TRANSPORTATION RESEARCH
CIRCULAR
Number E-C296
November 2024

Foundation Design and Construction for 100-Year Pavement Systems

NATIONAL ACADEMIES Sciences Engineering Medicine
TRB TRANSPORTATION RESEARCH BOARD

TRANSPORTATION RESEARCH CIRCULAR E-C296

Foundation Design and Construction for 100-Year Pavement Systems

Submitted
September 2024

Transportation Research Board
500 Fifth Street, NW
Washington, D.C.
www.trb.org

TRANSPORTATION RESEARCH CIRCULAR E-C296
ISSN 0097-8515

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Standing Committee on Mechanics and Drainage of Saturated and Unsaturated Materials

Prepared by

John Siekmeier

TRB Staff

Nancy Whiting, *Senior Program Officer*

NATIONAL ACADEMIES *Sciences Engineering Medicine*

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Contents

Presentations from the 2024 Workshop
Pavement Foundations: 100-Year Design Considerations

Presentations from the 2023 Workshop
Effects of Drainage on Pavement Structural Capacity and Resilience

Increasing Expectations for Pavement Foundations

KUMAR DAVE

NAYYAR SIDDIKI

Indiana Department of Transportation

The Indiana Department of Transportation (INDOT) established a task force about ten years ago comprised of geotechnical engineers, pavement engineers, material testing engineers, and contractors. This collaborative effort was focused on increasing the longevity of pavement systems in Indiana. Together, task force members explored numerous options for the pavement foundation layers and pavement surface layers with a focus on how traffic loading influences the foundation layers and underlying soil subgrade. The task force meticulously reviewed current design recommendations, including traditional soil support values, as well as the inputs required for AASHTO's mechanistic-empirical pavement design method. The following pavement system challenges and solutions were identified:

- Initial Cost (Alternate-Bid, Design-Bid-Build, and Best-Value)
- Quality Construction (Quality Control and Quality Assurance [QC/QA] and Intelligent Compaction)
- Rehabilitation and Maintenance Cycles
- Cost per Lane Mile per Year
- Drainage of Pavement Surface, Foundation, and Subgrade
- Industry Perspectives and Capabilities for both Asphalt and Concrete

The task force concluded that the pavement foundation strength must be increased at least threefold and that this would include constructing a more stable underlying subgrade (Figures 1 and 2). Quality control and quality assurance specifications were developed for consistency and uniformity for all materials underlying the pavement surfacing materials (asphalt or concrete). The contractor performs quality control, whereas INDOT performs quality assurance (Figure 3). Contractor quality control tests are performed with a frequency twice that of the quality assurance testing. Hence, the contractor takes responsibility for their work. A separation geotextile was introduced between the cement-stabilized subgrade and aggregate base, or subbase, to prevent soil intrusion into aggregate and hence increase the service life of the base or subbase. INDOT now expects enhanced strength of the subgrade and foundation layers to far exceed the service life of the surface layers. A policy has been implemented to include high-strength subgrade for all interstate widening and reconstruction in Indiana. Numerous projects with these specifications and recommendations have been and continue to be constructed in Indiana. Examples include I-65, I-70, I-69, and I-469.

FIGURE 1 Cement added to stabilize subgrade.

FIGURE 2 Fully compacted cement-stabilized subgrade.

FIGURE 3 Quality assurance by agency staff using lightweight deflectometer.

Based on the information collected so far, we expect these new pavement systems to last longer than traditional pavement. We believe these long-life pavement systems will reduce the number of short-term surface mill and overlays during the design life, which will save the department significant amounts of money in the long run. Therefore, the life-cycle cost of Indiana long-life pavement systems will be lower than the traditional design approach.

CONCLUSIONS

There continues to be a strong desire at INDOT to design and construct long lasting pavement systems that result in less disruption to the traveling public. A well-constructed subgrade and foundation are very important to achieving this goal. Essential also are quality materials, construction methods, and nondestructive construction testing, which provides important verification of design inputs. Appropriate drainage of the subgrade, pavement foundation, and surface layers are known to enhance pavement system life and therefore are included in these long-life pavement systems. The cost per lane mile per year will be less for these long-life pavement systems compared to traditional options.

Key considerations and insights that the INDOT staff learned from their efforts include the following:

- Long-term performance is achieved by implementing design, maintenance, and construction activities applied to all the materials comprising the pavement system.
- Geotechnical, pavement, and construction engineers must speak with each other.
- Pavement system design is less art, more science, and needs to expect service lives greater than 50 years.
- Pavement foundations must be uniform and stable for 50 to 100 years and pavement drainage must be designed and constructed intentionally.
- Successful subgrade and pavement foundation preparation includes both contractor quality control and agency quality assurance.
- It is essential that construction projects be staffed appropriately with well-trained personnel.

Innovative and Conventional Roadway Foundation Stabilization

BORA CETIN

Michigan State University Affiliation

Base and subgrade stabilization additives are used to increase the strength and stiffness of road foundations in weak and susceptible soils. Numerous additives exist for improving the performance of aggregate base and subgrade layers. While many conventional stabilizers (e.g., cement, lime, fly ash, liquid stabilizers) are the most commonly used for this application, there are new and innovative materials and techniques (e.g., water repellent agents, phase change materials, biocementation) that are improving the performance and increasing the durability of pavement foundation layers against climatic cycles (e.g., wetting-drying, freezing-thawing).

This particular presentation includes the following topics:

- Topic 1—Impact of Moisture on Pavement Foundation Performance and Design
  - Compaction
  - Pavement ME
- Topic 2—Use of Geosynthetics to Mitigate Impact of Moisture on Pavement Performance
  - Wicking Geotextile
  - Large Stone Subbase with Geosynthetics
- Topic 3—Engineered Geomaterials Designed to Mitigate Moisture Damage

DRAINAGE CHARACTERISTICS AND IMPACT OF MOISTURE ON PAVEMENT PERFORMANCE

A highway base layer must provide adequate drainage of the water that infiltrates through the top layer. Retained water in a base layer can elevate the pore water pressure in the porous media which:

- Decreases the effective contact stresses between the coarse aggregate particles,
- Weakens the mechanical strength and stiffness of the granular materials,
- Increases the susceptibility of the pavement structure to the climatic changes, and
- Reduces the service life of highways.

ENGINEERED GEOMATERIALS DESIGNED TO MITIGATE MOISTURE DAMAGE

Soil hydrophobicity is a natural phenomenon and occurs due to organic matter, fungi, microorganisms, and wildfires. Mostly associated with problems in hydrology and agriculture, soil hydrophobicity is extensively utilized in geotechnical and geoenvironmental engineering.

Water is the source of virtually all problems with subgrades and pavement systems. Thus, it is very important to control water to increase the pavement performance (Figure 1). Moisture control in pavement systems has become even more important for cold regions where freeze-thaw cycles could increase the deterioration rate of the roadways. There have been many different approaches to minimize the negative impacts of soil freeze-thaw cycles. While some of these techniques have had success, their applicability and efficiency are limited, particularly within frost-susceptible (e.g., silt-rich) subgrade soils. As an alternative, this presentation will discuss making subgrade soils water repellent via the use of nanoscale-organo-silane (OS) products as additives to mitigate the damage that occurs due to freeze-thaw cycles (Figure 2).

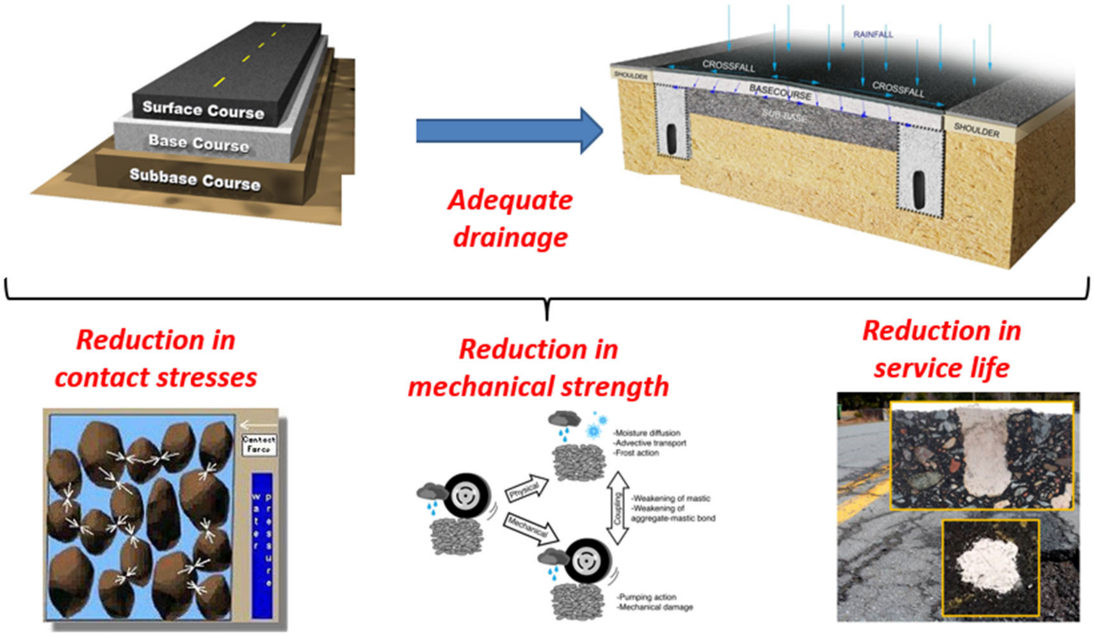


FIGURE 1 Schematic diagram of pavement systems and impact of moisture.

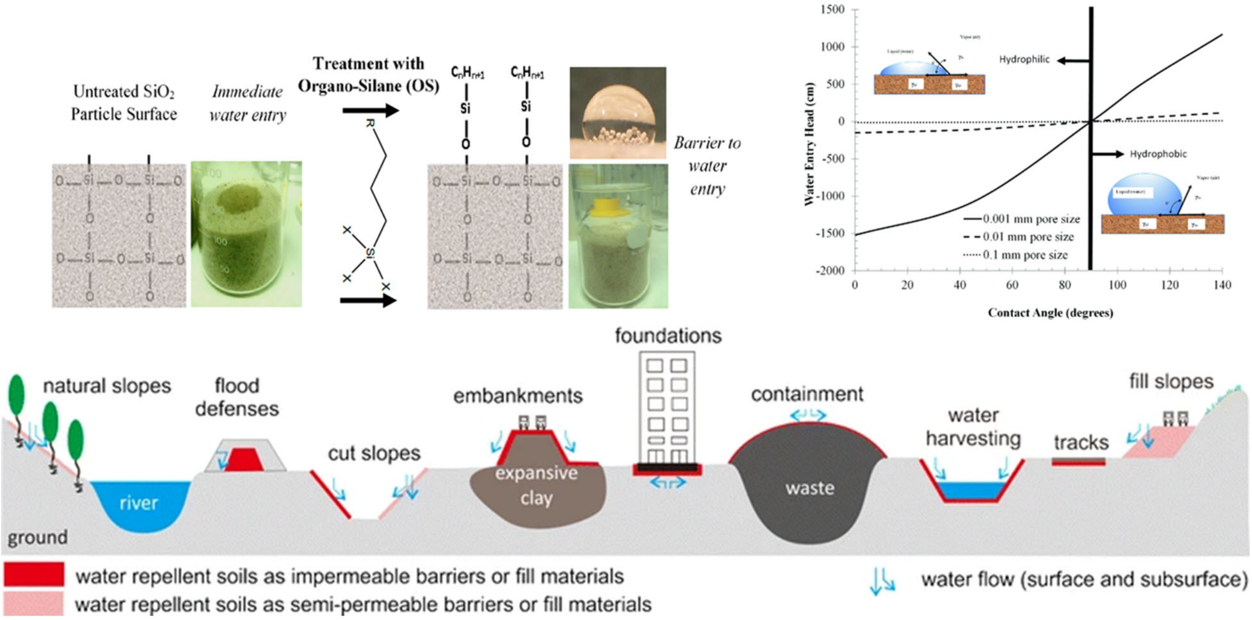


FIGURE 2 Applications of soil hydrophobicity and its working mechanism with organo-silane.

IMPACT OF ENGINEERED WATER REPELLENCY ON FROST HEAVE PERFORMANCE OF SUBGRADE SOILS

Overall results show that frost heave and thaw settlement performance of frost and moisture susceptible soils increased significantly when they were treated to be hydrophobic (Figure 3). It is evident that the utilization of an engineered water repellency technique (in this case it is the treatment with organo-silane material) has the potential to significantly diminish the maximum heave, even when employed at a relatively low concentration(s) (~as of 0.1% by volume).

USE OF GEOSYNTHETICS TO MITIGATE THE IMPACT OF MOISTURE ON PAVEMENT PERFORMANCE

Recent developments by geosynthetic manufacturers offer engineering products designed to remove water through passive drainage or wicking action. Wicking geotextile in pavement foundation layers (subgrade in particular) helps to remove moisture from groundwater and other sources (e.g., precipitation, snow melting) during freezing conditions. This, in turn, prevents ice formation and minimizes the freeze-thaw damage to pavement systems. Both field and laboratory measurements of this technology show that wicking geotextile tends to keep the pavement foundations drier than that of pavement foundations without wicking geotextile (Figure 4).

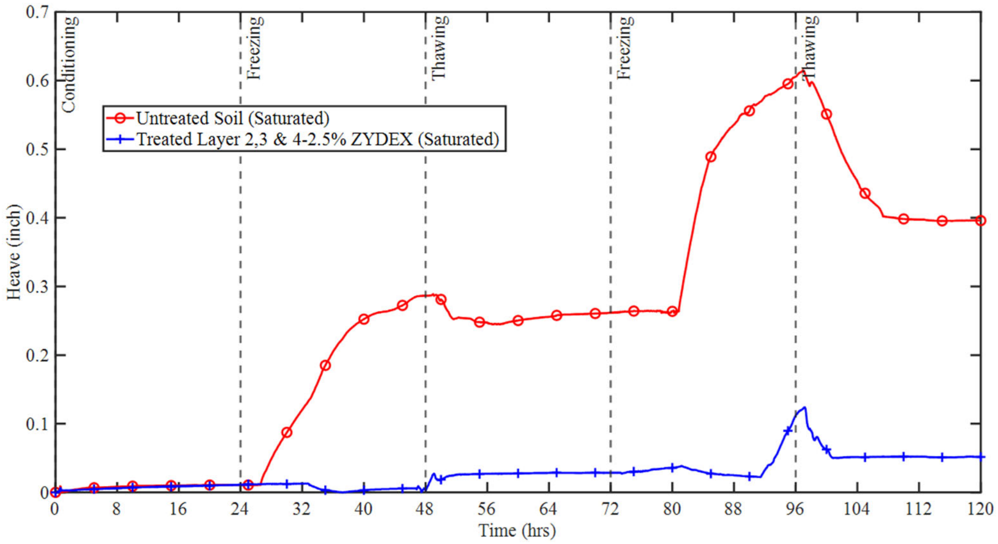
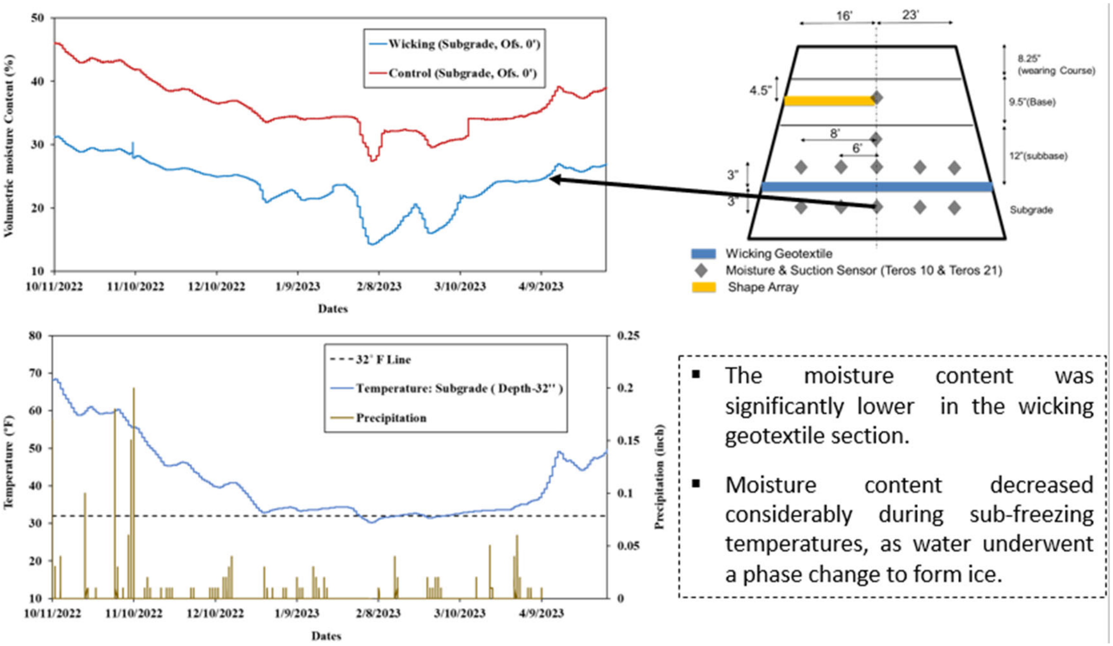


FIGURE 3 Frost heave–thaw settlement results for non-treated and treated soil.



