[\frac{I}{M_r \sqrt{I + \left(\frac{D}{a} \sqrt{\frac{E_p}{M_r}} \right)^2}} + \frac{\left(I - \frac{I}{\sqrt{I + \left(\frac{D}{a} \right)^2}} \right)}{E_p} \right] \quad [\text{Eq. 2}]$$

where

- d_o = deflection under load plate
- P = contact pressure
- M_r = resilient modulus of the subgrade
- D = total pavement thickness above subgrade
- a = radius of load plate
- E_p = effective pavement modulus of all layers on top of the subgrade.

Effective Structural Number

The effective SN of the pavement structure is calculated using Equation 3.

$$SN_{eff} = 0.0045 * D * \sqrt[3]{E_p} \quad [\text{Eq. 3}]$$

where

- SN_{eff} = effective SN
- D = total pavement thickness on top of the subgrade
- E_p = effective pavement modulus of all layers on top of the subgrade.

RESULTS AND DISCUSSION

Literature Review

Excessive moisture within a pavement system is one of the most influential factors in contributing to the early deterioration of pavements (Huang, 1993). Moisture may enter the pavement through surface infiltration, cracks, and joints and through movement of subsurface moisture. Subsurface moisture may be present in the pavement system because of areas of high water table, interrupted aquifers and springs, subsurface flow, and capillary action. Excessive

moisture in the pavement structure may cause one or more of the following: a reduction in the shear strength of unbound subgrade/subbase materials, creation of weak layers by movement of unbound fines into flexible pavement subbase/base courses, frost heave, reduction of strength during frost melt, durability cracking (D-cracking), loss of support by pumping of fines in rigid pavements, and stripping in asphalt pavements.

Rapid removal of any infiltrated water is the key to minimizing moisture-induced pavement damage. From a construction/design point of view, employing proper transverse and longitudinal grading of the pavement surface can minimize the infiltration of moisture. In addition, a typical multilane pavement will include a crown or a slope from the centerline toward the shoulders (VDOT uses a uniform slope of 2%). In addition, transverse slopes are often constructed on all tangent sections of high-volume roadways except in locations where superelevation from curves directs runoff to the inside of the curve. One of the earliest advocates of pavement drainage suggested that up to 33% to 50% of precipitation falling on an HMA pavement surface and 50% to 67% falling on jointed portland cement concrete (PCC) pavements would infiltrate the surface (Cedergreen et al., 1973). The actual volume of water that infiltrates a pavement can be estimated by multiplying this infiltration factor by the 1-hour duration/1-year frequency rain rate (ranges from approximately 1.0 to 1.6 in/hr for the western and eastern portions of Virginia, respectively). Ridgeway (1976) agreed with this discussion and stated that the rainfall duration was more important than the intensity at a given location in determining moisture infiltration.

Pavement drainage is most beneficial when excessive moisture can be rapidly removed from the structure (ideally within 2 hr, preferably within 24 hr); however, the benefits derived from a subsurface drainage system will vary depending on pavement type, annual rainfall, subgrade conditions, geometric design, and design of the overall pavement system (Huang, 1993). Permeability of the drainage system is a major factor in determining how fast moisture can be removed from the pavement structure and will vary depending on the composition of the drainage system. Typical components of a subsurface drainage system include the drainage layer (open-graded and usually stabilized), a filter or separator layer, and a system of collection and outlet pipes to remove water from the pavement structure. The filter or separator layer, a granular or geotextile separator, is included beneath the drainage layer to keep fine particles from the subgrade from clogging the overlying drainage layer. VDOT uses either cement-treated aggregate or cement-stabilized soil as a granular separator. These typical components are shown in Figure 1.

Figure 1 also shows the differences between two types of subsurface drainage systems: an OGDL used in conjunction with a longitudinal collector/outlet pipe and a daylighted OGDL. The OGDL used in conjunction with a longitudinal collector pipe is most often used by VDOT. Each system has particular advantages and disadvantages, as discussed in this report.

Location of Drainage Systems

Huang (1993) states that the most effective method for removal of infiltrated or subsurface moisture in a pavement system is a combination of an open-graded aggregate layer that is placed in conjunction with trenched longitudinal edgedrains and outlet pipes that collect

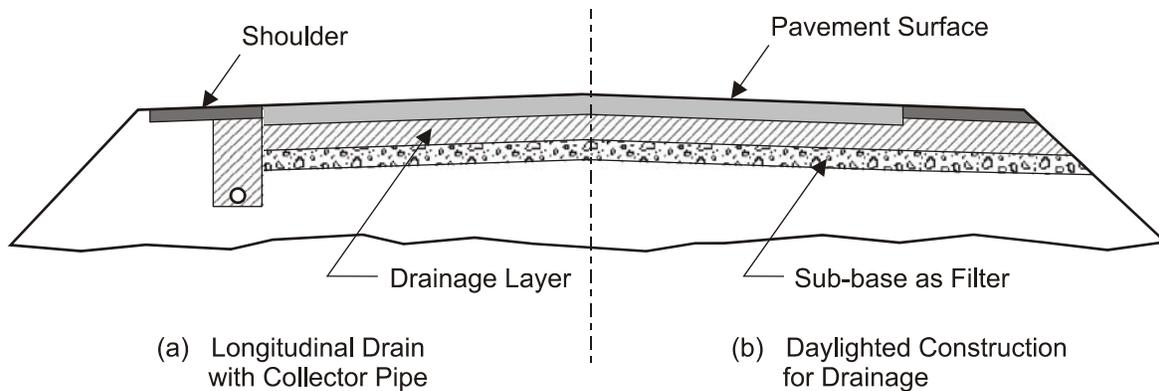


Figure 1. Typical Components of Subsurface Drainage System (from Huang, 1993)

water from the pavement structure. This approach typically offers the shortest drain times, thus decreasing the amount of time that a pavement structure remains in a saturated condition. If a drainage layer is incorporated into a pavement design without a means for removing the water that collects in the drainage layer (i.e., longitudinal edgedrains or transverse cross-drains), the drainage layer will act as a moisture reservoir, collecting infiltrated and subsurface moisture, and will cause more damage than if no drainage layer had been constructed.

