Quantification of Benefits of Subsurface Drainage on Pavement Performances in Indiana

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ABSTRACT

The objective of this research was to evaluate pavement subsurface drainage performance and its cost benefit in Indiana. This study presents a comprehensive pavement performance evaluation to determine the effectiveness of subsurface drainage in a few aspects: lab testing of subgrade materials due to the moisture variation, pavement distress field survey, outlet spacing and maintenance inspection, and annual monitoring and evaluation of pavement performances. The subgrade materials investigated are A-4, A-6, and A-7-6 soils commonly found in Indiana. It was observed that with an increase of 2% in optimum moisture content (OMC), the resilient modulus decreases as much as four times. The field survey showed that the distress in drained pavement have relative low severity and less distress than that of the undrained pavement. However, the benefit of a drainage layer may not be evident for all sites of investigated pavement because of incorrect maintenance and construction. An annual in situ monitoring program was initiated to determine the effects of subsurface drainage on the performance of asphalt and concrete pavements. The in situ pavement structural performance was evaluated using Falling Weight Deflectometer (FWD) testing and backcalculation. The pavement functional performance was evaluated using a profiler. Based on the annual monitoring data, the researchers found that the drainage layer appears to positively impact the structural and functional performance of pavement. Cost benefit analysis was performed to determine the benefits of subsurface drainage on initial construction costs.
Background
It has long been discussed that a positive subsurface drainage is beneficial in enhancing pavement performance and extending pavement service life. Although the Indiana Department of Transportation (INDOT) adopted drainage layers in pavement construction after the 1990s, Indiana still uses drainable and undrainable bases in the construction of its pavements depending on the level of traffic a pavement must handle. Common pavement problems associated with drainage systems include permeable layers filling with fines from subgrade layers, crushed, punctured, or clogged outlet pipes, and missing outlet markers. Therefore, many researchers (1,2) state that a pavement drainage system with outlet pipes that are not maintained may be more detrimental to pavements than having no drainage system at all.

During the practices of pavement design, construction, and maintenance, several questions have been raised as to whether (a) the drainable bases in pavements contribute to an improved pavement structure; (b) the drainage layer contributes to a higher in situ subgrade resilient modulus; and (c) incorporating a drainage layer is cost-effective for pavement. The Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures (3) suggested it can be implemented through (a) past pavement performance and experience in similar situations; (b) cost differences and anticipated increase in service life; and (c) anticipated durability and erodibility of pavement materials.

Feng, Hua, and White (4) showed that Indiana pavement sections that contained 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.

Elfino et al. (5) performed a forensic investigation of the failure mechanism that caused premature distresses in a jointed plain concrete pavement (JPCP) in Virginia caused by lack of subsurface drainage. To assess the overall condition of the pavement, a visual condition survey and two nondestructive tests were performed. The Falling Weight Deflectometer (FWD) test was performed to assess the load transfer efficiency (LTE), and a profiler was used to measure the ride quality of the section. It was concluded that lack of positive drainage along with heavily loaded truck traffic resulted in premature failure. The water entering the pavement because of poor joint sealing was trapped in the open-graded drainage layer; this led to severe faulting, midslab cracks, pumping, and eventual failure of the pavement.

A research project was conducted in Indiana by Zubair et al. (6) with the goal of evaluating the performance of pavement subsurface drainage systems and measuring and predicting moisture conditions underneath various types of pavements with and without subsurface drainage. It was recommended that Proper sealing of pavement-shoulder joints to reduce moisture infiltration, rip-rap protection for outlet pipes, periodic inspections of existing edge drains and use of a permeable subbase to rapidly remove entrapped water.

Fleckenstein et al. (7) performed FWD tests in Kentucky in an effort to compare the subgrade modulus of a pavement section before and after installation of pavement edge drains. Results of the FWD testing showed that two years after installation of edge drains, the subgrade modulus for the pavement section had increased by 64%. Soil samples were obtained from pavement sections with and without pavement edge drains. From these samples, normalized subgrade moisture content was determined. The results showed that the normalized subgrade moisture is approximately 28% lower for sites with edge drains than it is for sites without edge.
drains. FWD data indicate that edge drains significantly increase the strength of the subgrade by removing water. Increased subgrade strength should increase pavement life.