- The moisture content was significantly lower in the wicking geotextile section.
- Moisture content decreased considerably during sub-freezing temperatures, as water underwent a phase change to form ice.

FIGURE 4 Moisture data for sections with and without wicking geotextile.

Geosynthetic Stabilization of Subgrade Soils and Pavement Granular Layers

EROL TUTUMLUER
University of Illinois

INTRODUCTION

Geosynthetics have drastically changed the way roads are designed and constructed since the first use of nonwoven geotextiles in the late 1960s to successfully construct access roads at construction sites where driving trucks was otherwise impossible. The second major step in the development of the use of geosynthetics in roads was the advent of geogrids in the 1980s (Giroud, 2009). Other major steps are expected in the future, perhaps related to the development of new geosynthetics or to the growing use in roads of existing geosynthetics such as geocells and enhanced lateral drainage geocomposites.

The geosynthetics currently used in roads include geotextiles (woven and nonwoven), geogrids with different geometries, geocells, drainage geocomposites, and wicking geotextiles. These geosynthetics perform several functions, as discussed by Zornberg (2017a, 2017b). As a result, geosynthetics are highly beneficial to roads by providing better performance and increased service life. Alternatively, geosynthetics can be used to allow a smaller thickness of the road cross section or the use of lower-quality construction materials.

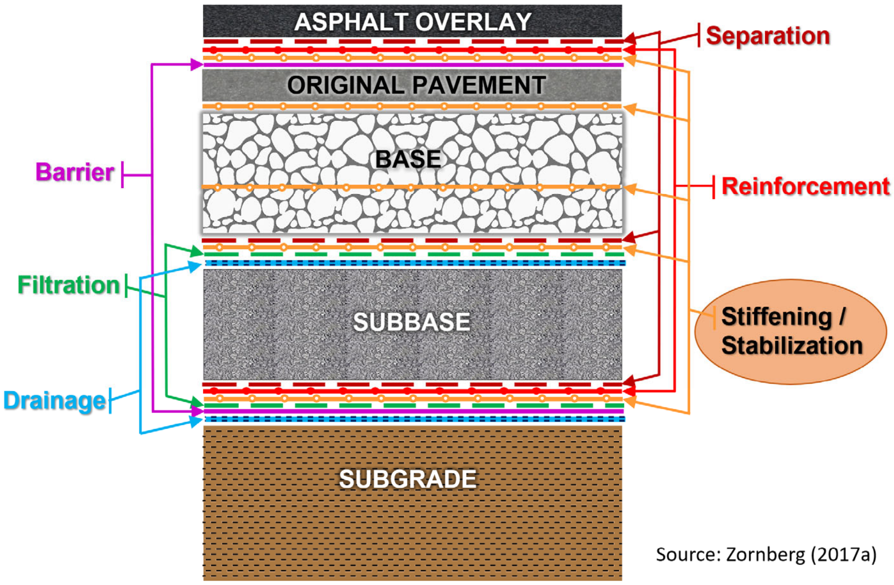
Geotextiles can reduce layer intermixing, facilitate moisture reduction, and provide confinement and stabilization to pavement subgrade and granular base and subbase materials. Geogrids provide mechanical stabilization by giving strength to base and full-depth reclamation material through lateral restraint and improved load-bearing capacity in pavement systems. Geosynthetics in paved road mechanical stabilization offers large benefits of extending pavement life and allowing reduced thicknesses. Nevertheless, geosynthetic stabilization design needs to be mechanistic-empirical (M-E). Recent promising research findings offer ways to quantify the magnitude and extent of enhanced stiffness zone in sublayers of granular base and subbase for M-E design.

STATE OF PRACTICE

There are multiple beneficial applications of geosynthetics for building long lasting pavements which include: (i) reduction of layer intermixing, (ii) reduction of moisture in structural layers, (iii) stabilization of soft subgrades, (iv) stabilization of unbound aggregate layers, and (v) mitigation of distress induced by frost heave and expansive clays. These applications involve many mechanisms that, in turn, require that geosynthetics make use of multiple functions (e.g., separation, filtration, reinforcement, stabilization, or stiffening) as illustrated in Figure 1. Understanding the different mechanisms is critical for the selection of the proper design methods and geosynthetic properties to incorporate the benefits of geosynthetics within the framework of design approaches such as M-E, limit state, and empirical designs. The different applications involving the use of geosynthetics in roadways allow quantification of the benefits of adopting their use, in relation to conventional design approaches, in terms of improved performance, extended design life, and decreased carbon footprint.

SUBGRADE RESTRAINT OR STABILIZATION

The objective of subgrade restraint or stabilization with geosynthetics is to increase the bearing capacity of soft subgrade soils. The identified mechanisms include vertical restraint of the subgrade and membrane effect. The vertical restraint accounts for the increased vertical confinement induced by the geosynthetics and provides a relevant contribution to subgrade



Source: Zornberg (2017a)

FIGURE 1 Geosynthetic applications in roadway applications (Zornberg, 2017a).

stabilization. The membrane effect, in contrast, requires significant deflection of the subgrade, often more than 100 mm (4 in.) to be mobilized. The functions of reinforcement, stiffening, separation, and filtration are all involved. The primary function (reinforcement) is to increase the bearing capacity of subgrade soils and restrain soils against shear failure at low stress (stiffening). Note that the stiffening function is also relevant to complement the stabilization of the subgrade with that of the base (Zornberg, 2017a). The development of local shear failure in the subgrade may lead to significant deflections, as depicted in Figure 2(a) and Figure 2(b), and illustrates the impact of geosynthetics in increasing the bearing capacity of subgrade soils.

The main mechanisms to take place include vertical restraint beyond the wheel path and some membrane-induced tension under the wheel path. Such subgrade restraint can decrease time-dependent rutting by minimizing vertical and shear stresses in the subgrade under the wheel path and redistributing shear and normal stresses beyond the wheel path. Note that higher deformation is required to mobilize such a mechanism. Therefore, subgrade restraint is particularly applicable for projects with a subgrade California Bearing Ratio (CBR) of less than 3%. Typical applications include:

- Facilitate expediency in the construction of roadways over very weak subgrade.
- Reduce aggregate thickness and depth over excavation for pavement construction over weak subgrade.
- Some rutting is allowed for the initial lift in construction.
- A serious alternative to other stabilization options when thick granular backfill is required or subgrade soil has a high gypsum or sulfate content.

An ideal performance management process strives to balance the field stiffness of the foundation layer, with its uniformity after compaction, while ensuring that the final product is durable. A pragmatic solution to the implementation of this process requires considering the importance of the project, the sophistication of the pavement design, the pre-construction laboratory efforts, and the amount of effort placed on field quality testing.

FIGURE 2 Use of geosynthetics in stabilization of subgrades: (a) roadway designed without geosynthetics and (b) roadway designed with geosynthetics (Zornberg, 2017a).

UNBOUND AGGREGATE STABILIZATION

The aim of unbound aggregate base and subbase stabilization using geosynthetics is to provide initial compaction. The aim is also to increase the construction-bound modulus and decrease the time- and trafficking-dependent modulus of unbound aggregate layers. Stiffening is the primary function that can lead to decreased lateral displacements within the aggregate-geosynthetics composite (Zornberg, 2017a). The identified mechanism is the development of lateral restraint through tension and shear transfer to minimize the lateral displacement of unbound aggregates. The typical placement location to facilitate constructability is at the interface between the base being stabilized and the underlying subgrade. Multiple layers of geosynthetics can be used in aggregate layers thicker than 450 mm (~18 in.).

The degradation of the base layer happens when lateral displacement of aggregate particles occurs under repeated traffic loading, and significant displacement usually happens in the lower portion of the base layer, directly below the wheel path, where tensile stresses are more prone to develop (Zornberg, 2017a). The potential lateral displacement within the base layer under a wheel load is illustrated in Figure 3(a). The base material modulus is expected to decrease due to the resulting decreased lateral stresses. The higher modulus the base material holds, the wider the distribution of vertical loads can be achieved, and, in turn, a smaller vertical stress is applied at the base-subgrade interface. The function of geosynthetics in base stabilization is illustrated in Figure 3(b). The shear stress from the base material is taken by lateral restraint and geosynthetic in tensile stresses. Additionally, the tensile stiffness of the geosynthetic contributes to limiting lateral strain development. Note that both friction and interlocking contribute to the base stabilization. Stabilization is often associated with a paved road and an aggregate base constructed over a subgrade having CBR ranging from 3 to 8 (Holtz et al., 2008). The main benefits of unbound aggregate base stabilization include (i) decreasing time-dependent rutting by providing an increased modulus of unbound aggregates at the time of construction and added confinement from compaction-induced geosynthetic tension and (ii) minimizing degradation of the modulus of unbound aggregates over time by proper control of lateral displacements in unbound aggregates and maintaining initial confinement of unbound aggregates.

QUANTIFYING GEOSYNTHETIC STIFFENING AND STABILIZATION

Stabilization geosynthetics installed in the unbound aggregate base or subbase of the pavement provide the lateral restraint in the layer, especially for geogrids by interlocking with the aggregate particles. The bender element test is a research approach adopted recently at the University of Illinois to directly measure shear wave velocity in a geogrid influence zone and quantify the stiffening effect in this stiffened zone, which was unavailable through previous research approaches. Shear wave transducers used as a source-receiver pair are called bender elements (BEs), which have been commonly used to evaluate the stiffness of the granular material in laboratory studies (Lee and Santamarina, 2005). A BE transducer is composed of three layers—a thin metal plate sandwiched between two piezoceramic plates. The piezoceramic plates deform when an electric field passes through them, and the physical deformation generates an elastic wave propagation through the medium, such as an unbound aggregate material. Conversely, the physical deformation of the piezoceramic plate generates the electrical

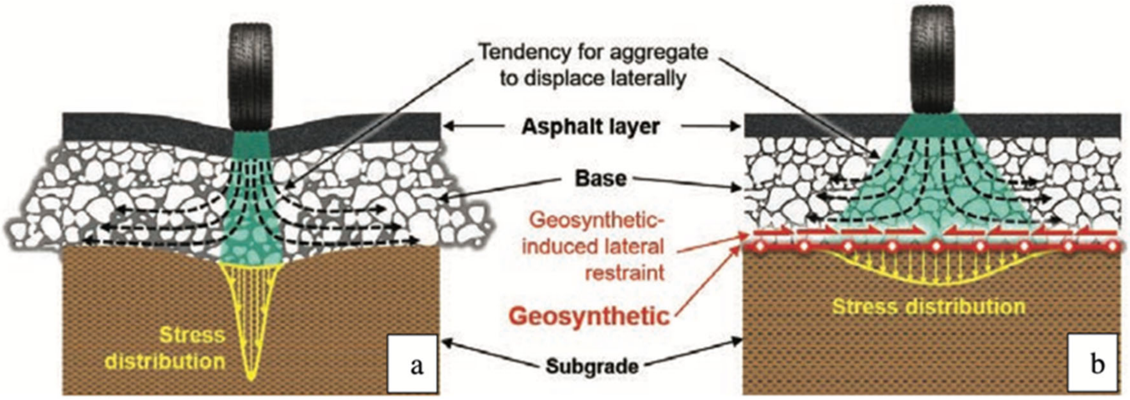


FIGURE 3 Use of geosynthetics in the stabilization of base and subbase: (a) roadway designed without geosynthetics and (b) roadway designed with geosynthetics (Zornberg, 2017a).

charge. Thus, a BE can be utilized as an elastic wave source or receiver. A flat shape and the fishtail oscillation movement of the BE enable a superb coupling between the transducer and granular materials such as aggregates.

Recent studies using BE pairs to measure the shear wave velocity of geogrid-stabilized cylindrical aggregate specimens during triaxial tests have confirmed that the BE pairs are able to evaluate the characteristics of a geogrid-stiffened zone (i.e., changes in shear wave velocity) along with depth above the geogrid (Byun and Tutumluer, 2017; Kang et al., 2020). From the shear wave velocity measured using BEs, a shear modulus can be expressed in terms of shear wave velocity as follows: $G_{max} = \rho V_s^2$, where ρ is density of the specimen, G_{max} is small-strain shear modulus, and V_s is shear wave velocity. Further, based on continuum mechanics, the elastic modulus (in a small-strain range) can be estimated as follows: $E_{BE} = E_{max} = 2G_{max}(1+\nu)$, where E_{BE} is the elastic modulus from a BE sensor in a small-strain range, and ν is the Poisson's ratio of the aggregate material.

Figure 4 illustrates the test setup for the repeated load triaxial test with geogrid and bender elements. Bender elements installed at different heights above the geogrid successfully quantified the stiffening effect of the geogrid-stabilized specimen compared to an unstabilized specimen. Furthermore, a BE field sensor to monitor and evaluate the shear wave velocity of the unbound aggregate layer of the in situ pavement or full-scale test sections was developed and verified by Kang et al. (2021). The BE field sensor can monitor and quantify the stiffness enhancement in the vicinity of the geogrid in pavement. Figure 4 also shows the BE field sensor along with the shear wave signal measurement system. The test results performed in a large-scale testbed using the BE field sensor indicated the improved stiffness near the geogrid and the existence of a mechanically stabilized layer profile.