Huang (1993) also states that a drainage system is most effective in removing moisture from the overlying pavement layers if it is placed directly underneath the HMA or PCC layers. The OGD is most often constructed as a treated aggregate layer using asphalt binder or cement to bind the aggregate particles together, forming a solid base for construction of the overlying layers. The drainage layer is typically placed on a separator layer, an aggregate subbase that acts to filter fine particles from the subgrade and keep them from entering the OGD. A layer of suitable geotextile may also be used for this purpose. It should be common practice to compare the particle sizes of the drainage layer, any underlying subbase, and the subgrade such that the drainage layer and the subbase layer do not become contaminated with fines. Fines that migrate into these layers over time will create several thinner and weaker layers within the pavement structure.

Two studies present research findings regarding drainage layers for two-lane and for multilane pavements. Elseifi et al. (2000) studied the placement of a geocomposite material, placed to act as a moisture barrier, beneath a cement-stabilized OGD. It was shown that the moisture content beneath the geocomposite material remained constant during periods of heavy precipitation when compared to that of a control section having no geocomposite. The subsurface moisture content was measured using time-domain reflectometry probes. A survey with ground-penetrating radar showed that the pavement section containing an OGD with no geocomposite material tended to exhibit higher moisture at the bottom of the OGD. The section that contained the OGD with the geocomposite did not show an accumulation of moisture at this location. Mahboub, Liu, and Allen (2003) investigated the use of a centrally located longitudinal underdrain, in addition to edgedrains, for a multilane pavement structure. Through the use of finite-element modeling, it was reported that the incorporation of a center drain for a very wide pavement structure improves the efficiency of a drainage system.

Drainage Effectiveness

Several researchers, through the use of full-scale pavement testing and laboratory analysis, have investigated the effectiveness of subsurface drainage layers. Bejarno and Harvey (2002) used a heavy vehicle simulator and showed that flexible pavement sections containing both drained layers and conventional dense-graded layers had similar service lives. However, the section containing the dense-graded layers failed because of fatigue cracking and the section containing drained layers failed because of permanent deformation. The drainage layer used in this study consisted of a 75-mm-thick asphalt-treated base layer. It was found that the life of the asphalt-treated layer was shortened because of stripping problems underneath the loading wheel and that the bottom of the drainage layer was clogged with fines from the layer below. This is an important indication, as the drainage layer was separated from the subgrade only by an application of a prime coat and not a dense-graded layer designed using a filter criterion (inclusion of a filter layer was a recommendation from the report). Bejarno et al. (2004) analyzed stripping in a drainage layer and stated that the failure was likely due to high pore pressures created within the aggregate because of the saturated condition. It was postulated that these pore pressures forced the water into the pores of the aggregate and reduced the cohesive bond between the aggregate and the binder in the drainage layer.

Studies of pavements in Indiana (Feng, Hua, and White, 1999) showed that sections of pavement containing a drainage layer drained more rapidly after a rain event than did sections without a drainage layer; thus, the pavement spent less time in a saturated condition. This was shown by comparing the output from instruments to measure the moisture content within the pavement structure. In addition, it was found that the moisture content tended to remain constant in the subgrade below the drainage layer rather than fluctuate with each precipitation event.

Kazmierowski, Bradbury, and Hajek (1994) presented comparisons of the deflection and permeability for three concrete pavement sections; the drainage systems for these sections consisted of a cement-treated drainage layer, an asphalt-treated drainage layer, and an untreated permeable aggregate base. It was found that the permeability of all three materials was sufficient but the strength of the treated drainage layers was superior to that of the untreated base. In addition, the cement-treated drainage layer (120 kg cement per m³) was found to exhibit 17% less deflection than the asphalt-treated drainage layer (1.8% asphalt content).

Hagen and Cochran (1996) recommended the use of a drainable base layer for all concrete pavements. It was shown that for jointed reinforced concrete pavements with a 27-ft joint spacing, less mid-slab cracking after 6 years was seen in sections with an asphalt-stabilized base layer (when compared to a dense-graded base with and without transverse drains at the transverse joints—all sections had longitudinal edgedrains). Although all systems were capable of draining infiltrated moisture, the asphalt-stabilized base layer drained the most water within 2 hr of a precipitation event.

The National Cooperative Research Program (NCHRP) performed an extensive study of many subsurface drainage systems. NCHRP Project 1-34, Performance of Pavement Subsurface Pavement Drainage, summarized findings on the effectiveness of subsurface drainage on flexible pavements (NCHRP, 2002). It was found that structural capacity and drainability were key

factors in the performance of flexible pavements. If either factor was poor, there was an increased incidence of rutting and fatigue cracking. It was noted that these factors should be carefully considered during the design phase of flexible pavements.

The use of edgedrains was also examined in NCHRP 1-34 (NCHRP, 2002). For conventional HMA pavements with unbound dense-graded aggregate bases, the addition of edgedrains appeared to reduce fatigue cracking, but not rutting. The use of asphalt-treated permeable base sections with edgedrains produced significantly less rutting than did unbound dense-graded aggregate base sections. However, the fatigue cracking performance for both types of base sections with edgedrains was comparable. Climate also was a factor for unbound dense-graded aggregate sections. For colder climates (freezing index = 1,000), there was much more rutting than for warmer climates (freezing index = 100). The asphalt-stabilized permeable base sections appeared to perform about the same regardless of the climate, with the rutting being lower than that of the unbound sections. Overall, the asphalt-stabilized permeable base sections were effective in reducing rutting when compared to unbound dense-graded aggregate base sections.