Diefenderfer et al. (8) sought to determine the effectiveness of these systems by conducting a literature review and by comparing the strength of pavement sections with and without a subsurface drainage layer in a limited field investigation involving two pavement structures in Virginia using the FWD test. The researchers concluded that the drainage layer appears to positively affect the in situ structural number. They also found 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 the outlet pipes in good working condition is highly important.

**Objectives**

The first objective of this research was to evaluate subsurface drainage on hot-mix asphalt (HMA) and Portland Cement Concrete (PCC) pavement performances and subgrade modulus. The second objective of this research was to quantify the cost benefits of including subsurface drainage by comparing any potential extension in service life.

**Testing Locations**

In order to quantify the benefits of providing good drainage over the service life of a pavement in terms of reduced maintenance, an annual monitoring program was carried out to evaluate the performance of highway pavements with and without subsurface drainage. The selection of pavement test sections was accomplished after consulting the study advisory members from INDOT. The main criterion used in the pavement section selection was that the pavement sections should be representative of typical INDOT pavement cross sections and environmental conditions. Candidate projects were selected in various locations throughout the state (Figure 1). There were five PCC projects (Table 1). The control sections contained no positive drainage elements. The control project, SR-61 in Vincennes District, was constructed in 1965 and was rehabilitated in 1998. The other control project, US-6 in La Porte District was constructed in 1991. The concrete pavements that have positive drainage features include I-164 (constructed in 2010, Vincennes District), US-30 (constructed in 1994, La Porte District), and SR-51 (constructed in 1997, La Porte District). I-164 is a special case. Several drainage problems were reported due to moisture effect on the subgrade, and therefore this section was reconstructed in 2010. Asphalt control pavement sections are SR-545 (constructed in 2000, Vincennes District) and SR-42 (constructed in 2007, Crawfordsville District). The test sections used to compare positive drainage features on asphalt are US-231 (constructed in 2007, Crawfordsville District) and SR-67 (constructed in 2002, Vincennes District).
FIGURE 1  FWD tests sites around Indiana.
### TABLE 1 Testing Section Summary

<table>
<thead>
<tr>
<th>ROUTE</th>
<th>Construction Year</th>
<th>Traffic AADT</th>
<th>Traffic AADTT</th>
<th>DISTRICT</th>
<th>Construction Thickness (in)</th>
<th>BEG_RP</th>
<th>END_RP</th>
<th>PAV_TYPE</th>
<th>DRAINAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR-545</td>
<td>2000</td>
<td>2650</td>
<td>182</td>
<td>Vincennes</td>
<td>13.0</td>
<td>4+00</td>
<td>8+00</td>
<td>HMA</td>
<td>Without</td>
</tr>
<tr>
<td>I-164</td>
<td>2010</td>
<td>26980</td>
<td>4780</td>
<td>Vincennes</td>
<td>10.0</td>
<td>2+30</td>
<td>20+80</td>
<td>PCCP</td>
<td>Underdrain</td>
</tr>
<tr>
<td>SR-61</td>
<td>1998</td>
<td>5680</td>
<td>664</td>
<td>Vincennes</td>
<td>10.0</td>
<td>4+00</td>
<td>8+00</td>
<td>PCCP</td>
<td>Without</td>
</tr>
<tr>
<td>SR-67</td>
<td>2002</td>
<td>5760</td>
<td>718</td>
<td>Vincennes</td>
<td>13.0</td>
<td>8+00</td>
<td>10+00</td>
<td>HMA</td>
<td>Underdrain</td>
</tr>
<tr>
<td>US-231</td>
<td>2007</td>
<td>7980</td>
<td>1590</td>
<td>Crawfordsville</td>
<td>12.0</td>
<td>175+00</td>
<td>176+37</td>
<td>HMA</td>
<td>Underdrain</td>
</tr>
<tr>
<td>SR-42</td>
<td>2007</td>
<td>2090</td>
<td>90</td>
<td>Crawfordsville</td>
<td>11.0</td>
<td>39+00</td>
<td>42+00</td>
<td>HMA</td>
<td>Without</td>
</tr>
<tr>
<td>US-30</td>
<td>1994</td>
<td>34140</td>
<td>3050</td>
<td>La Porte</td>
<td>12.0</td>
<td>0+00</td>
<td>0+65</td>
<td>PCCP</td>
<td>Underdrain</td>
</tr>
<tr>
<td>US-6</td>
<td>1991</td>
<td>15810</td>
<td>910</td>
<td>La Porte</td>
<td>12.0</td>
<td>15+31</td>
<td>15+71</td>
<td>PCCP</td>
<td>Without</td>
</tr>
<tr>
<td>SR-51</td>
<td>1997</td>
<td>8360</td>
<td>510</td>
<td>La Porte</td>
<td>12.0</td>
<td>9+05</td>
<td>9+56</td>
<td>PCCP</td>
<td>Underdrain</td>
</tr>
</tbody>
</table>