The use of BE sensor technology to evaluate the effectiveness of geogrids in unbound aggregate base stabilization has been successfully applied in field projects (e.g., recent US 20 reconstruction project near South Bend, Indiana, and Federal Aviation Administration's (FAA's) National Airport Pavement Test Facility (NAPTF) Construction Cyle (CC) 9 full-scale geosynthetic test sections). This stiffened zone quantification approach will allow a more accurate pavement analysis and design methodology for geogrid-stabilized pavements by

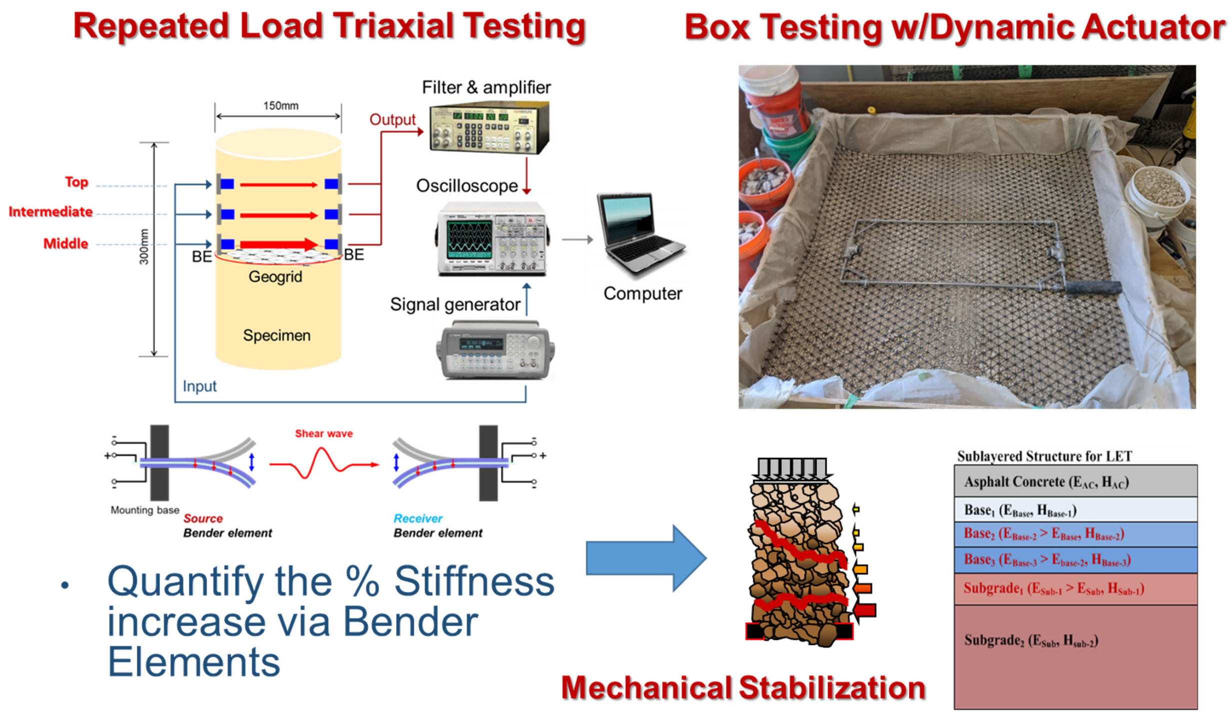


FIGURE 4 Quantifying geosynthetic stiffening and stabilization via bender element shear wave technology.

adopting a sublayering analysis approach where the unbound aggregate base is divided into sublayers, as shown in Figure 4. Each of the sublayers will be assigned a modulus equal to the modulus of the base layer multiplied by a stiffening factor prior to conducting the analysis. This will be an M-E design approach for incorporating stiffened influence zones provided by geogrid into pavement mechanistic analysis following the mechanically stabilized layer concept.

CONCLUDING REMARKS

Geosynthetics (i.e., the most used geotextiles and geogrids in transportation applications), provide engineered solutions for constructing 100-year or permanent foundation layers for long lasting road and airfield pavements. They provide soft subgrade restraint and pavement base/subbase stabilization through reinforcement and unbound aggregate stiffening functions. Geotextiles also provide separation to minimize layer intermixing, and pumping resistance by considering the most recent research findings on geotextile clogging and permeability criteria. These standards can be used for filter fabrics, geotextile separation layers under both asphalt and concrete pavements, and geotextiles used for separation on top of weak and muddy subgrades. The use of modern geosynthetic products, such as geotextiles with enhanced (suction-driven) lateral drainage and geocells for subgrade restraint, no doubt will provide the most sought out engineered solutions for 100-year pavement foundations. By presenting findings on the geogrid-stiffening effect in unbound aggregates, this document provided insights into the optimization of geosynthetic products and their most effective uses in different transportation facility applications thus underscoring the importance of tailored approaches for each facility to achieve effective mechanical stabilization with geosynthetics. Recent advents such as the bender element shear wave technology highlighted in this document in quantifying geosynthetic stabilization benefits reaffirm the pivotal role geosynthetics play in providing a well-engineered and effective solution to constructing safe, sustainable, resilient transportation infrastructure.

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Role of Performance Management in Long Lasting Pavement Foundation

Soheil Nazarian

University of Texas at El Paso

INTRODUCTION

A well-designed and constructed pavement system provides the following three attributes:

- Safety
- Smoothness
- Durability

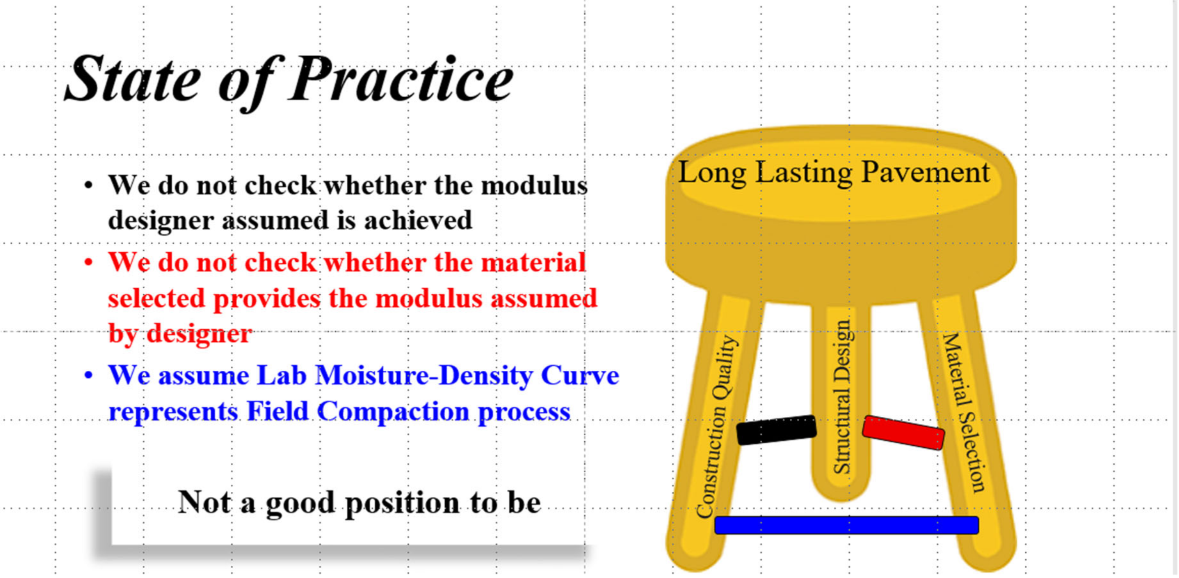
Properly designing and constructing all the foundation layers supporting the surface layer will strongly contribute to these three items. NCHRP Project 01-62, "Impact of Flooding on the Resiliency of Pavement Systems," defines the pavement system as all the different layers and materials constructed to support and distribute traffic loads to the non-engineered roadbed material. *NCHRP Report 453: Performance-Related Tests of Aggregates for Use in Unbound Pavement Layers* indicates that several pavement distresses manifested on the pavement surface (e.g., rutting and cracking) can be attributed to a poorly executed or designed base, subbase, or subgrade. The theme of this section can be summarized in the following manner:

> An ounce of attention to foundation issues during construction saves a ton
> of aggravation (and money) during the life of the pavement.

STATE OF PRACTICE

Durable and well-performing foundation layers are only possible if the following three aspects are considered harmoniously (Figure 1):

- Structural Design
- Material Selection
- Construction Quality Management



State of Practice

- We do not check whether the modulus designer assumed is achieved
- We do not check whether the material selected provides the modulus assumed by designer
- We assume Lab Moisture-Density Curve represents Field Compaction process

Not a good position to be

FIGURE 1 State of practice in pavement design and construction.

The state of practice does not consider these three interrelated activities holistically. The pavement design is usually performed based on the moduli selected based on the designer's experience or the local policies before the sources of the materials are selected. The focus of the material selection process is ensuring constructability and durability, usually independent of the design parameters. The construction quality management (i.e., quality control and quality acceptance, or QAQC) is traditionally based on the field density, not the parameters used in the design. As such, a concerted effort is needed to tie these three items holistically. The remainder of the presentation is focused on the concept of performance management to potentially minimize the lack of coordination among these three items.

PERFORMANCE MANAGEMENT

The impetus for performance management is to ensure that pavement lasts for a pre-defined life uniformly. The goal is to ensure that the pavement is stiff enough, uniform enough, and durable enough. To achieve this goal, a transition from the traditional QAQC to a performance management process is needed.

An ideal performance management process strives to balance the field stiffness of the foundation layer, with its uniformity after compaction, while ensuring that the final product is durable. A pragmatic solution to the implementation of this process requires considering the importance of the project, the sophistication of the pavement design, the pre-construction laboratory efforts, and the amount of effort placed on field quality testing (Figure 2).

Durability: A dense or stiff layer does not necessarily translate to a durable one. As much as possible durability should be considered during the material selection and design. Durability should be considered based on the best practices and local experiences since it cannot be quantified in the current design algorithms. For example, issues such as potential long-term decompaction of layers, significant modulus mismatch between adjacent unbound foundation layers, and inclusion of geosynthetics to avoid contamination or improve the strength of weak layers, should be incorporated into the pavement structure. Parameters such as hardness of aggregates, percent fines, and plasticity should be the subject of a well-planned process control. For stabilized layers, the concentration of additives should be part of the process control.

Uniformity: Managing the uniformity of the final product is also important. To ensure uniformity in a statistically significant manner, the final product should be tested more frequently than is currently done. For this step to be cost-effective, a simple and fast test with adequate precision should be selected over a more rigorous but time-consuming test. For example, a lightweight deflectometer (LWD) that can test a point in a couple of minutes is preferred over a plate load test that can typically take more than an hour. Intelligent compaction (IC) is an effective tool for ensuring uniformity because a compacted layer can be evaluated in almost real time as long as the roller used for that purpose is operated at a constant speed and roller vibration level and frequency.

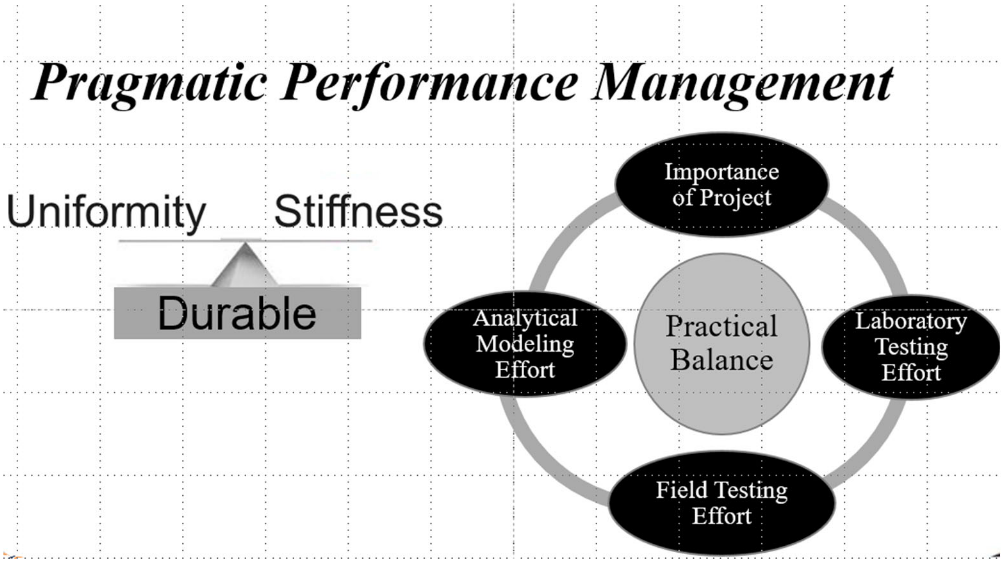


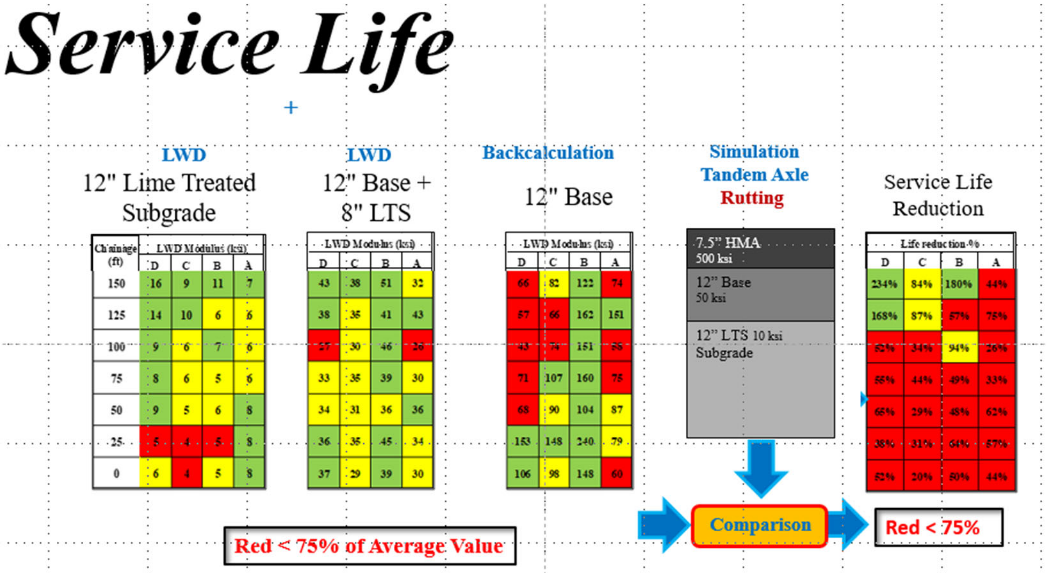
FIGURE 2 Aspects of a pragmatic performance management process.

In-place Stiffness: Since the relationship between the density and modulus is rather weak, ideally, the stiffness of the foundation should be measured. In that scenario, measuring density and moisture content can be part of the process control. Again, devices like LWD can be adopted for this purpose. More recently, algorithms based on the Federal Highway Administration (FHWA) Level 4/5 IC concept have been developed for this purpose. Level 4/5 IC algorithms combine artificial intelligence with rigorous numerical models to extract moduli from the roller measurements. To implement the IC method properly for extracting stiffness, a rigorous field calibration program is needed.

Figure 3 demonstrates the consequences of traditional quality control on the performance of an actual pavement section. Both the subgrade and base passed the density requirements. Despite proper workmanship by the contractor, the in-place modulus of the subgrade was substantially less than the value assumed by the designer. A simple structural analysis shows much less expected life compared to what the designer intended.

PRACTICALITY OF PERFORMANCE MANAGEMENT

To be implemented properly the process has to be practical, transparent, and perceived fair to the owner agencies and contractors. To ensure transparency and fairness in the process, all the assumptions and algorithms used should be explained, discussed, and agreed upon before the project starts. Simple items like implementing virtual sublots, using the coefficient of variation of each sublot for uniformity, and the average of locally calibrated modulus in each sublot can help make the process more practical (Figure 4).