NCHRP 1-34 (NCHRP, 2002) stated that another key factor in the performance of subsurface drainage was whether edgedrain outlet pipes were clogged. Clogged outlet pipes were found to have a detrimental effect on the performance of flexible pavements. Clogged outlets led to increased fatigue cracking and rutting and could lead to stripping. In addition, daylighted permeable base sections were found to have better fatigue performance than all other types of evaluated pavement sections. However, there was not a significant difference in the rutting performance of daylighted sections and other sections. Inclusion of a separation layer between the open-graded asphalt-treated base and the subgrade was also considered on two projects; it was reported that the pavement at these two locations appeared to perform well.

Maintenance of Drainage Systems/Common Problems

Many researchers (Bejarno and Harvey, 2004; Mallela et al., 2000; Hassan et al., 1996; Fleckenstein and Allen, 1996) state that a pavement drainage system with outlet pipes that are not maintained may be more detrimental to pavements than no drainage system at all. Common problems associated with drainage systems include permeable layers filling with fines from subgrade layers, crushed or punctured outlet pipes, clogged outlet pipes, edgedrains sloping less than 1% and filled with sediment, missing debris/rodent screens or bars, missing outlet markers, and daylighted layers that were covered by soil. NCHRP (2002) states that the installation of a subsurface drainage system carries inherent risks that the drainage system may not function as designed. This could negate any anticipated enhancement in the service life by including the drainage system. The report states further that neglecting continual maintenance of drainage system outlets or daylighted drainage layers may lead to a more rapid failure of the pavement. It should be anticipated that inclusion of a subsurface drainage system necessitates future action in the form of a general survey procedure. This should, at a minimum, consist of an annual or bi-annual observation of the outlet ends and the location of outlet pipes. In addition, the condition of the pavement should be documented in this area to give an indication of the effectiveness of the drains in the area.

FWD tests were performed by Fleckenstein and Allen (1996) to determine the effects of installing longitudinal edgedrains. The FWD testing compared the subgrade modulus on a section of roadway prior to and following the installation of edgedrains (a 9-mi section). FWD testing 2 years after the edgedrains were installed showed that the subgrade modulus had increased by an average of 64%. In comparison, control sections (no edgedrains installed) did not show an increase in modulus (a 3-mi section). In another location, FWD tests were performed 2 weeks following installation of the edgedrains. Testing showed an increase in subgrade modulus of 18% over that of similar sections with no edgedrains. In addition to common problems with drainage layers reported elsewhere, Fleckenstein and Allen (1996) encountered multiple instances where guardrail posts were driven through drainage outlet pipes or longitudinal edgedrain pipes. The researchers recommended that drainage outlets be constructed using a smooth interior pipe with a corrugated exterior and/or a schedule-40 PVC for added strength to minimize possible pipe crushing.

Cost Analysis

Although subsurface drainage is often included in the new construction of high-priority pavements, some researchers feel that determining the cost-effectiveness of including a drainage layer may show that a drainage layer is not efficient in all locations. Mallela et al. (2000) states that drainage elements should be employed only if the life-cycle costs outweigh the cost of installation. In addition, criteria such as traffic volume, subgrade permeability, and climate (e.g., wet-freeze, wet-nonfreeze) may be used as criteria for the decision of whether to include a drainage layer. One situation where drainage layers may not be cost-effective is in areas that receive little precipitation. Christopher and McGuffey (1997) state that subsurface drainage layers may not be cost-effective in locations that receive less than approximately 15 in of precipitation per year (Virginia typically receives approximately 42 in of precipitation per year). Bejarno and Harvey (2002) stated that drainage layers may not be needed where annual rainfall is less than 125 mm/yr or the permeability of the subgrade exceeds 0.35 mm/s.

Forsyth, Wells, and Woodstrom (1987) summarize previous attempts at assessing the life-cycle cost of including subsurface drainage on flexible and rigid pavements. Conservative estimates performed during field testing indicate that the life of PCC pavements increases 50% when subsurface drainage is included, offering a 10-year extension on a typical 20-year life. When considering a typical 20-year life, the addition of subsurface drainage reduces the life-cycle costs for material by approximately 41%. The life of HMA pavements was found to increase 4 years; assuming that a 12-year life is the norm, this equates to a savings of approximately 36% when the extended life and material costs are considered.

NCHRP 1-34 (NCHRP, 2002) also presented limited findings on the cost-effectiveness of drainage systems. Overall, the findings indicated that if the subsurface drainage features are designed and constructed properly, the performance of the pavement will be enhanced. This will in turn reduce the occurrence of distress in the pavement, thus leading to an increase in the initial life of the pavement and the delay of rehabilitation. It was also noted that the use of permeable base layers and edgedrains increases the cost of a project significantly. Therefore, a detailed cost-benefit analysis should be performed to determine the cost-effectiveness of the subsurface drainage system.

Summary of Literature Review

Properly designed and constructed subsurface drainage systems enhance the life of pavement structures. Clogged underdrain outlet pipes are detrimental to the performance of the pavement structure. Therefore, many studies recommend regular inspection of the underdrain outlet pipes as a key part of maintaining a pavement that includes subsurface drainage features.

Installation of longitudinal edgedrains in pavements containing no subsurface drainage layers significantly increases the subgrade resilient modulus. In addition, installation of edgedrains improves the fatigue performance of pavements constructed on unbound dense-graded aggregate layers. When two types of base layers where both pavement structures contained longitudinal edgedrains were compared, the use of a treated permeable drainage layer improved the rutting performance over that provided by unbound dense-graded aggregate base layers; however, the fatigue performance was similar.

Visual Survey and Coring

Visual Survey

The visual survey of the drained section of Route 19 revealed very few distresses in the pavement surface. The only visually observable distress was the minor longitudinal cracking evident between the northbound and southbound lanes. The survey of the drainage outlets, however, painted a different picture. More than 50% of the drainage outlets appeared to be partially blocked (approximately 30% to 50% of the opening) with debris or sediment (outside the rodent screen, so presumably the sediment was from the ditch itself and not from within the pavement structure). In addition, there were several instances where the level of the drainage outlet pipe fell near the bottom of the ditch, possibly setting up the case where water from the ditch might enter the pavement through the outlet pipe.