### Moisture Effects on Soil Samples

During the construction stage, pavement materials are typically compacted to over 95% of optimum densities. However, the moisture and densities of the pavement structure will change with time, due to environmental and traffic factors. The in situ moisture content and densities of the soils were collected from the field test program. Using the same soils obtained from the field, the modified proctor compaction tests were conducted in the laboratory to determine the optimum moisture content (OMC) and maximum dry densities. The moisture content of most cohesive soil materials has been found to affect the resilient response characteristics of the material in both laboratory and in situ conditions. A previous study by Russell and Hossain (9) showed that at high degrees of saturation, the resilient modulus of these materials was notably dependent on moisture content: the resilient modulus decreased significantly as the moisture content increased above the OMC. The triaxial tests following the AASHTO T307-99 (10) procedure were conducted on the A-4, A-6, and A-7-6 cohesive soils compacted at optimum water content and at 2% above the optimum. The study did not perform the cyclic load triaxial testing at 2% below the optimum because dry side has typical stiffer for fine grain soil. Testing of OMC is critical, and difficult of testing in dry soil. The measured resilient modulus for A-4, A-6, and A-7-6 soils is presented in Figure 2. As shown in this figure, with an increase of 2% in OMC, the resilient modulus decreases as much as four times with the average value of 1.685 times. This indicates that an increase in moisture content causes significant degradation of the resilient modulus of cohesive soils. Extra moisture in the pavement or underlying subgrade, or both, generally results in a decrease in strength or ability to support heavy axle loads. Potential problems associated with saturation of the structural section and subgrade include (a) pumping action; (b) differential expansion (swelling) of expansive subgrade; (c) frost damage in freeze-thaw areas; (d) erosion and piping of fine materials, creating voids which result in the loss of subgrade support; (e) stripping of asphalt concrete aggregates; and (f) accelerated oxidation of asphalt binder.
FIGURE 2  Modulus variation and moisture content soil (σ_d=6 psi and σ_c=2).

FWD Data Collection

The FWD testing is commonly used for pavement evaluation and rehabilitation purposes. This testing applies an impact load to the pavement surface and measures the induced surface deflections. The FWD testing was conducted each year for four years for all sites listed in Table 1. The primary goal of the deflection testing was to assess the relative structural contributions of subsurface drainage. The backcalculated modulus is the key parameter that characterizes pavement response. Based on the formed deflection basin due to loading, Structure Number (SN), subgrade support condition, and layer moduli can be calculated using a FWD backcalculation technique. FWD tests were conducted in the driving lanes in both directions at a 10-meter to 100-meter interval. Three drop load levels consisting of 9 kip, 11 kip, and 13 kip were used in testing protocols.