Chainage (ft)	LWD Modulus (ksi)			
	D	C	B	A
150	16	9	11	7
125	14	10	6	6
100	9	6	7	6
75	8	6	5	6
50	9	5	6	8
25	5	4	5	8
0	6	4	5	8

LWD Modulus (ksi)			
D	C	B	A
43	38	51	32
38	35	41	43
27	30	46	26
33	35	39	30
34	31	36	36
36	35	45	34
37	29	39	30

LWD Modulus (ksi)			
D	C	B	A
66	82	122	74
57	66	162	151
43	74	151	55
71	107	160	75
68	90	104	87
153	148	240	79
106	98	148	60

Life reduction %			
D	C	B	A
234%	84%	180%	44%
168%	87%	57%	75%
52%	34%	94%	26%
55%	44%	49%	33%
65%	29%	48%	62%
38%	31%	64%	57%
52%	20%	50%	44%

FIGURE 3 A case study demonstrating the importance of performance management.

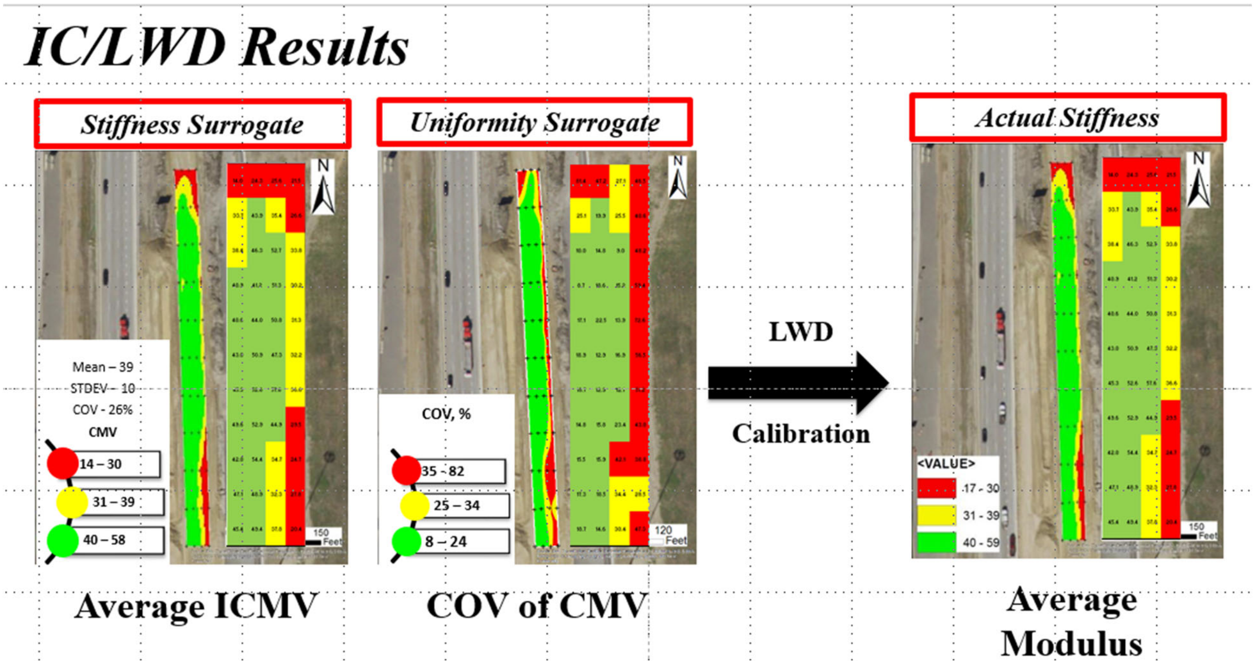


FIGURE 4 Some concepts of practical performance management.

FOR MORE INFORMATION

The information provided here is explained in detail in the following two publications:

- Nazarian, Soheil, Aria Fathi, Cesar Tirado, Vladik Kreinovich, Sergio Rocha, and Mehran Mazari. *NCHRP Research Report 933: Evaluating Mechanical Properties of Earth Material During Intelligent Compaction*. Transportation Research Board, Washington, DC, 2020. https://doi.org/10.17226/25777.
- Tirado, Cesar, Aria Fathi, Sergio Rocha, Mehran Mazari, and Soheil Nazarian. Deflection-based field testing for quality management of earthwork. No. FHWA/TX-19/0-6903-1, 0-6903-01. Texas Department of Transportation. Research and Technology Implementation Office, 2018. https://library.ctr.utexas.edu/hostedpdfs/utep/0-6903-1.pdf

E-Compaction for Pavement Foundations

David J. White

Ingios Geotechnics

THE CHALLENGE

The Iowa Department of Transportation (DOT) has undertaken a multi-year implementation plan to help significantly increase the performance life of its pavements. Early distresses in pavements related to the foundation layers (pavement roughness, unevenness, and cracking) are a leading cause of pavements having higher than necessary maintenance requirements (patching, overlays, and removal) over their lifetime and shortened performance life requiring early pavement rehabilitation activities.

The approach taken by the implementation plan developed is to implement design modulus assessment during construction and ensure that the design requirements are achieved. Pavements are designed assuming a modulus of subgrade reaction (k-value) or resilient modulus (M_r) for the pavement foundation support which can be directly and efficiently measured in the field using currently available technologies for plate load testing and modulus mapping. The critical question, however, is: Given the low accomplishment of the intended design assumptions with the current specification requirements, what can realistically be achieved? Is the low achievement of desired support a result of poor construction or material specifications, the contractor not complying with specifications, or specifying foundation designs that are not capable of providing the needed pavement support?

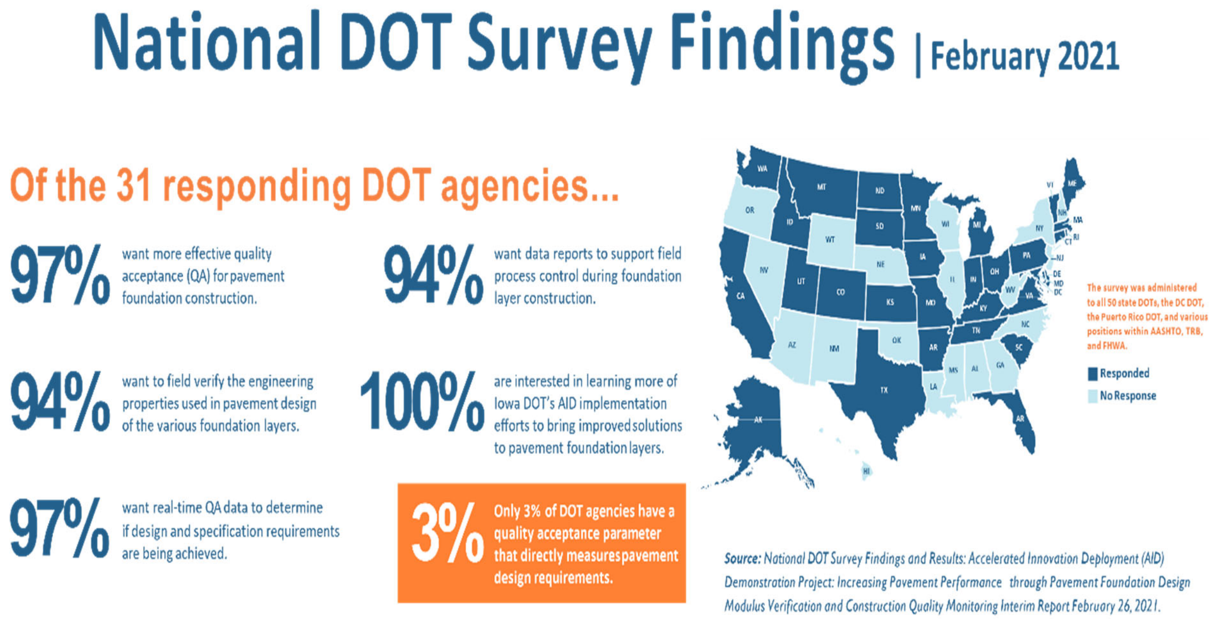
WHAT IS e-COMPACTION?

e-compaction is the information system and workflow process developed to produce pavement foundations that achieve pavement design parameters. Components include (1) calibrated compaction machines enabled with technology to directly measure pavement foundation design values, (2) geo-located measurements over 100% of the compacted area, (3) real-time e-compaction reporting system to document results and drive decision-making, (4) web-based platform to remotely manage compaction from desktop or mobile devices, and (5) a new quality control and quality assurance (QC/QA) workflow process to help achieve compaction efficiently.

EARLY RESULTS

The Iowa DOT, with support from the Federal Highway Administration (FHWA), invested in an Accelerated Implementation and Deployment (AID) Grant in 2019 to evaluate building pavement foundations using modulus-based assessment to directly measure and control construction practices to achieve the design requirements. The project demonstrated that the modulus and deformation of the pavement foundation layers can be practically and efficiently measured in the field in real time as the foundation materials are being placed. The outcome of that project was an implementation plan for the Iowa DOT to transition from the current construction and design requirements to modulus-based specifications and construction requirements. The TRB workshop presentation highlighted the key features of the e-Compaction process and results from selected projects.

Figure 1 provides a summary of findings from a national survey led by Iowa DOT to assess interest in approving QA methods for pavement foundation. Of the 31 responding state highway agencies (SHAs), most were interested in implementing improved QA methods for foundation layers. Figure 2 presents the roadmap created to work toward implementation of new QA processes involving direct modulus measurements and e-Compaction mapping.



National DOT Survey Findings | February 2021

Of the 31 responding DOT agencies...

97% want more effective quality acceptance (QA) for pavement foundation construction.

94% want data reports to support field process control during foundation layer construction.

94% want to field verify the engineering properties used in pavement design of the various foundation layers.

100% are interested in learning more of Iowa DOT's AID implementation efforts to bring improved solutions to pavement foundation layers.

97% want real-time QA data to determine if design and specification requirements are being achieved.

3% Only 3% of DOT agencies have a quality acceptance parameter that directly measures pavement design requirements.

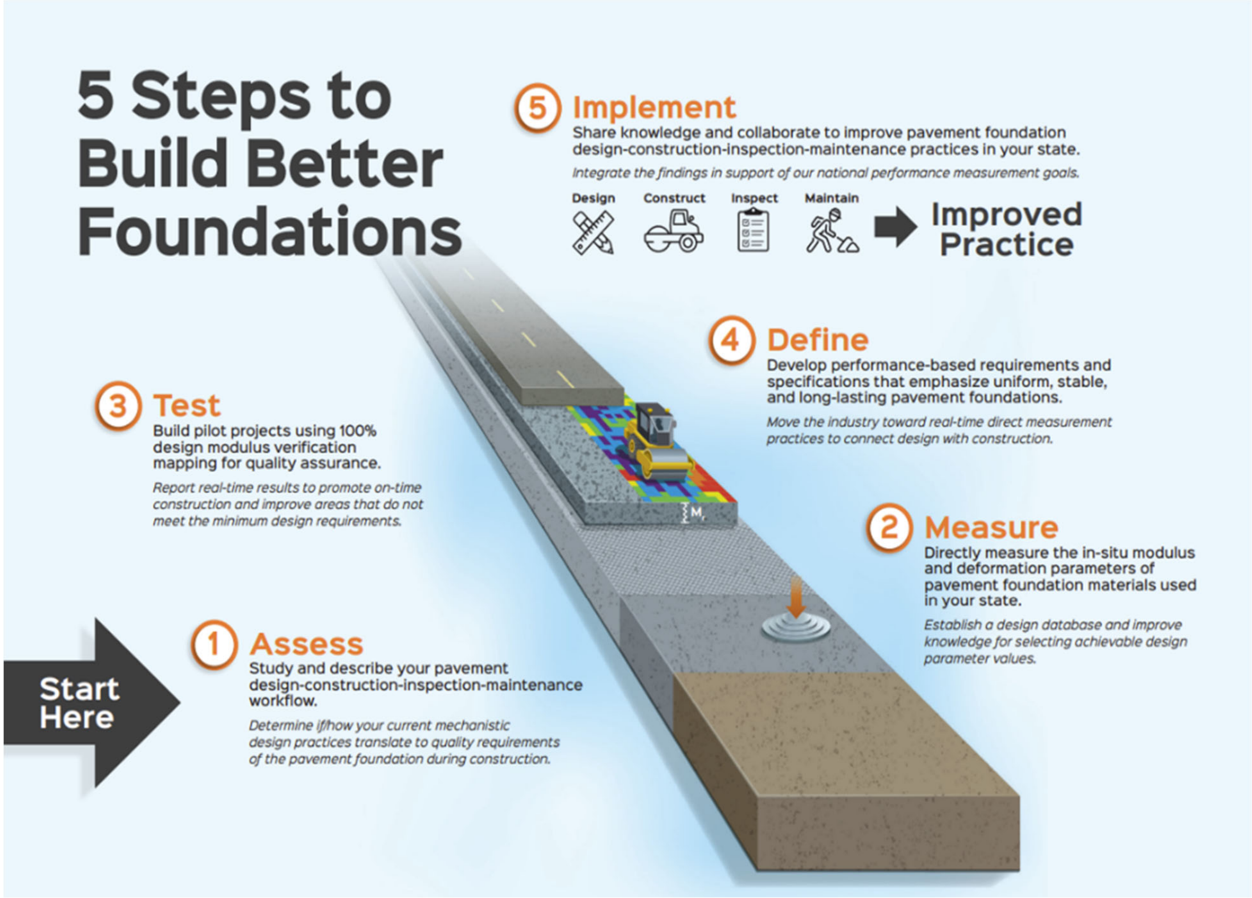
The survey was administered to all 50 state DOTs, the DC DOT, the Puerto Rico DOT, and various positions within AASHTO, TRB, and FHWA.

▇ Responded

▢ No Response

Source: National DOT Survey Findings and Results: Accelerated Innovation Deployment (AID) Demonstration Project: Increasing Pavement Performance through Pavement Foundation Design Modulus Verification and Construction Quality Monitoring Interim Report February 26, 2021.

FIGURE 1 Iowa DOT survey finding from AID demonstration project for pavement foundations.



5 Steps to Build Better Foundations

5 Implement
Share knowledge and collaborate to improve pavement foundation design-construction-inspection-maintenance practices in your state.
Integrate the findings in support of our national performance measurement goals.

4 Define
Develop performance-based requirements and specifications that emphasize uniform, stable, and long-lasting pavement foundations.
Move the industry toward real-time direct measurement practices to connect design with construction.

3 Test
Build pilot projects using 100% design modulus verification mapping for quality assurance.
Report real-time results to promote on-time construction and improve areas that do not meet the minimum design requirements.

2 Measure
Directly measure the in-situ modulus and deformation parameters of pavement foundation materials used in your state.
Establish a design database and improve knowledge for selecting achievable design parameter values.

1 Assess
Study and describe your pavement design-construction-inspection-maintenance workflow.
Determine if/how your current mechanistic design practices translate to quality requirements of the pavement foundation during construction.

FIGURE 2 Roadmap for achieving improved foundations for long-life pavements.

The National Concrete Pavement Technology Center (CP Tech Center) is under a cooperative agreement with FHWA-sponsored demonstration projects in Minnesota, Pennsylvania, and Indiana to demonstrate e-Compaction for concrete pavements in 2023 and additional projects for 2024. Figure 3 shows an example of pavement foundation modulus before and after the selected treatment of subgrade using cement. The results demonstrated improved stiffness and uniformity. Case histories and technical resources are being created along with plans for additional demonstration projects to further assess how best to use new technology to improve pavement foundations and support long-life pavements.