The visual survey of the undrained section of Route 29 revealed numerous instances of minor to moderate reflective cracking. The reflective cracking primarily was found in the travel lane, although instances were recorded in the passing lane. The crack spacing was not constant, however; it varied from approximately 30 to 35 ft. It was noted during the coring process that the cement-treated aggregate found beneath the undrained section appeared to have a high cement content, almost like a concrete mix. The drained section of Route 29 exhibited minor fatigue cracking (longitudinal cracking in the wheelpaths with some interconnection) near MP 5.5. The drainage outlet pipes in this location were covered with heavy vegetation that may impede proper water flow.

Coring

The results of the coring are presented in Table 3.

Table 3. Measurements of Pavement Layer Thickness from Coring

Location	Pavement Type	Average Thickness, in		
		All HMA Layers	Drainage Layer	Aggregate Base
Route 19	Drained	8.4	2.7	-
	Undrained	10.6	-	8.0
Route 29	Drained	10.8	3.5	-
	Undrained	9.5	-	6.0 (cement treated)

Field Tests with the Falling Weight Deflectometer

Tables 4 and 5 summarize the FWD results for the drained and undrained sections of Routes 19 and 29, respectively. The average values of the subgrade resilient modulus, the effective pavement modulus, and the effective SN are summarized. The tables also show the standard deviation (SD) and the coefficient of variation (COV) of these average values. In addition, the tables show the as-designed SN (i.e., as-constructed) that shows the similarity of the two pavement sections at the time of construction.

Table 4. Subgrade Resilient Modulus, Effective Pavement Modulus, and Effective Structural Number for Route 19 (Drained And Undrained Pavement Sections)

Pavement Type	Statistic	Subgrade Resilient Modulus, psi	Effective Pavement Modulus, psi	Effective Structural Number	As-constructed Structural Number
Undrained	Average	94,635	467,224	5.60	5.00
	SD	59,390	144,106	0.55	
	COV	62.8%	30.8%	9.8%	
Drained	Average	78,543	413,047	6.78	5.25
	SD	33,741	196,750	0.76	
	COV	43.0%	47.6%	11.2%	

Table 5. Subgrade Resilient Modulus, Effective Pavement Modulus, and Effective Structural Number for Route 29 (Drained and Undrained Pavement Sections)

Pavement Type	Statistic	Subgrade Resilient Modulus, psi	Effective Pavement Modulus, psi	Effective Structural Number	As-constructed Structural Number
Undrained	Average	22,365	408,741	7.12	5.76
	SD	5,670	74,424	0.44	
	COV	25.4%	18.2%	6.2%	
Drained	Average	26,094	359,611	7.20	5.81
	SD	12,192	70,992	0.48	
	COV	46.7%	19.7%	6.7%	

If the OGDL is functioning properly, it keeps the subgrade relatively dry and the total pavement performance improves, resulting in a lower deflection. On the other hand, if the OGDL is not functioning properly, the subgrade will likely be relatively wetter, resulting in higher deflection. A higher deflection suggests that the drainage layer (as a weak layer) contributed to the weakness of the pavement, including the subgrade layer. Tables 6 and 7 show that the center deflection, or D1, and the subgrade deflection, as measured by D7, D8, and D9, were low.

Table 6. Average Deflection Data for Route 19 from Geophones 1, 7, 8, and 9, mills

Pavement Type	Statistic	D1	D7	D8	D9
Undrained	Average	3.3	0.6	0.5	0.3
	SD	0.8	0.2	0.2	0.2
	COV	24.2%	33.3%	40.0%	66.7%
Drained	Average	3.3	0.5	0.4	0.3
	SD	0.7	0.2	0.2	0.2
	COV	21.2%	40.0%	50.0%	66.7%

Table 7. Average Deflection Data for Route 29 from Geophones 1, 7, 8, and 9, mills

Pavement Type	Statistic	D1	D7	D8	D9
Undrained	Average	5.2	2.2	1.9	1.6
	SD	0.7	0.4	0.4	0.3
	COV	13.5%	18.2%	21.1%	18.8%
Drained	Average	5.6	2.0	1.6	1.3
	SD	1.3	0.7	0.6	0.5
	COV	23.2%	35.0%	37.5%	38.5%

Detailed Data for Route 19

Figures A1 through A6, in the Appendix, show the subgrade resilient modulus, the effective SN, the effective pavement modulus, and the calculated California Bearing Ratio (CBR) of the drained and undrained pavement sections on Route 19.

Subgrade Resilient Modulus

The undrained section on Route 19 has a higher average subgrade resilient modulus than the drained section. However, given the high standard deviation, there is no statistically significant difference between the two sections. It is also shown that the drained section has a lower standard deviation than the undrained section, indicative of a more consistent subgrade. Table 4 shows a very high subgrade resilient modulus value for Route 19. During the coring operation, rock fill was found at the top of subgrade.

Effective Pavement Modulus

The average effective pavement modulus is slightly higher for the undrained section than for the drained section. Again, given the high standard deviation, there is no statistical difference between the effective pavement modulus of the drained and undrained sections. As the drainage layer aids in removing moisture from the pavement structure, the higher variability could be explained by variations in the moisture present in the drained layer.

Effective Structural Number

The average effective (in-situ) SN of the drained section is higher than that of the undrained section. Both sections have a higher average effective SN than the as-designed (as-constructed) SN. This is an indication that the OGDL does not contribute to a weaker structure.

The difference in the average effective (in-situ) SN and the as-designed SN is much higher for the drained section. This may be a result of the drainage layer contributing to the strength of the pavement. A layer coefficient of 0.12 was used for the OGDL to determine the as-constructed SN of the drained pavement section.

Detailed Data for Route 29

Figures A7 through A12, in the Appendix, show the subgrade resilient modulus, the effective SN, the effective pavement modulus, and the calculated CBR of the drained and undrained pavement sections on Route 29.