Pavement Distress Field Survey

The visual survey of the drained sections revealed very few distresses in the asphalt pavement surface. Specifically, the original pavement of SR-42 was still in excellent condition with no patching, while SR-545 has shown transverse cracking, block cracking, and minor rutting; visually observable distress also included longitudinal cracking. On the other hand, the pavements of US-231 and US-67 have shown good conditions with minor longitudinal cracking. On PCC it was found that, in terms of percentage of cracked slabs, the permeable base (drained) sections of US-51 and US-30 had significantly lower rates of slab cracking. There was no
faulting or pumping, and substantially reduced frost penetration. Of the three permeable base sections evaluated, three of which were constructed in the 2000s, two had no cracking, whereas the undrained control sections of SR-61 and US-6 had 10 and 25% transverse cracking, respectively. A drained section had 5 to 10% longitudinal cracking compared to 10 to 30% for the undrained section. These dense-graded base sections were the worst performing in terms of pavement distress (i.e., faulting, cracking, D-cracking, and spalling). Pumping was noted on these sections as well. Spalling of the longitudinal joints was noted on some test sections.

Pavement Effective Thickness

For the flexible pavement sections, a two-layer analysis procedure based on the 1993 AASHTO Design Guide (11) was used to determine the in-place elastic modulus of the subgrade and an elastic modulus of the pavement structure (all layers combined) above the subgrade. Deflections measured at load levels closest to 9,000 lb. are used and normalized with respect to temperature. For the purpose of comparing the relative structural capacities of the pavement sections at each site, the actual total pavement thickness and structure number were used to calculate an effective thickness for a fixed asphalt concrete modulus of 500,000 psi. Considering that the full depth asphalt pavement structures are on top of the subgrade soil, the asphalt effective pavement can be computed as:

$$D = \frac{(SN_{eff})}{a_1}$$

Where,

- $a_1$ = the layer coefficient for the asphalt layer material corresponding to 500,000 psi;
- $SN_{eff}$ = the effective structural number; and
- $D$ = the effective thickness of the asphalt layer, in inches.

For the rigid pavement sections, a two-layer analysis procedure was used to determine the in-place composite k value of the subgrade and an elastic modulus of the PCC pavement. Interior deflections were used to compute the effective thickness, which can indicate deterioration of the PCC pavement (12). After backcalculation of the radius of relative stiffness and dynamic foundation k-value, the effective thickness of the concrete slab was estimated from

$$D = \sqrt[3]{\frac{11.73i^4k}{E_{concrete}}}$$

where: $D$ = effective slab thickness, inches

$E_{concrete}$ = assumed slab modulus of elasticity, psi ($= 5,000,000$ psi)

Annual Analysis of Effective Thickness
FIGURE 3  Annual comparison of effective thickness.

Figure 3 presents comparisons of pavement effective thickness for four years. It is clear from Figure 3 (a) that, despite the construction asphalt concrete (AC) thicknesses, the backcalculated effective pavement thicknesses for the sections with the drainage layer are, in nearly every case, greater than those for the construction sections, and the undrained section thickness is always less than the construction thickness. The average backcalculated effective thicknesses of the undrained test sections are 8 in. versus 12.5 in. (construction thickness) on SR-545 and 8 in. versus 11 in. (construction thickness) on SR-42. In the case of drained test sections, the average
backcalculated effective thicknesses of the drained test sections are 14 in. versus 12 in. (construction thickness) on US-231 and 13 in. versus 13 in. (construction thickness) on SR-67, indicating that pavement structure deteriorated more in undrained pavement than in drained pavement. The average effective thickness for PCC pavement shows that backcalculated effective pavement thicknesses are greater than construction thicknesses in every pavement section; however, it does not necessarily indicate that PCC pavement has a better structural performance than HMA pavement because the equations performed to evaluate the effective thickness of PCC pavement differ from those performed to evaluate the effective thickness of HMA pavement. Figure 3 (b) shows that both US-30 and SR-51 sections have a higher average effective thickness than the control sites of SR-61 and US-6. In general, The average effective thickness of pavement sections with underdrain is 30 to 40% greater than the construction thickness. On the other hand, the average effective thickness of pavement sections without underdrain is only 5 to 10% greater than the construction thickness. In nearly every case, it is the pavements with underdrain that have the greatest backcalculated effective pavement thickness. This can be a result of the drainage layer contributing to the strength of the pavement.