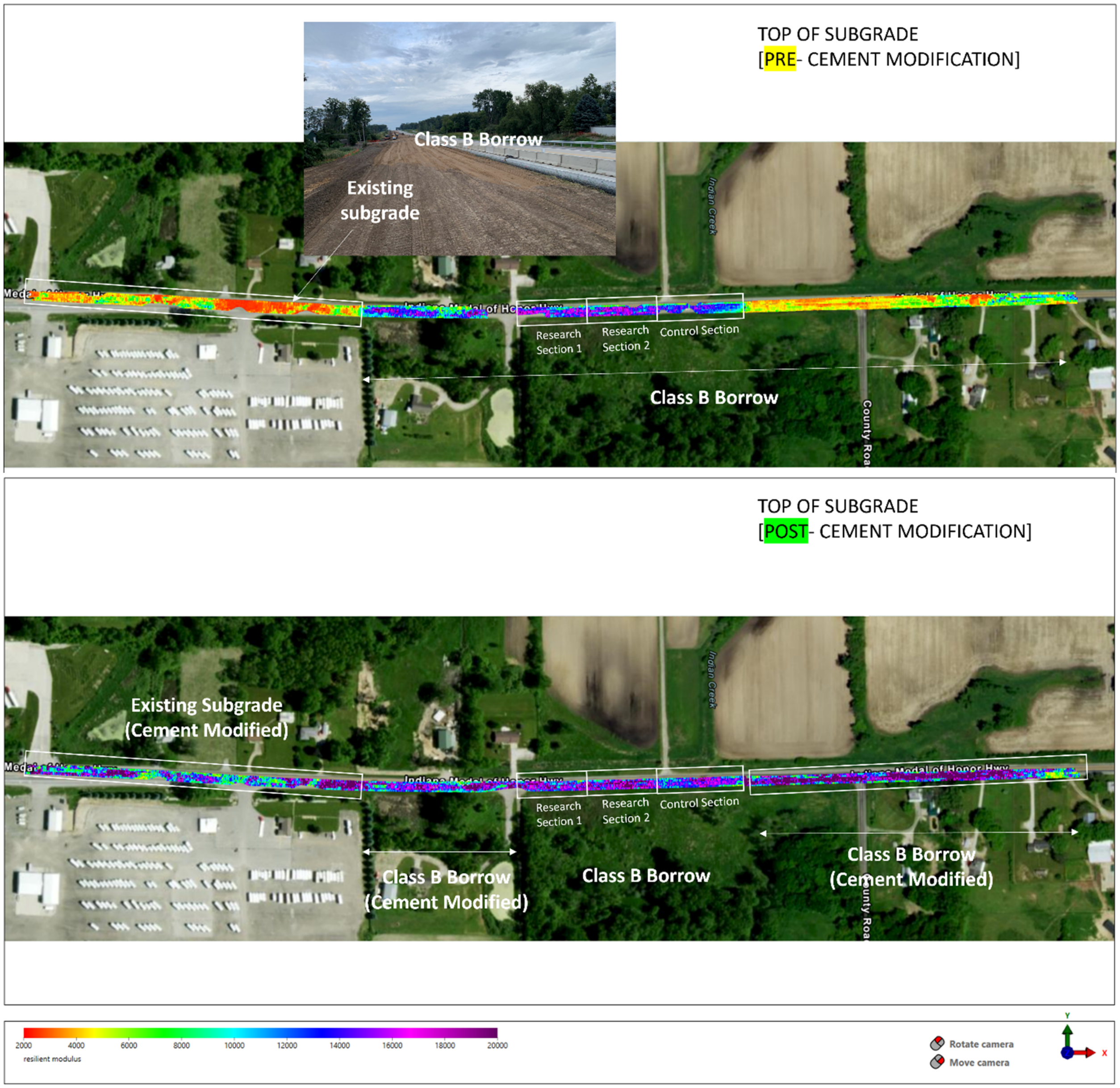


FIGURE 3 e-Compaction reports for INDOT project showing before-and-after results for cement treatment of subgrade.

Effect of Subsurface Drainage System on a Rural Principal Arterial Using LTPP Data

ISSAM KHOURY
HAKEEM ALSHAWABKEH
Ohio University
GABRIEL BAZI
pulsuus, llc

BACKGROUND

> "Subsurface drainage is a method of controlling the moisture content of subgrade soils and base courses for pavements by restricting the entrance of water or providing means for its escape. Lack of subsurface drainage may result in excessive moisture beneath or adjacent to pavements, which can cause poor performance or failure of the pavement system." (Barber, 1959)

> "It would be difficult to select the date when the early road builders first became aware of the need for adequate subsurface drainage. Certainly, it was understood that appropriate subsurface drainage was necessary for the satisfactory long-term performance of roadways." (FHWA-TS-80-224, 1980)

The foundation structure of many paved and unpaved roads is subjected to problems caused by excess water. This is due to water infiltrating the roadway surface or shoulders, groundwater seeping in from upslope areas, high water levels in roadway ditches, or groundwater rising from beneath the roadway. Water infiltration is exacerbated when cold temperatures occur, or when we have temperature variations in a short time period. Roadway foundations become weak due to excessive wetness, eventually leading to the surface's failure, whether paved or unpaved.

Problems attributable to water presence in pavement layers occur in all regions and across the climates of the United States. A National Cooperative Highway Research Program (NCHRP) study estimated that excess water reduces the life expectancy of pavement systems by more than half (Christopher and McGuffey, 1997). The principal method of handling excess water conditions is through subsurface drainage, while surface drainage helps alleviate some of the issues (Arika et al., 2009).

INTRODUCTION

Two Long-Term Pavement Performance (LTPP) sections were used from the Specific Pavement Studies (SPS-2) program built on US 23–a rural principal arterial—in a wet-freeze climatic zone in Delaware, Ohio.

Both sections (390101, and 390108) were built with identical layer thicknesses; a 7-inch asphalt concrete layer and, an 8-inch unbound granular base layer over a clayey subgrade. Section 390108 had an additional 4-inch asphalt-treated permeable base between the asphalt concrete and granular base layers. Table 1 provides additional information on the test sections.

OBJECTIVES

The objectives of this study were to quantify the effect of the subsurface drainage system by performing an on-site forensic investigation, back-calculation using falling weight deflectometer (FWD) data and evaluating the moisture contents using time-domain reflectometry (TDR) data.

METHODOLOGY

The methodology for the analysis includes the following points: Collect and analyze FWD data, collect and analyze dynamic cone penetrometer (DCP) Data, and TDR data,

TABLE 1 Section Information.

	Section 390101	**Section 390108**
☐ Subsurface Drainage system	No	Yes
☐ Opened to Traffic	August 14, 1996	August 14, 1996
☐ Projected ESAL	650,200	1,719,200
☐ Failed on	December 3, 1996	April 24, 2002
☐ Projected Failure	December 18, 1998	March 27, 2001
☐ Station	350+00 – 355+00	394+75 – 399+75
☐ Structural Number (SN)	3.57	4.13
☐ MR (psi) used in design	3,000	3,000
☐ DGAB thickness (inch)	8.00	8.00
☐ Asphalt thickness (inch)	7.00	11.00

FWD DATA

FWD data using the Ohio Department of Transportation (DOT) equipment were collected according to the LTPP protocol every 50 feet along the centerline and the right wheel path. Data was collected every 6 months. Testing data for each section is shown in Table 2.

TABLE 2 FWD test dates.

<table>
<tr><th rowspan="2">Section Name</th><th colspan="6">Testing During Construction</th></tr>
<tr><td>Subgrade</td><td>DGAB</td><td>PATB</td><td>ATB</td><td>PCTB</td><td>AC</td></tr>
<tr><th rowspan="2">390101</th><td>08/29/1995</td><td>09/12/1995</td><td>NA</td><td>NA</td><td>NA</td><td>06/11/1996</td></tr>
<tr><td>08/29/1995</td><td>09/12/1995</td><td>NA</td><td>NA</td><td>NA</td><td>06/11/1996</td></tr>
<tr><th rowspan="2">390108</th><td>08/28/1995</td><td>10/05/1995</td><td>10/11/1995</td><td>NA</td><td>NA</td><td>06/11/1996</td></tr>
<tr><td>08/28/1995</td><td>10/11/1995</td><td>10/11/1995</td><td>NA</td><td>NA</td><td>06/11/1996</td></tr>
<tr><td></td><th colspan="6">In-Service Testing</th></tr>
<tr><th>390101</th><td colspan="6">The section failed</td></tr>
<tr><th rowspan="2">390108</th><td>05/05/1998</td><td>09/14/1999</td><td>09/25/2000</td><td>04/11/2001</td><td colspan="2">03/19/2002</td></tr>
<tr><td>05/05/1998</td><td>09/14/1999</td><td>09/25/2000</td><td>04/11/2001</td><td colspan="2">03/19/2002</td></tr>
</table>

Inputs for Analysis

The inputs used in the back-calculation analysis were as follows; the thicknesses were as in-design values, seed value for Young's modulus and Poisson's ration were according to ASTM D5858.

The FWD data were then analyzed using BAKFAA software to get the subgrade back-calculated moduli values. Further analysis was done on the results using Excel (to exclude the out layers such as negative and abnormal values).

DCP Data

Dynamic Cone Penetration tests were conducted every 100 feet in both the centerline and wheel path, as well as the trench locations. The resilient modulus (MR) of the subgrade was calculated from the DCP test for each section using the following equation (Livneh, 1987):

$\text{Log (CBR)} = 2.20 - 0.71\ \text{Log}(PI)^{1.5} \pm 0.075$
and PI is the DCP penetration index (mm/blow)
MR = 1200×CBR (units are in kip per square inch [ksi])

Moisture Measurement

As part of the Strategic Highway Research Program (SHRP) and the LTPP program, these test sections were instrumented according to the SHRP protocols with TDR sensors to measure the moisture at various locations in the subgrade and base of each section.

Throughout the two selected sections, TDR probes were placed at various depths below the surface of the pavement in order to measure subsurface moisture. Volumetric moisture was measured with these probes in percent. Data was collected using on-site data loggers that collected and stored daily averages for each of the sensors.

RESULTS AND DISCUSSION

FWD Data Analysis

Results from the FWD data analysis are shown in Figure 1. Since section 390101 failed within 111 days of opening to traffic, only one FWD data set was collected.

As can be seen in Figure 1, section 390108 reached "Major Rehab" criterion set by Ohio DOT after the April 2001 testing, at that point, the MR value for section 390108 had a similar value to that for section 390101 when it was replaced.

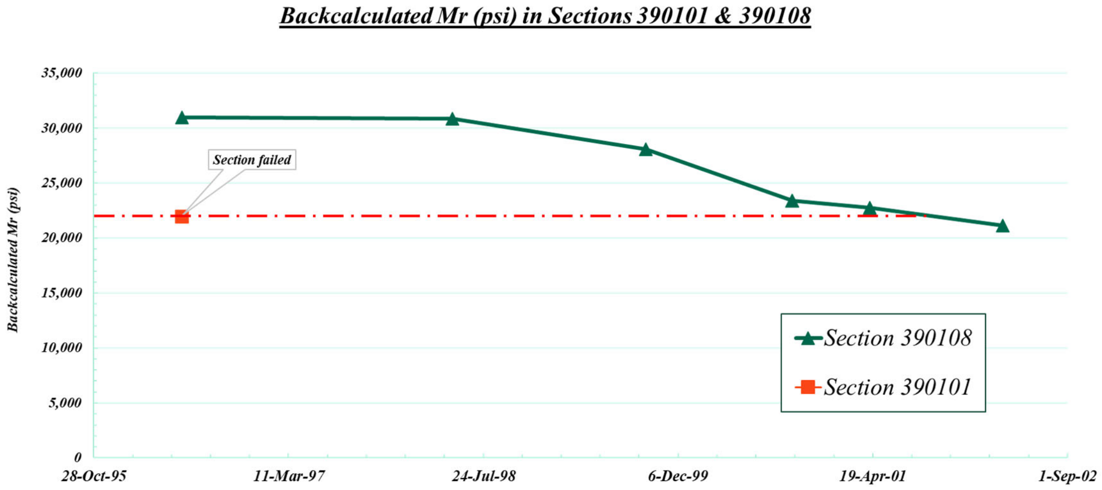


FIGURE 1 Back-calculated MR values for both test sections.

DCP Data

The average MR based on the DCP data was 23.4 ksi for section 390108 (which is close to the average back-calculated value 22.7 ksi) and 22.6 ksi for 390101 (which is close to the average back-calculated value 21.9 ksi). DCP data validated the FWD data analysis.

Subgrade Moisture Analysis

The TDR data is shown in Figure 2 below. In all the data shown, the section without drainage has a higher water content. The big gap in the moisture levels between the two sections is related to the drainage feature. It is noticeable that the moisture is decreasing through the pavement starting at around 22 inches in section 390108 and this is due to the subsurface drainage system in the section. On the other hand, the moisture is increasing at almost the same depth in section 390101, and this is due to the lack of drainage ability in this section.

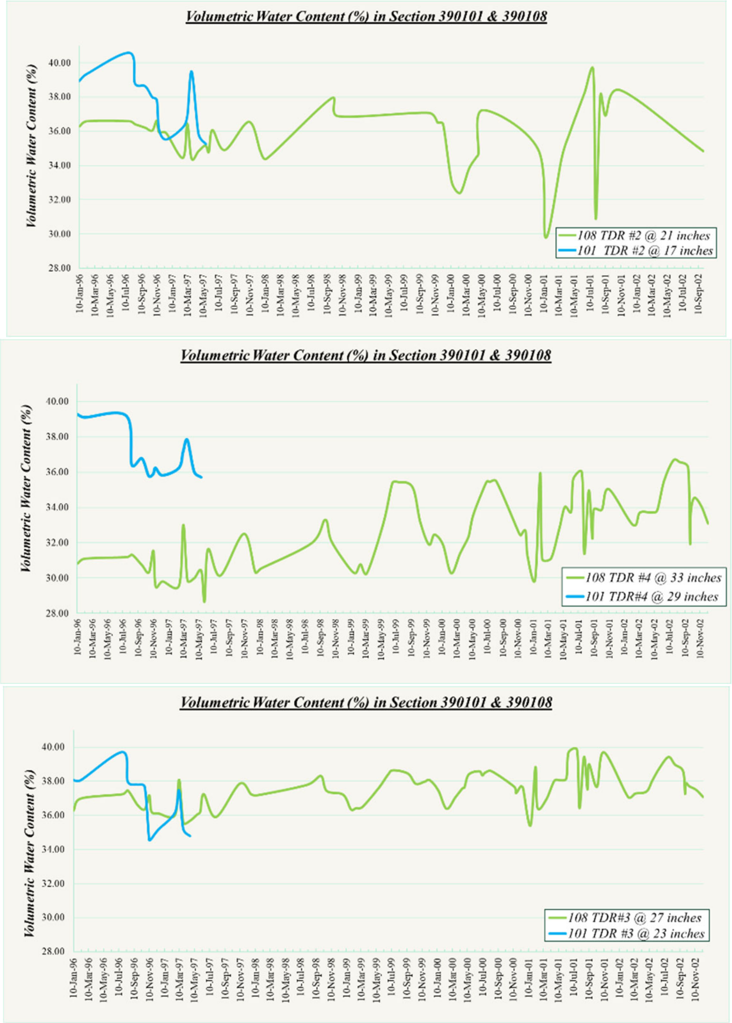


FIGURE 2 Volumetric water content sections 390101 and 390108 (TDR #2, #3, #4).

FORENSIC INVESTIGATION

In order to understand the failure mode for these sections, an extensive forensic investigation was conducted. Trenches were excavated where the most rutting and cracking occurred. The dimensions of these trenches were 5 feet (1.5 m) wide and 4 feet (1.2 m) deep. They were excavated at different stations to determine various levels of distress, 2 trenches in section 390108 and 3 trenches in section 390101. Figure 3 shows pictures of the trenches.