Subgrade Resilient Modulus

The drained section on Route 29 has a slightly higher average subgrade resilient modulus and a higher standard deviation. However, there is no statistically significant difference between the two sections. A higher subgrade resilient modulus of the drained section may support that the subsurface drainage features are performing as anticipated.

Effective Pavement Modulus

The average effective pavement modulus is higher for the undrained section. In addition, the standard deviation of the effective pavement is slightly higher for the undrained section, for the same reasons discussed previously. Given the standard deviation, there is no statistical difference in the effective pavement modulus between the undrained and drained sections. A higher effective pavement modulus of the undrained section may support that the subsurface drainage features are not providing the same structural contribution to the pavement as a dense-graded layer.

Effective Structural Number

The average effective (in-situ) SN of the drained section is slightly higher than the average effective SN of the undrained pavement section. Both pavement sections have a higher average effective SN than the as-designed (as-constructed) SN. This also indicates that the OGDL did not contribute to a weaker structure.

The difference in the average effective (in-situ) SN and the as-designed SN is slightly higher for the drained section. This again may be a result of the drainage layer contributing to the strength of the pavement. A layer coefficient of 0.12 was used for the OGDL to determine the as-constructed SN of the drained pavement section.

CONCLUSIONS

- The FWD appears to be an effective tool in evaluating the performance of a drainage layer as it contributes to the structure of the pavement system. The backcalculated moduli and the coefficient of variation are indicative of the strength of these materials.
- The drainage layer appears to impact positively the in-situ SN in the two projects investigated.
- The in-situ subgrade resilient modulus was positively influenced for only one of the two projects investigated.
- The drainage layer does not negatively influence the measured deflection.
- Clogged drainage outlet pipes have been reported in the literature to be detrimental to the performance of a pavement structure. This may be influencing some of the results for the Route 29 location.
- Subsurface drainage features do not appear to be positively benefiting the Route 19 location, possibly due to the pavement being located in primarily a rock-fill area.

RECOMMENDATIONS

1. VDOT's Materials Division should continue recommending bound permeable drainage layers and longitudinal underdrains for new construction and retrofitting longitudinal edge drains in existing pavements that show deterioration from excessive moisture within the pavement structure. These subsurface drainage features are justified on high-priority routes where conditions warrant.
2. VDOT's Maintenance Division should develop a maintenance program consisting of periodic (annual or semi-annual) visual and/or video inspection of drainage outlet pipes.

3. VTRC should repeat the FWD testing on the study project sites in the spring when the moisture within the pavement structure is expected to be highest to determine if time of year has any effect on drainage layer performance. In addition, future research into subsurface drainage should include additional sites to confirm the conclusions presented herein, which were based on a limited field investigation.
4. VTRC and VDOT's Materials Division should perform a life-cycle cost analysis to determine the differences in the increased construction costs of including a drainage layer versus any variation in service life.
5. VTRC should conduct an accelerated pavement testing study to help define any contribution of including a drainage layer and to aid in quantifying the life-cycle costs, especially concerning fatigue and rutting performance.

COSTS AND BENEFITS ASSESSMENT

Water-related pavement damage is known to reduce significantly the service life of flexible pavements. In particular, stripping of the asphalt binder from aggregate particles in bound pavement layers and fatigue cracking from saturated and weakened pavement structures rapidly decrease the load-carrying capacity of flexible pavements.

In 2005, VDOT anticipates spending approximately \$45 million on resurfacing interstate and primary roadways. According to the literature review, the average service life of flexible pavements (time between successive rehabilitation efforts) is approximately 9 years and the inclusion of subsurface drainage features will extend the service life by 4 years (a 44% extension). Thus, VDOT's current practice of including subsurface drainage features is saving VDOT approximately \$20 million per year.

However, the amount of this cost savings may not be fully realized. The visual survey of Route 19 revealed that approximately 50% of the drainage outlet pipes were partially blocked. If it is assumed that half of this number (25%) of all drainage outlet pipes is nonfunctioning, VDOT is losing approximately \$5 million per year in the likely benefits of including subsurface drainage features. This figure does not account for the potential, as reported in the literature review, that nonfunctioning drains accelerate pavement deterioration and thus may actually shorten the service life of pavement structures.