**Annual Analysis of Concrete Joint**

Load transfer efficiency (LTE) and total edge deflection (TED) have a significant influence on the performance of rigid pavements. Low LTE (or high TED) can indicate a high chance of potential void and bigger bending stresses of concrete pavement under vertical loading. They can be expressed as:

\[
LTE = \frac{D_U}{D_L} \times 100\% \tag{3}
\]

\[
TED = \frac{9000 \times (D_U + D_L)}{P} \tag{4}
\]

Where,

- LTE= load transfer efficiency, %; TED = total edge deflection, inches, normalized to 9-kip load;
- \(D_U\) = unloaded slab deflection, mils (12 inches from the load center); and
- \(D_L\) = loaded slab deflection, mils (at the center of loading).
- \(P\) = FWD applied load (lb.)

Figures 4 and 5 show the annual variation in LTE and TED for pavement sections, respectively. It is also found that TED with underdrain has lower joint deflections, indicating a stronger support to the slab joint from subgrade. The maximum deflections and bending stresses of concrete pavement under vertical loading increase with the decrease of joint load transfer efficiency. Specifically, the results obtained suggest that the LTE and TED are significantly affected by subsurface drainage by 5 to 10% in LTE and 30 to 40% in TED. The annual effects of load transfer efficiency on the pavement are considered as negligible with a change of 1 to 7%, except the section at I-164. On the other hand, TED in all sections fluctuated greatly, with a range of 1 to 39%
except I-164. It is noted that I-164 may not be a good testing section because it had either drainage or weak subgrade issues before and it has been reconstructed. Both the LTE and TED show it is worst in the all testing section. The further investigations are needed.

Variation Analysis of Subgrade

The resilient modulus of subgrade materials was reported to be affected by several factors, including state of stress, moisture content, density, gradation, and angularity. Figures 6 and 7 show box plots for the in-situ subgrade modulus. A box plot is a way of summarizing a set of data measured on an interval scale. It is a type of graph which is used to show the shape of the distribution, its central value, and variability. Figures 6 and 7 show the most extreme values in the data set (maximum and minimum values), the lower and upper quartiles, and the median. If
the drainage layer is functioning properly, it keeps the subgrade relatively dry, and the subgrade resilient modulus improves. If the drainage layer is not functioning properly, the subgrade will likely be relatively wet, resulting in a lower modulus value. AASHTO suggested that the k value for A-4, A-6, and A-7-6 soils is about 50–250 pci.

**FIGURE 6** Comparison for k value for concrete pavement.
FIGURE 7 Comparison for subgrade resilient modulus for asphalt pavement.

Figure 6 shows that the median values for I-164, SR-51, and US-30 (range from 200 to 140 pci) are higher than those for US-6 and SR-61 (120 to 140 pci). It shows that the subgrade modulus outperforms the modulus of undrained pavements greatly.

Figure 7 shows a box plot in the subgrade layer modulus in asphalt sections. The figure shows a very high subgrade resilient modulus value for the drainage pavement section of SR-67 with A-4 or A-7-6 soils and of US-231 with A-4 soil. On the other hand, it shows that the pavement sections without drainage on SR-545 (A-4 or A-6) and SR-42 (A-4 or A-6) have low subgrade resilient modulus values. The elastic modulus for an unbounded aggregate base typically ranges from 13 to 15 ksi (3). Figure 7 shows a subgrade median modulus with a permeable layer to be about twice the modulus of the undrained sections. This is an indication that without drainage, excessive water content in the pavement base, subbase, and subgrade soils can cause high moisture content and a high chance of structural or functional pavement failure.

Variation Analysis of Effective Thickness

Figure 8 shows the variation for PCC effective thickness in five concrete sections. As expected, the drainage pavement has lower variation and the median value is much higher than the construction thickness value that was shown in Figure 3.