To maintain natural water content in the base and subgrade during the removal of asphalt concrete layers no water was used in sawing the asphalt concrete (AC) layers. Water was seen in the trenches which was present in the base layers of the trenches.

Trenches for section 390108 presented low to moderate distresses. No change in the AC layers thickness from the design thickness. Some consolidation of the base material was noted, this would indicate that rutting observed in the pavement surface had reflected up from the base and subgrade.

Soon after the test road was opened to traffic, section 390101 exhibited rutting of ~1/2 in. (13 mm), cracks in the wheel path, and a distress level of moderate to severe. Subgrade moisture was considerably higher than anticipated throughout the section. The same thickness was found for the AC layer. All the rutting happened because of the base and subgrade consolidated to excessive moisture.

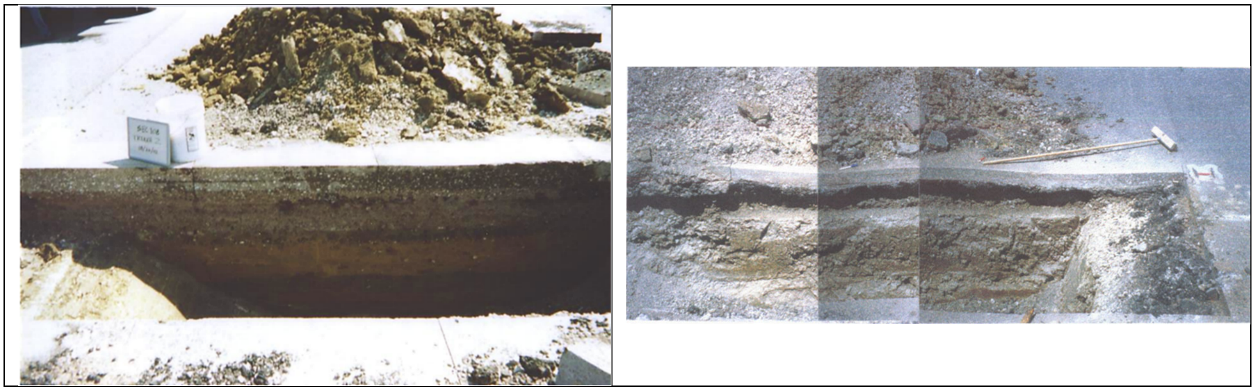


FIGURE 3 Pictures of the forensic trenches (390108 and 390101).

CONCLUSIONS

Low to moderate distresses were found in the section that has a subsurface drainage network. The existence of a subsurface drainage system extends the pavement life. Sections without drainage tend to have higher moisture content. The moisture content decreased by 10% at a depth of 22-40 inches in the section that has a drainage system. Along the trenches, the AC layer thickness remained consistent with the design conditions. The base material did consolidate a little. This would suggest that the rutting in the pavement surface was a result of reflection from the subgrade and base. It was found that there was reasonable agreement between the back-calculation and the DCP test results when comparing the resilient moduli value. The MR decreased after construction and during forensic investigations due to pavement distress.

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Eielson Air Force Base Drainage Case Study

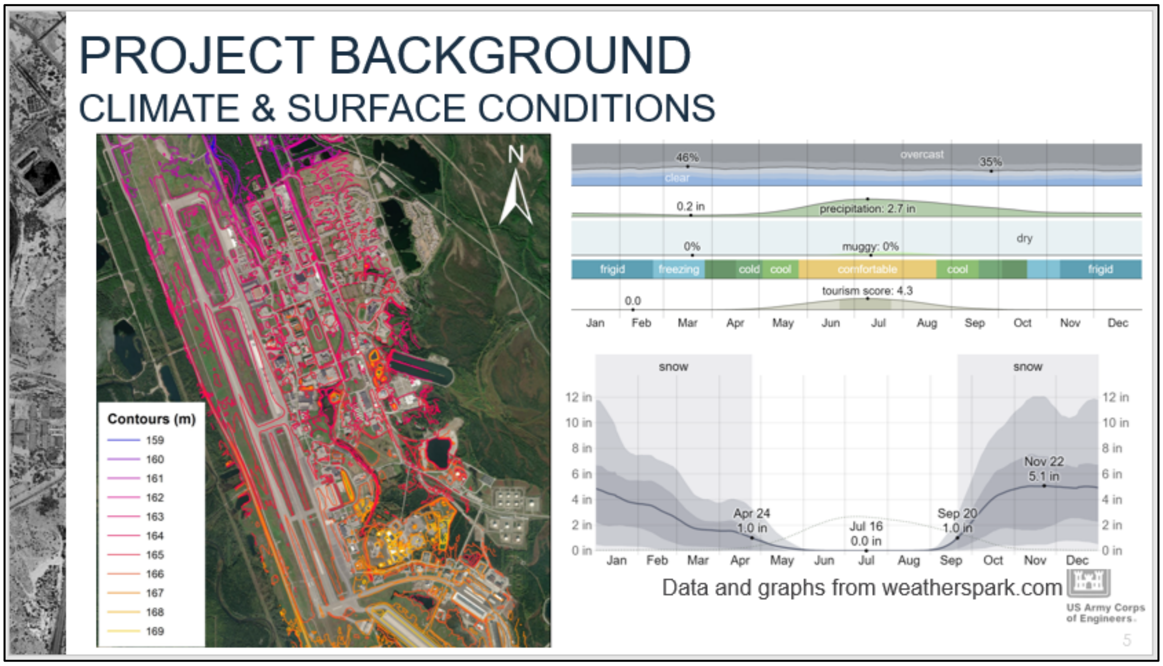
Rachel Hastings

US Army Corps of Engineers

In the spring of 2022, Eielson Air Force Base experienced significant water ponding and refreezing on the airfield during the winter thaw period. This presentation focuses on a team performing a site visit and field inspection at Eielson AFB from 28 May to 1 July 2022. The objective of this site visit was to investigate the existing airfield drainage system following severe spring flooding on the airfield in 2022. The scope of the visit included 1) a field search of existing drainage infrastructure; and 2) providing recommendations to improve drainage to prevent/reduce further flooding.

The region experiences significant freezing and long periods of snow coverage. Contours developed from a recent LiDAR survey of the base show that the airfield is mildly sloped from south to north (Figure 1). Groundwater is low at the south end of the runway and high at the north end.

The team conducted a field inspection of the existing swale-and-culvert drainage system for the airfield. This required locating existing culverts, swales, and catch basins and inspecting them. Figure 2 provides the locations of the inspected drainage infrastructure.



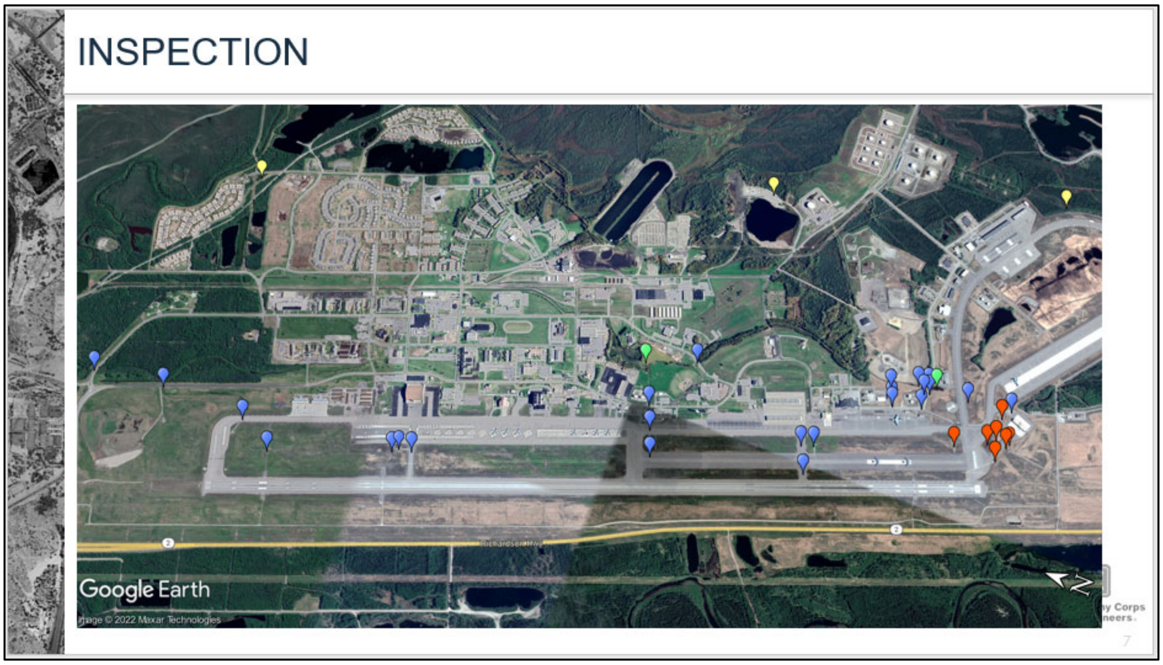
PROJECT BACKGROUND

CLIMATE & SURFACE CONDITIONS

Data and graphs from weatherspark.com

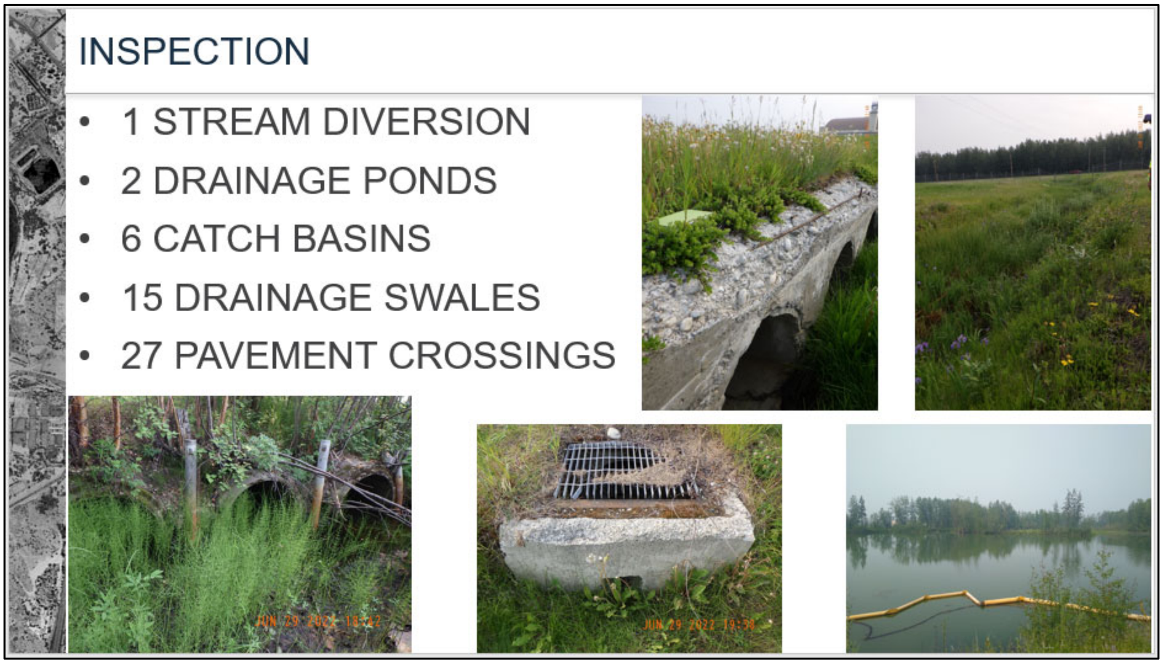
FIGURE 1 Eielson site conditions and climate.

The drainage infrastructure was located, measured, inspected, and documented. Photos from the inspection are presented in Figures 3 through 5.



INSPECTION

FIGURE 2 Location of drainage infrastructure.



INSPECTION

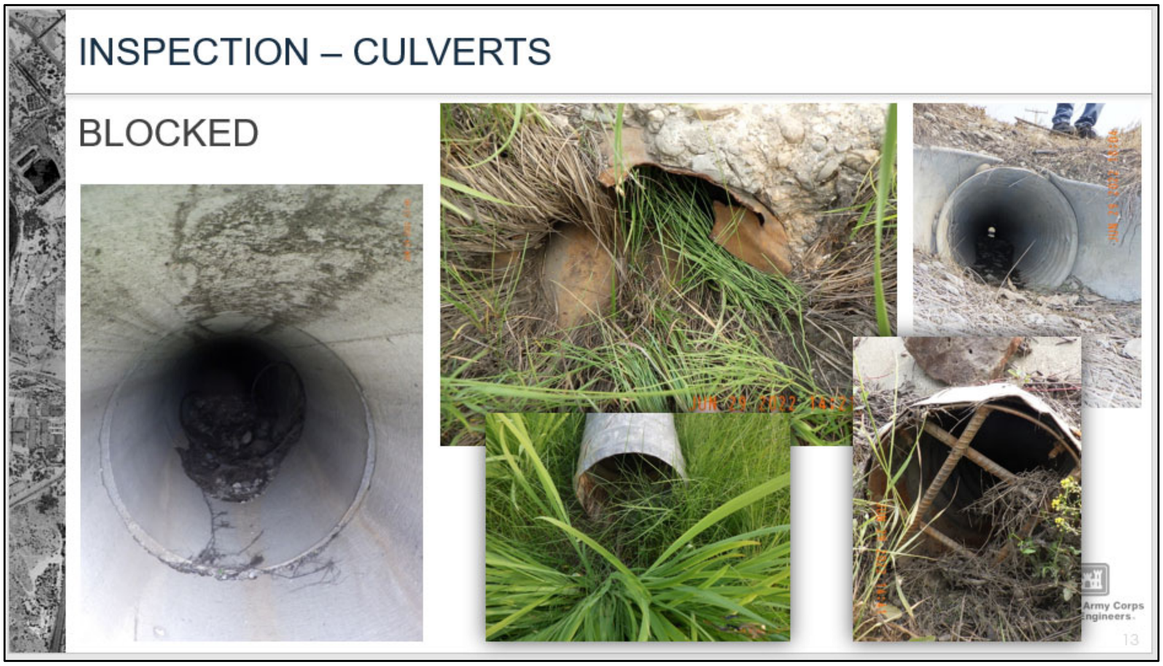
- 1 STREAM DIVERSION
- 2 DRAINAGE PONDS
- 6 CATCH BASINS
- 15 DRAINAGE SWALES
- 27 PAVEMENT CROSSINGS

FIGURE 3 Inspection photos, an overview.

INSPECTION – STREAM DIVERSION

- SOUTH END OF GARRISON SLOUGH
- DIVERTED INTO THREE 40 IN. CIRCULAR CULVERTS

FIGURE 4 Photos of stream diversion.



INSPECTION – CULVERTS

BLOCKED

FIGURE 5 Photos of culverts.

The findings of the field inspections include drainage features that are unmaintained and possibly undersized in some cases. Sediment buildup and drainage features being blocked, buried, damaged, or unmarked were also observed.

The recommendations from this inspection were to create a drainage maintenance plan and replace all collapsed or damaged culverts. A comprehensive drainage study should be conducted. Metal pipes should be replaced or relined. Unfound or buried pipes should be located. Headwalls for all drainage pipes should be considered. Finally, regrading portions of the airstrip may promote and improve drainage.