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APPENDIX

RESULTS OF FWD TESTING AT U.S. ROUTES 19 AND 29

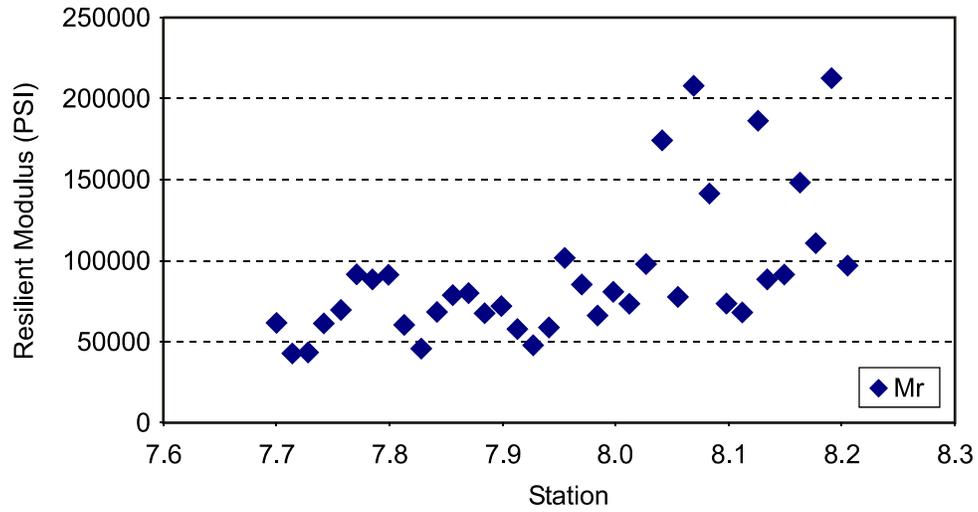


Figure A1. Subgrade Resilient Modulus for Undrained Section of Route 19

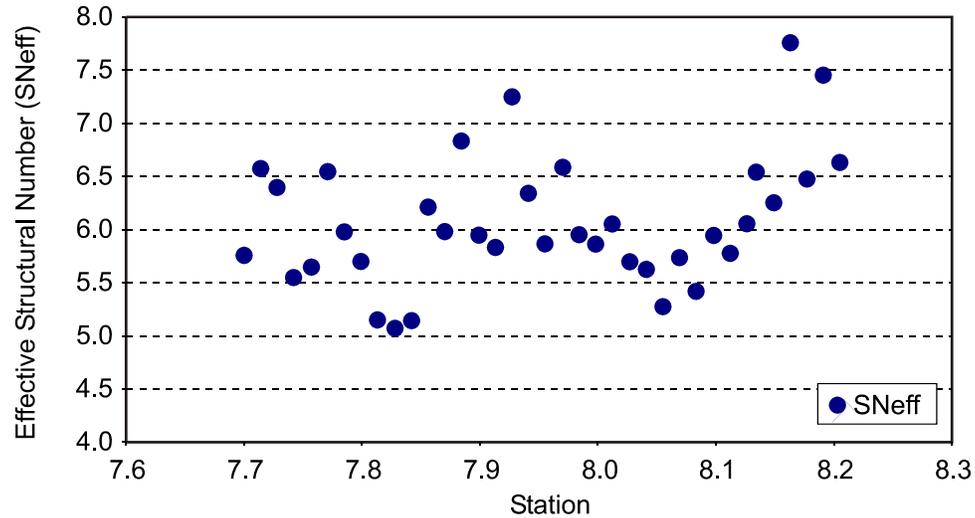


Figure A2. Effective Structural Number for Undrained Section of Route 19

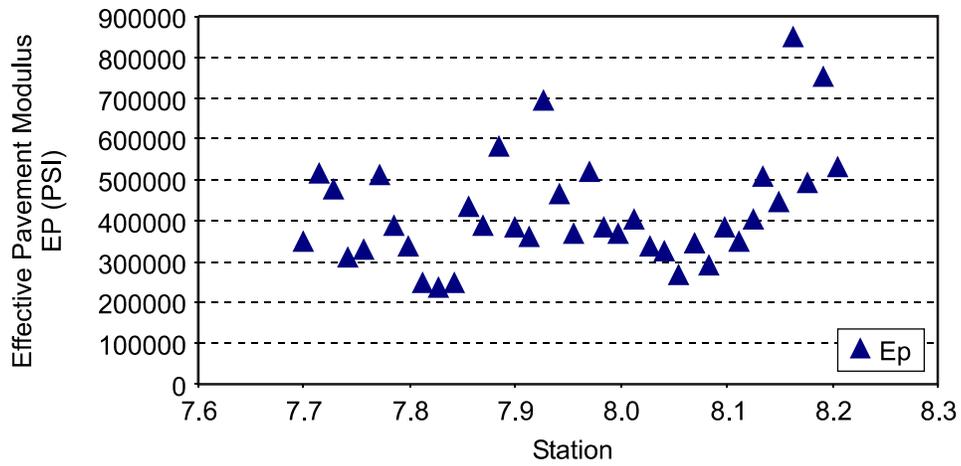


Figure A3. Effective Pavement Modulus for Undrained Section of Route 19

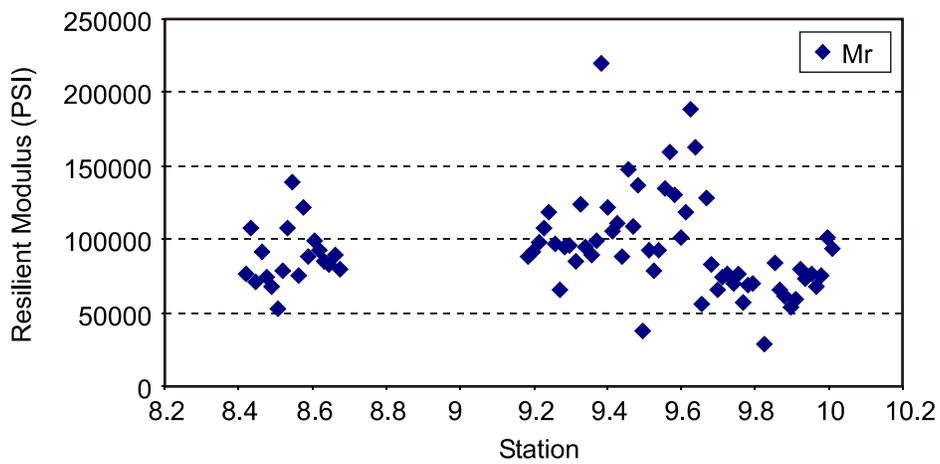