Similarly to what is shown in Figure 8, Figure 9 shows that HMA effective pavement with a drainage layer has less variation than does pavement without a drainage layer. It is believed that pavement with a more uniformly effective thickness will have better structural performance.

FIGURE 8 Comparison for PCC effective thickness.
Variation Analysis of LTE and TED

The presence of water, the erodibility of a subbase material, large deformations, and the number of loads are factors that influence erosion of pavement. LTE (or TED) and erosion are typically highly related to each other; joints with low LTE are often associated with high rates of erosion due to independent deflection behavior between two slabs. Figure 10 indicates good LTE median values in general. However, there are still some joints that have relatively low LTE, with the value close to 35 or 45%. Below 70% it is recommended to retrofit because the dowel bar cannot transfer the traffic loading functionally under this point. Figure 11 shows that SR-51 and US-30 have lower TED than do US-6 and SR-61, and the TED for I-164 falls in the middle. TED is a relative indicator of the overall structural capacity of the pavement at the transverse joint. This suggests pavement with permeable in edge structural capacity.
Annual Analysis of IRI Data
Pavement roughness is the principal measure of public satisfaction within the highway system. The International Roughness Index (IRI) is determined by measuring the profile of the road and passing it through an algorithm or filter known as the quarter-car model. There are several reasons that the IRI might decrease from one testing date to the next: seasonal variation; measurement in different paths; different starting locations; and problems with the profilometer electronics, sensors, or distance measurement (13).

The projects were monitored annually to determine the IRI for both PCC and AC pavements. The pavement profiler test and analysis performed during the initial year evaluation indicated significant difference between sections of IRI in asphalt and concrete pavement. Figures 12 and 13 show that, in general, better initial smoothness levels were obtained in the asphalt pavement sections (US-231, SR-67) and in the concrete pavement test sections (I-164, SR-51). It is because these sections were built in the early 2000. The other sections have been there for a while and been resurface for many times. The drained and undrained sections show a slight increase after each year, and there is no statistically significant difference during the four-year observation in each site. Correlating the drainage features with IRI has revealed that drainage features can not only have significantly affected initial IRI values but also not accelerated deterioration rates significantly during this four-year period.

![FIGURE 12 Annual IRI for HMA pavement.](image)
Subsurface Drainage Outlet Conditions

The outlet is one of the most important parts of subsurface drainage; its role is to drain the infiltrated water out of the pavement as soon as possible. Ceylan et al. (14) conducted field investigations on 64 selected (JPCP and HMA) pavement sites in Iowa and were mainly focused on the drainage outlet conditions. The study presents the distributions of these four drainage outlet conditions observed in JPCPs and HMA pavements. About 35% of outlets in JPCPs and 60% of outlets in HMA pavements were not blocked by any materials. About 35% of outlets in JPCPs were blocked by tufa, about 17% were blocked by sediment, and about 14% were blocked by soil deposits. Although higher blockage rates reduce the flow rate of water inside outlet pipes, blockage does not always stop water flow unless it is complete. In the case of moisture-related distress or failure that can be attributed to poor subdrain performance, it was found that (a) little pavement surface distress was observed near a subsurface drainage system showing poor performance; (b) both field observations and performance analyses indicate that drainage outlet conditions do not have a significant effect on pavement performance; and (c) rather than surface distresses, more shoulder distresses (shoulder drop or cracking) were observed near blocked drainage outlet spots.
The survey of the drainage outlets in the current study was conducted on nine selected (JPCP and HMA) pavement sites during the fall of 2011 and 2012 and was mainly focused on the drainage outlet conditions. Although not damaged, more than 60% of the drainage outlets appeared to be partially blocked (approximately 85 to 90% of the opening) with algae outside the rodent screen. (Sediment was seldom found, and what was found may have come from the ditch itself and not from within the pavement structure.) Among the drainage sections, I-164 has worst outlet conditions, the Figure 14 shows outlets of I-164 are block by weeds and soil erosion are found as well in these areas. The section of PCC pavement on I-164 was reconstructed in 2010 using a permeable open-graded base drainage layer after it failed twice in just a few years—the main reason being a drainage problem in the pavement. Considering relative low effective thickness, LTE, and TED, it may indicate that good maintenance and construction play important roles in pavement performance.