Performance of Flexible Pavements Reinforced with Wicking Geotextiles Built Over Expansive Soils

NRIPOJYOTI BISWAS
ANAND J. PUPPALA
Texas A&M University

Pavements and lightweight infrastructures built on problematic expansive soils suffer from long-term serviceability, and durability issues due to cracking, rutting, and differential settlements. Traditional geotextile reinforcement improves layer strength and stiffness and helps in partial drainage through gravity. However, due to the development of capillary barrier effects between the macropores of geotextile fabric and the fine pores of the soil, the traditional geotextiles often fail to desaturate the subgrade moisture effectively [*1*]. Accumulation of the water leads to the lowering of the subgrade stiffness and strength and consequently leads to a rutting failure. A newly available wicking geotextile capable of multiple functions, including separation and reinforcement as well as both gravity and capillary suction-induced drainage, has been investigated over the last decade.

A research study was designed and executed to understand the feasibility or efficiency of using a recently available drainage and strengthening wicking geosynthetic layer to improve the performance of pavement sections built on high-PI and expansive soil subgrades. The research tasks were divided into two major phases, Phase 1 and Phase 2 (Figure 1). Two reinforced test sections (TS), each of 40 m (130 ft), were constructed on FM-1807, Venus, Texas, during the fall of 2018 (Figure 2). Both sections were reinforced with wicking geotextiles between the base and subgrade layers and heavily instrumented using moisture sensors, shape array accelerometer-based deformation sensors and pressure plate sensors. The base layer in TS-1 was constructed with 38 cm (15 in.) reclaimed asphalt pavement (RAP) aggregates and TS-2 with 15 in. of conventional crushed stone aggregate (or, Flex-Base, FB) conforming to Grade-1 of the recommended material guide by the Texas Department of Transportation (TxDOT). The base layers were overlaid by a 5 cm (2 in.) asphalt concrete (AC) course and opened to traffic. The control section (CS) was composed of approximately 10 cm (4 in.) AC layer and 33 cm (13 in.) FB layer over the local subgrade soil (Figure 2).

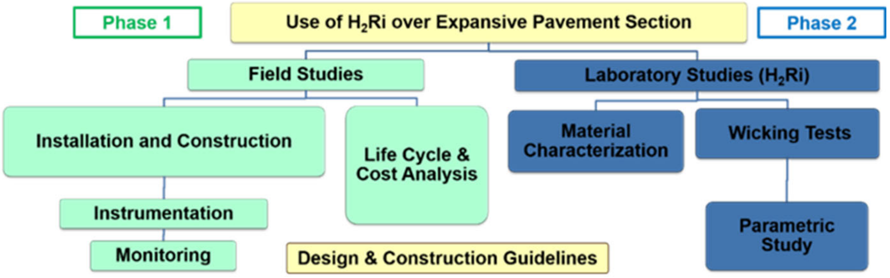


FIGURE 1 Test and control sections near FM1807, Venus, TX.

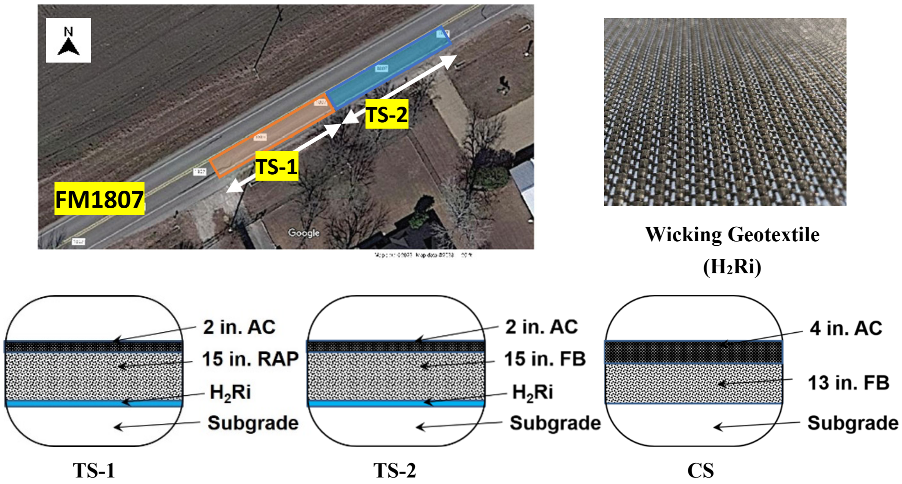
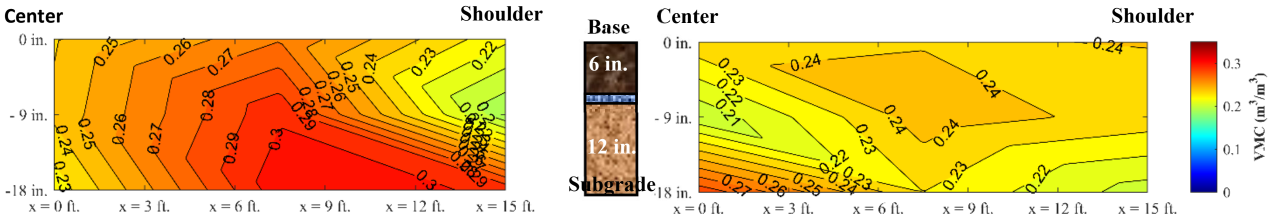


FIGURE 2 Test and control sections near FM1807, Venus, TX.

The performance of the test sections was monitored using different nondestructive testing methods, such as automated plate load tests (APLT), falling weight deflectometer (FWD) tests, and visual monitoring after the construction of the sections. In addition to field test sections, laboratory studies were performed to understand the wicking ability of the geotextile and provide a comparable understanding under controlled environmental conditions. Figure 3 illustrates the construction of the field test sections and the laboratory test setup.

The performance of the test sections was monitored using the moisture sensors and it was observed that TS-2 was more effective in draining moisture as compared to TS-1 (Figure 4). The presence of fines and residual binder in the RAP base layer potentially interfered with the drainage ability of the section. In addition to the material properties, the efficacy of the drainage was also observed to be affected by the natural gradient of the FM road in the longitudinal direction and the accumulated water in the drainage ditch from the adjacent agricultural fields.

FIGURE 3 (a) Construction of test sections in Venus, TX, and (b) Laboratory test setup.



(a)

(b)

FIGURE 4 Moisture distribution in pavement cross-sections (a) TS-1 and (b) TS-2 [*2*].

In addition to the moisture migration below the pavements, shape array sensors were also used to monitor the permanent deformation at the top of the subgrade (Figure 5a). The results of the deformation below the wheel path indicated that the deformation recorded under TS-2 was lower than TS-1. The APLT test results are illustrated in Figures 5b and c for both reinforced test sections. The APLT device uses an advanced electronic-hydraulic control system to impart controlled static or cyclic loading conditions [*3*]. The back-calculated dynamic moduli for the TS-1 with wicking geotextile and RAP aggregates were observed to be higher than the traditional flex-base section. Similar observations were also noted in the back-calculated resilient moduli values between both sections. The RAP materials, even though prone to lateral spreading and permanent deformations, have higher resilient moduli as compared to crushed stone aggregates. Therefore, the presence of RAP, coupled with the tension membrane effect of the geotextile reinforcement, resulted in a marginally higher moduli value of the TS-1 as compared to TS-2 or the CS.

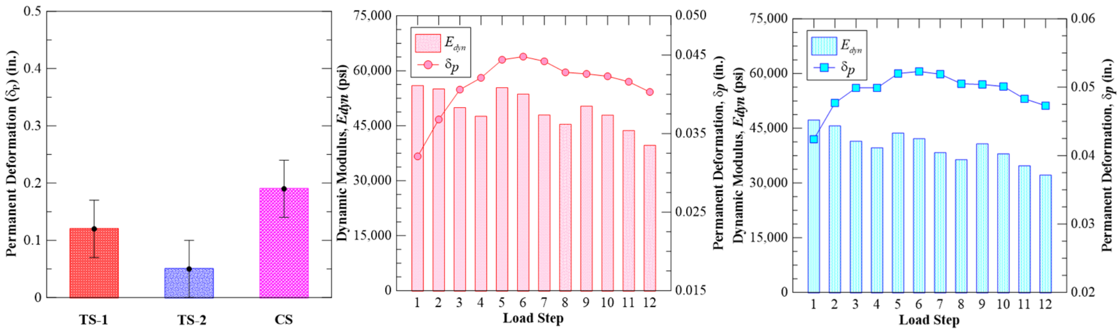


FIGURE 5 Permanent deformation (a) using an in situ deformation sensor at the end of two years of monitoring, (b) at each loading step from APLT studies in TS-1, and (c) at each loading step from APLT studies in TS-2 [*3* and *4*].

Similar to APLT tests, FWD test results were used to back-calculate the layer moduli values in the test and control sections (Figure 6a). It should be noted that the CS, in this case, was constructed using approximately 4 inches of AC over traditional FB material. It was observed that the back-calculated moduli values for the RAP base were much higher than the crushed stone base corroborating the outcome from the APLT tests. The wicking geotextile reinforced section with RAP aggregates showed a comparable rut-life as the CS with 4 inches of AC layer, indicating the efficacy of the current geotextile to cut down the amount of asphalt or base material required to sustain long-term repeated traffic loads. The laboratory studies in a controlled environment indicated the efficacy of wicking geotextile to improve lateral drainage in pavement layers. The ability of the wicking geotextile to drain moisture was found to be more effective in the base layers as compared to the subgrade layer (Figure 7). Additionally, the zone of the efficacy of the geotextile to drain moisture in the subgrade layer was found to extend up to 12 inches approximately below the geotextile layer.

Currently, the field test sections are still being monitored to develop a comprehensive guideline based on long-term performance. Additional studies are being performed to develop a comprehensive life-cycle analysis such that a comprehensive design and construction guideline could be developed for the state and federal DOTs and transportation practitioners. Overall, after 5 years of construction, the reinforced sections are performing appropriately as designed and will be continuously monitored for any future distresses (Figure 6b). Some conclusions are as follows:

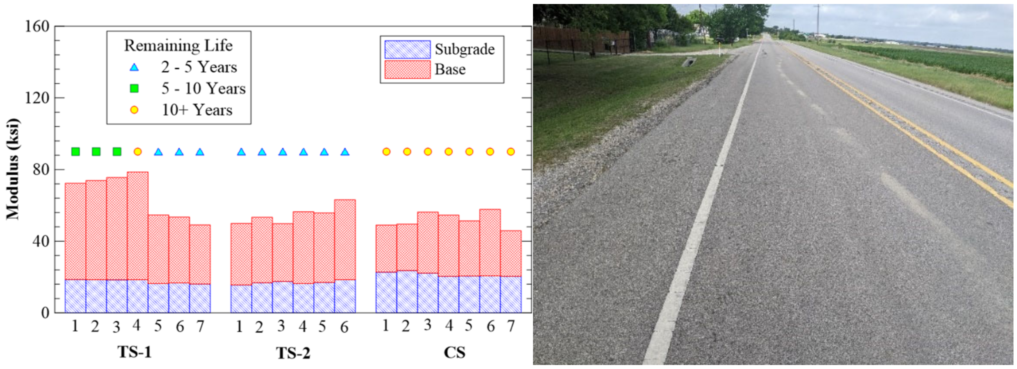


FIGURE 6 (a) Layer moduli and rut-life for test and control sections [*4*] and (b) Present-day road condition.

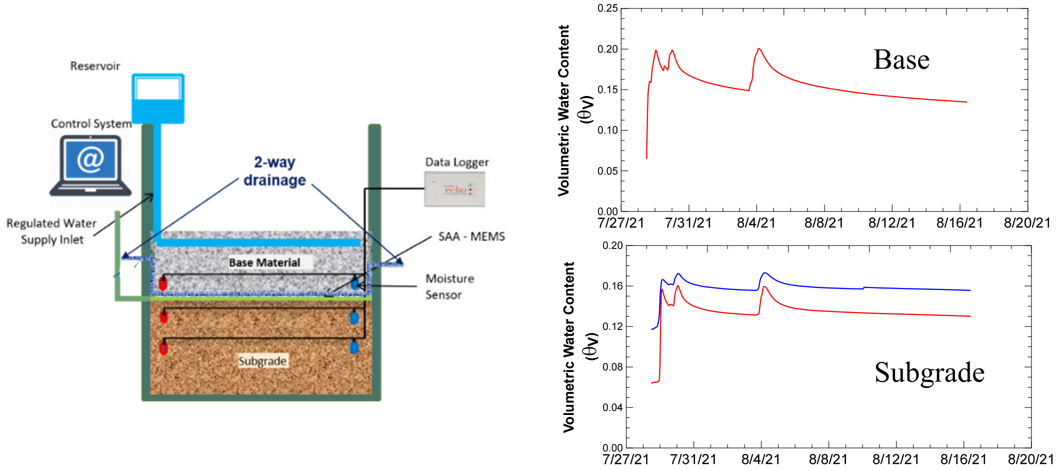


FIGURE 7 Wicking geotextile enhanced lateral drainage in laboratory studies.

- Application of wicking geotextile (H_2Ri) was found to be effective in improving pavement performance over expansive soils by improving lateral drainage and increasing layer moduli.
- Use of marginal materials with geotextile provided comparable performance to the traditionally constructed sections.
- Nondestructive tests (APLT and FWD) concurred with the improvement in moduli and permanent deformation as compared to traditional sections.
- Laboratory studies provided evidence of the efficacy of geotextiles.
- The long-term benefits of the application of the wicking geotextiles could be comprehensively characterized after performing life-cycle analyses of the test and control sections.

ACKNOWLEDGMENTS

This research was funded by Solmax (Mr. John Lostumbo, P.E.) as a part of the NSF Industry-University Cooperative Research Center (I/UCRC) program for the Center for Integration of Composites into Infrastructure (CICI) site at TAMU (NSF PD: Dr. Prakash Balan; Award #2017796). The authors would like to thank the Texas Department of Transportation (TxDOT) - Fort Worth district and Johnson County Area Office for their support in the construction of test sections.

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Using FWD and GPR to Monitor the Effects of Seasonal Moisture Variation on the Structural Capacity of Pavements

EYOAB ZEGEYE
THOMAS CALHOON
MICAH HOLZBAUER
RAUL VELASQUEZ,
JACOB CALVERT
SHONGTAO DAI
Minnesota Department of Transportation

The presentation provided by the Minnesota Department of Transportation (MnDOT) synthesizes the works and findings discussed in two consecutive publications (*1, 2*) on the use of ground penetrating radar (GPR) for efficiently monitoring moisture fluctuations in pavement foundations. The primary objective driving this study originates from recognizing the significant impact of environmental conditions—such as heavy precipitation, freeze-thaw cycles, and groundwater table variations—on pavement foundations' moisture fluctuations, which in turn profoundly impact both short- and long-term pavement performance.

Monitoring and assessing the moisture levels in the pavement foundation, particularly during and after extreme environmental events such as flooding and freeze-thaw cycles, enables pavement engineers to manage traffic flow adeptly, whether it involves restrictions or increased traffic, based on subsurface moisture conditions. Unfortunately, traditional pavement moisture measuring approaches, which consist primarily of sensors installed in the pavement structure (in-place sensors), are expensive, time-consuming, invasive, have limited spatial coverage, and negatively affect the traffic flow.

In response, MnDOT researchers have dedicated efforts to explore the potential of nondestructive testing (NDT) technologies, particularly GPR, aiming to develop an approach that facilitates continuous and non-invasive monitoring of moisture fluctuations within pavement foundations. Both published studies utilized data from GPR, falling weight deflectometer (FWD) and moisture sensors collected from specific cells at MnDOT's Minnesota Road Research Project (MnROAD) test facility. These selected cells encompassed unique combinations of base and subbase materials, representing a broad spectrum of geotechnical behaviors. All testing efforts were coordinated in such a manner as to collect within a similar range of time during the day. Spanning 17 months, the data collection aimed to capture seasonal moisture changes, including the pivotal spring freeze-thaw cycle.