Figure A4. Subgrade Resilient Modulus for Drained Section of Route 19

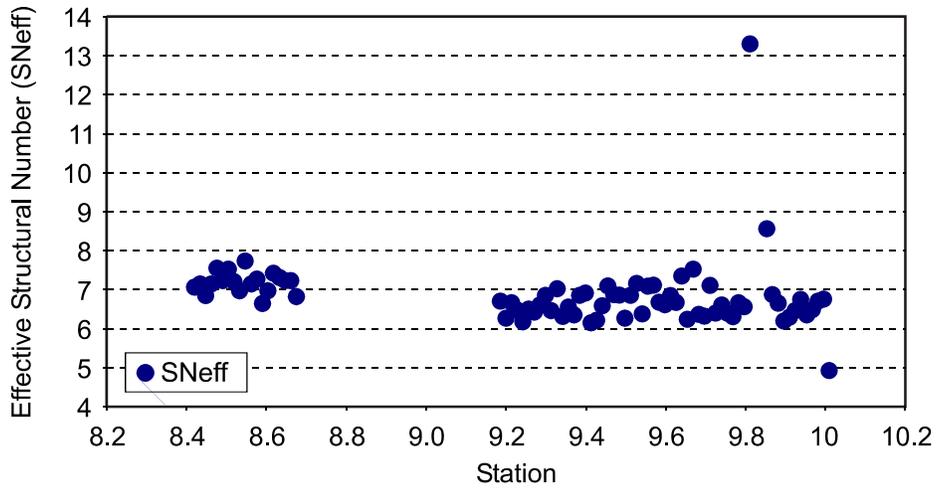


Figure A5. Effective Structural Number for Drained Section of Route 19

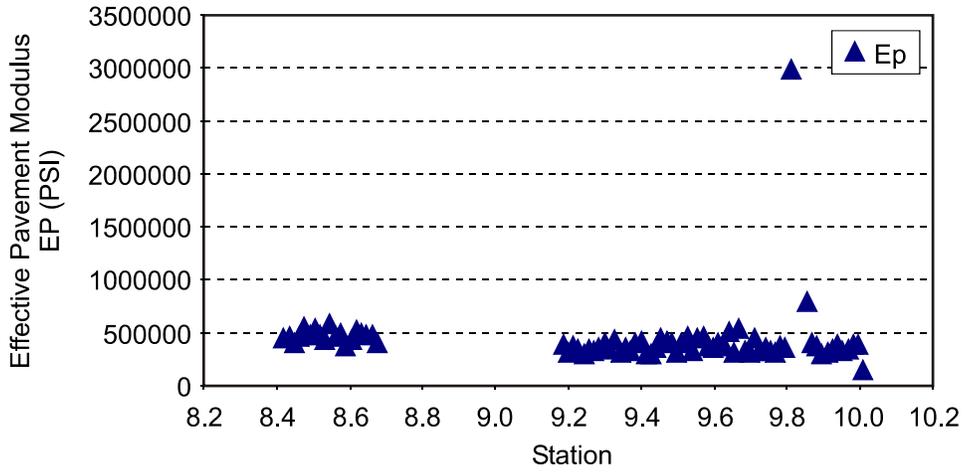


Figure A6. Effective Pavement Modulus for Drained Section of Route 19

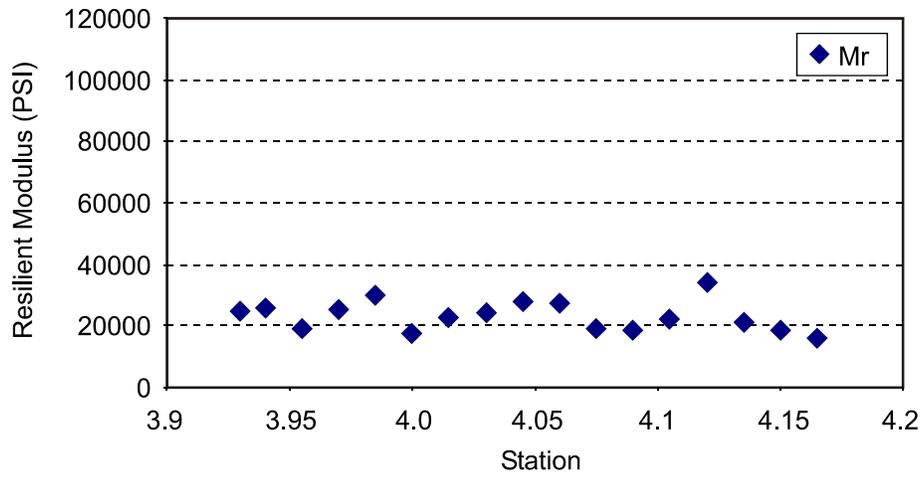


Figure A7. Subgrade Resilient Modulus for Undrained Section of Route 29

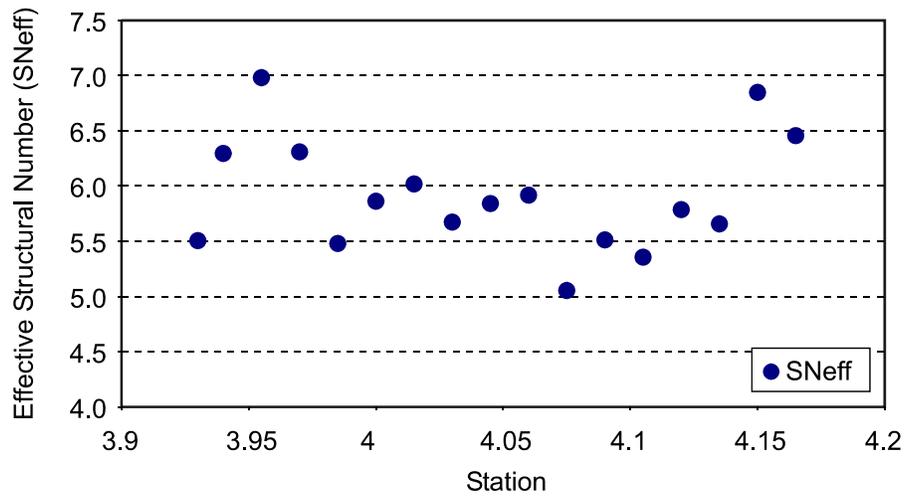