Cost and Benefit Analysis

Moisture content has been proven to have dramatic effects on the life of a pavement. A study in New Jersey by Zaghoul et al. (15) looked at the effect on service life and cost savings due to lower moisture content as a result of a pavement section having a daylighted base. The study provided that increasing the base course moisture content from 16% to 45% would result in a
decrease in pavement service life from 13 years to 7 years. It was concluded that substantial long-term savings could be achieved with the installation of subsurface drainage in flexible pavements. 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. Heath et al. (16) 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. Fleckenstein et al. (7) conducted a preliminary cost analysis and indicated that in most cases edge drains can be cost-effective. The average cost savings per 1 km (0.62 mi) over a 30-year design life is approximately $15,535.

Due to the uncertainty of the maintenance strategy and vehicle operating costs, this study only focused on the cost-effectiveness of subsurface drainage in pavement design thicknesses under fixed traffic. The construction costs of asphalt pavement for a surface course and an intermediate course are about $39,379/lane-mile and $43,785/lane-mile in the 2005 INDOT Cost Index, respectively. Determining the cost-effectiveness of subsurface drainage herein can be analyzed in these two aspects in asphalt; the construction of concrete is approximately $18,773/in. PCCP/lane-mile.

The contribution of the positive subsurface drainage to the strength of the pavement can be categorized in two ways: the improvement of the stiffness of the subgrade and the increase of HMA modulus to prevent stripping and cracking. The 1993 AASHTO Design Guide (11) considers drainage factors in the design equations to prevent pavement moisture-related failures such as pumping action, loss of support, and rutting. Figures 15 and 16 show design pavement thickness calculated based on the in situ subgrade modulus in Figures 6 and 7, respectively, in which the variability of subgrade strength are affected by drainage layer. Figure 15 and 16 show that undrained pavement is calculated to be approximately 2 in. thicker than drained pavement with different traffic level; therefore, undrained pavement yields approximately $40,000 to $60,000 more in costs for each lane-mile. It is found that traffic may cause significant differences in pavement lift and heavy traffics (30 MESALs) has big thickness differences between undrained and drained pavement compare to that under medium traffic (10 MESALs). That indicates that the moisture under heavy traffic loading cause more pavement damage than the light traffics does. Further investigation of traffics variation is needed to accurately analyze the cost savings.

![Statistical Range for 10MESALs](image1.png)

![Statistical Range for 30MESALs](image2.png)

**FIGURE 15 Design concrete pavement thickness.**
Conclusions

Considerable monitoring, testing, and analyses were performed during this study. Based on the field performance data and the theoretical analysis conducted during this study, the following conclusions can be made:

1. The lab subgrade resilient modulus was positively influenced by moisture content. With an increase of 2% in OMC, the resilient modulus decreases as much as four times with mean value of 1.685. Results from laboratory and field tests conducted on a number of roads indicated that the moduli of base and subgrade materials were strongly affected by having a drainage layer.

2. Continuous monitoring of FWD testing of pavement sections with and without subsurface drainage provides better understanding of the effective thickness. The drainage layer appears to have impacted positively the effective thickness investigated. The pavement section without drainage has relatively low structural performances, which includes subgrade stiffness for both pavements and joint performances for concrete pavement.

3. Profiler testing of pavement sections with and without subsurface drainage does not favors pavement sections with subsurface drainage, and the drainage layer does not positively influence the decrease rate in drained and undrained pavement.

4. Approximately $40,000 to $60,000 per lane-mile can be saved at the traffic level of 10 to 30 MESALs if a drainage layer is installed properly. Therefore, providing adequate drainage to a pavement system has been considered as an important design implementation to ensure satisfactory performance of the pavement, particularly from the perspective of life cycle cost and serviceability. However, cost benefit varies if traffic volume is different.
REFERENCES