Figure A8. Effective Structural Number for Undrained Section of Route 29

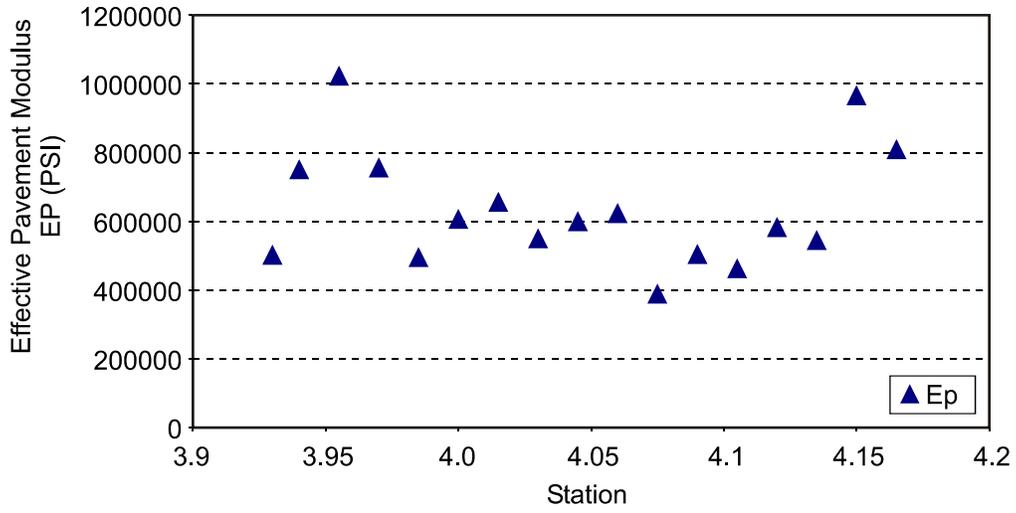


Figure A9. Effective Pavement Modulus for Undrained Section of Route 29

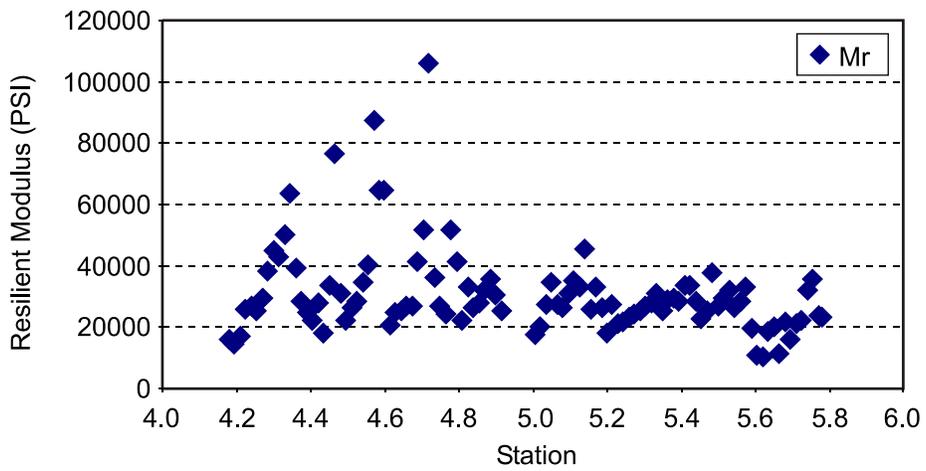


Figure A10. Subgrade Resilient Modulus for Drained Section of Route 29

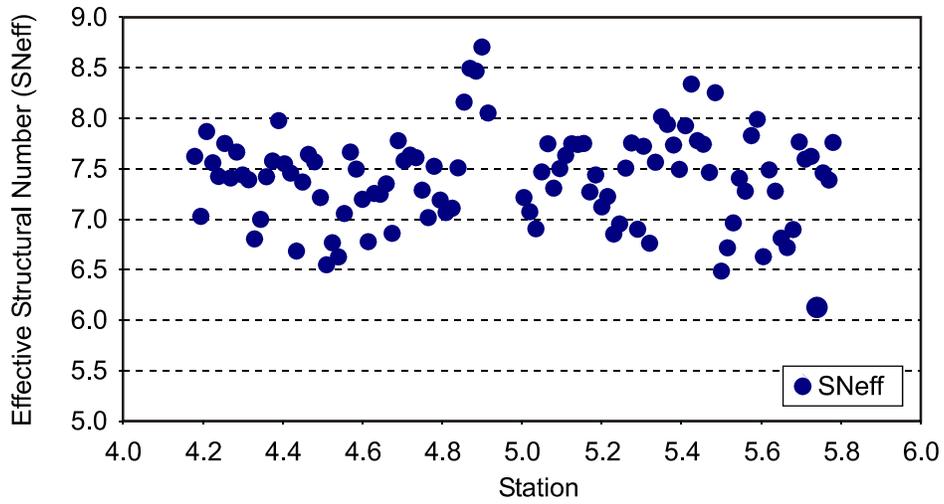


Figure A11. Effective Structural Number for Drained Section of Route 29

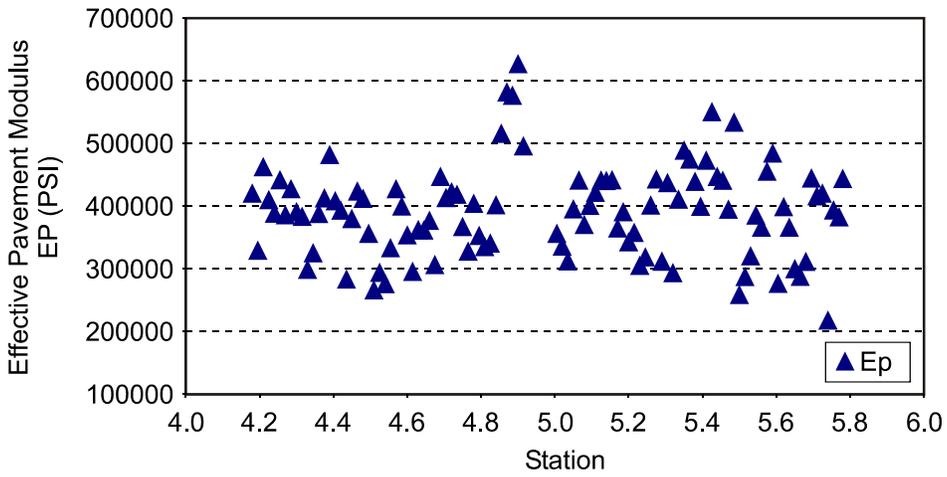


Figure A12. Effective Pavement Modulus for Drained Section of Route 29