The test sections shared a clay loam subgrade and surfaced with a 90 mm (3.5 in) asphalt concrete layer. In terms of base layer materials, sections 188 and 189 utilized limestone and an aggregate blend consisting of recycled concrete aggregate (RCA) and recycled asphalt pavement (RAP), both with a thickness of 305 mm (12 in). Cell 127 employed a 152 mm (6 in) dense-graded Minnesota aggregate base known as Class 6 (CLS 6). Apart from limestone, all base materials fell under the A-1-a category in the AASHTO soil classification system, while the limestone material was classified as A-1-b. Among the subbase aggregate materials, select granular borrow (SGB) was used for cells 188 and 189, while large stone subbase (LSSB) obtained from crushed granite stone was employed for cell 127. See Figure 1 for reference.

USING GPR TO ASSESS MOISTURE IN BASE LAYERS OF IN-SERVICE PAVEMENTS

The first publication (*1*) introduced a rapid and simplistic methodology for monitoring moisture fluctuations within aggregate base layers of existing pavements by utilizing GPR measurements along the top surface of the wearing course. The dielectric properties of the aggregate base, determined based on the analysis of the GPR data, were translated into volumetric moisture content (VMC) values via Topp's generic transfer equation. These GPR-derived VMC values were then cross-referenced with VMC values obtained from in-place moisture sensors (ECHO-5TE) installed within the same test section where the GPR data was collected.

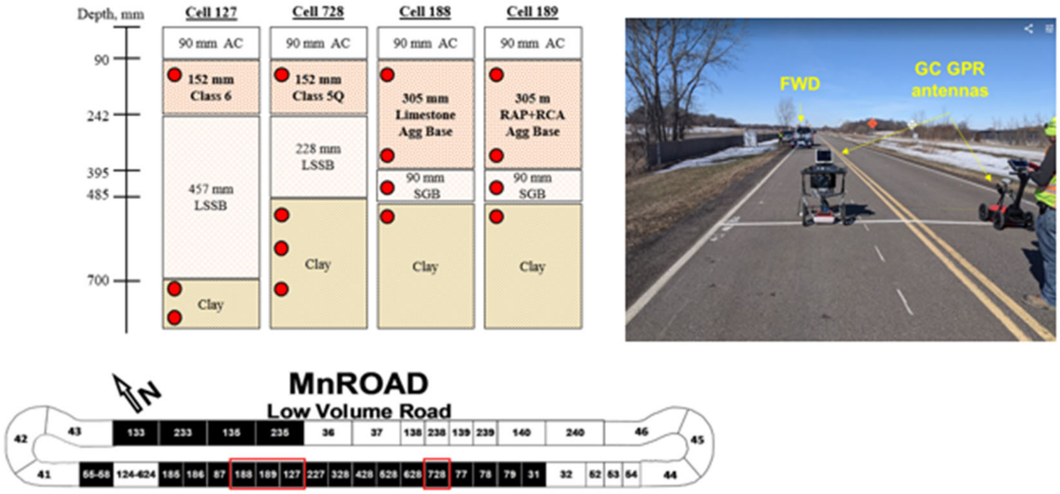

FIGURE 1 Schematic representation of the pavement structures considered in the study.

The results of this comparative analysis, drawn from data collected across three distinct Minnesota Road Research Project (MnROAD) pavement test sections (cells 127, 188 and 189) over an approximately two-year period, demonstrated a strong correlation between the VMC estimated by GPR and the in-place sensors. Furthermore, the GPR method proved its merit in providing continuous moisture profiles. It simplifies the identification and localization of roadway sections and aggregate base materials likely to encounter spikes in moisture levels. However, certain conditions can pose challenges to accurate GPR analysis. For example, Cell 728 was originally considered for this study, but inspection of the GPR radargram and further examination of the MnROAD's construction history revealed that this cell experienced substantial clay pumping and hydraulic erosion from the subgrade to the surface during its construction phase. The soil contamination made accurate GPR analysis difficult. This instance highlights the limitations of employing GPR in heavily contaminated or damaged structures where the boundaries between layers might become obscured. This issue is discussed in the first publication (*1*). Figure 2 shows the correlation observed between the aggregate dielectrics determined by the GPR and the in-place sensors installed in the test section.

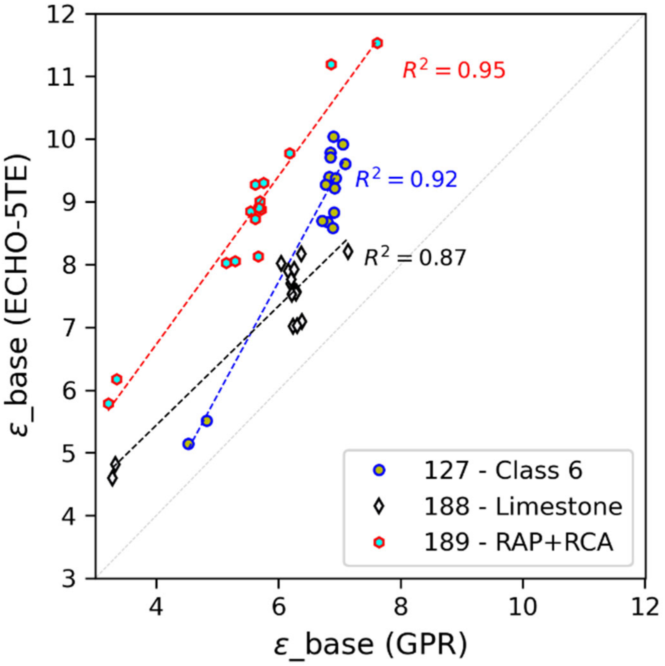

FIGURE 2 GPR linear relationships between GPR and 5TE sensor dielectrics.

Figure 3 compares VMC values measured by GPR (dots) and the in-place sensors (lines) on a MN ROAD test section over a period of 17 months. The charts demonstrate the two independently determined moisture content results matched closely and captured the seasonal moisture variation in the base aggregates reasonably well. A note of interest here is the low moisture content measured during winter months. This is due to the moisture in the base layer being frozen. The moisture sensors and GPR are responsive to liquid moisture, not solid ice. Further discussions of the analysis and results can be found elsewhere (*1*).

CORRELATION OF GPR-BASED MOISTURE CONTENT TO FWD PARAMETERS

The second publication (*2*) delved into exploring the relationship between GPR-based moisture measurements and FWD-based assessments of asphalt pavement's structural capacity. It's important to note that the authors did not intend to suggest GPR to replace FWD measurements in evaluating pavement structural conditions. Recognizing that moisture fluctuations can impact both the structural responses and the dielectric constants of base aggregate layers, the study aimed to explore correlations between GPR and FWD parameters. Therefore, while both methods serve different purposes, they might provide complementary insights into pavement conditions affected by moisture variations. The study employed FWD, GPR, and moisture-sensor data collected on three cells at MnDOT's Minnesota Road Research Project (MnROAD) test facility.

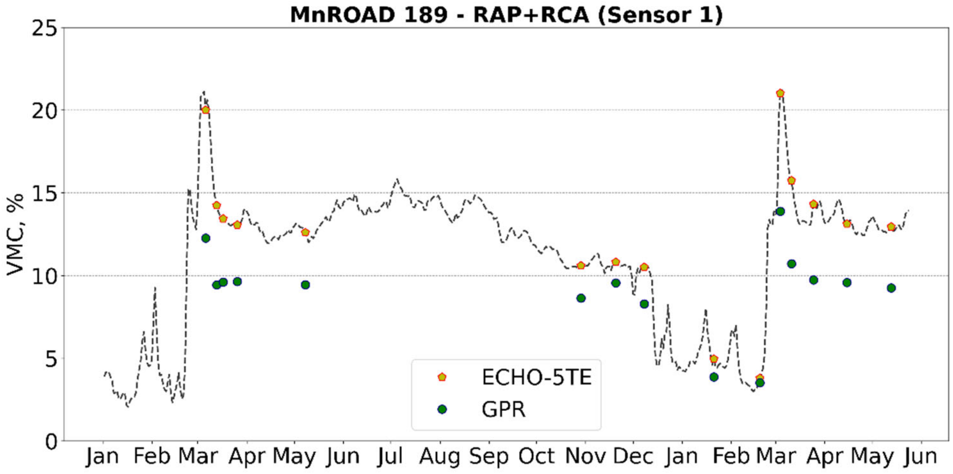

FIGURE 3 Volumetric moisture contents for the aggregate base layer in cell 189.

The second publication focused primarily on the relationship between FWD basin parameters and the GPR computed moisture variations. The deflection basin parameters considered are described in the paper (*2*). To remove the effects of temperature from the deflection measurements and better isolate the effects of moisture, the deflection directly beneath the load (D0) was adjusted for temperature ($D0_{adj}$) using equations described in the paper.

As expected, and shown in Figure 4, the FWD deflection results, particularly the $D0_{adj}$, reflected reasonably well the effect of seasonal moisture fluctuation in the structural response of the pavement structures. The temperature adjustment to D0 allows for the seasonal changes seen in the figure to be attributed to changes in the base moisture content (i.e., due to the freeze-thaw phenomenon). Cold winter conditions drastically affect the stiffness of the asphalt pavement. Hence, very little deflection is recorded in this period.

Furthermore, the investigation revealed that the Base Deflection Index (BDI) and alternate shape factor (F-2alt) most agreed with the GPR-based and sensor-based moisture measurements. Moreover, upon considering the thickness of the base aggregate layer and normalizing the two FWD parameters, the correlation notably strengthened, as illustrated in Figure 5.

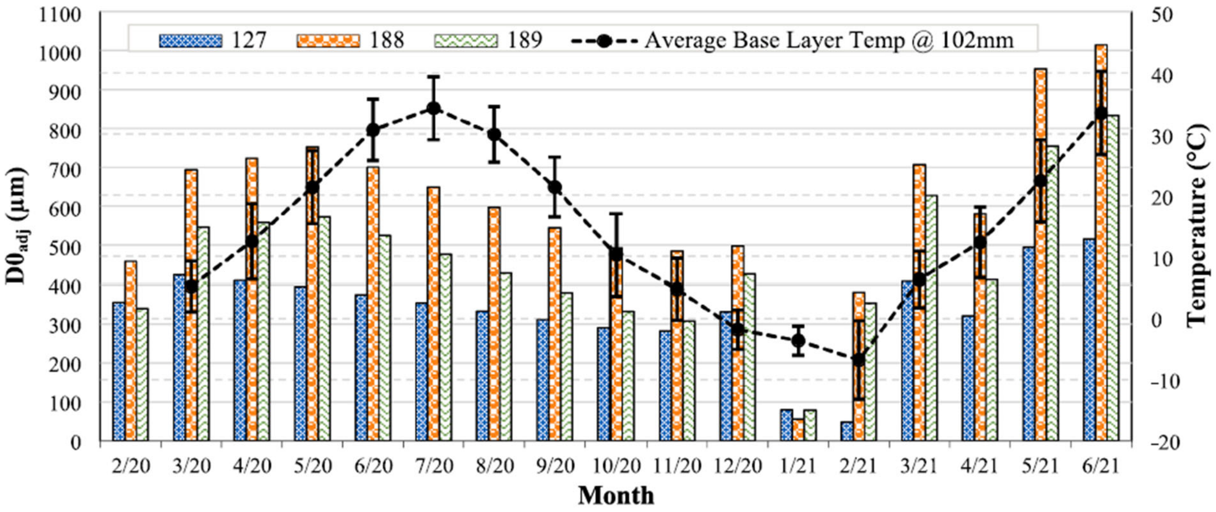

FIGURE 4 Seasonal variation of FWD deflection (under the plate).

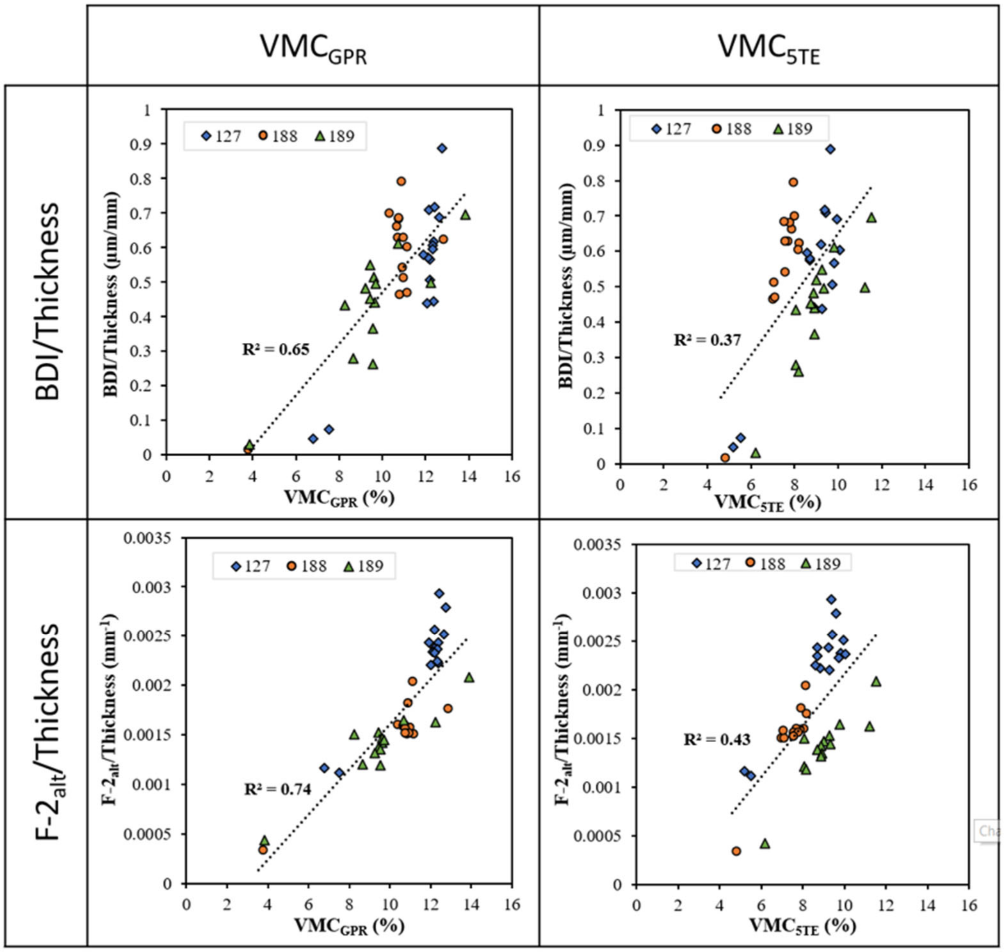

FIGURE 5 Correlation between VMC and FWD parameters after normalizing for thickness.

SUMMARY OF FINDINGS AND FUTURE WORKS

In summary, this document presents and demonstrates the application of GPR-based methodology for routine evaluations and monitoring of moisture fluctuations in the foundations of in-service pavements. The methodology's validity was established by comparing it to direct and indirect methods of assessing moisture and its impact on pavement foundations, such as in-place moisture sensors and FWD parameters. The comparison yielded favorable results, demonstrating the methodology's effectiveness. The proposed GPR method holds potential for rapid and frequent moisture fluctuation assessments, enabling road agencies to identify pavement roadways susceptible to freeze-thaw damage and implement appropriate traffic load management strategies. Additionally, GPR evaluation can optimize the utilization of FWD testing, which assesses pavement structural capacity after weather or climatic stressors by identifying optimal testing times and locations. For further details and compressive discussion of the study, readers are kindly invited to refer to the papers cited in the reference section.

At present, MnDOT is refining the GPR data analysis algorithm to expand its compatibility with various antenna configurations, including those readily available to road agencies and other advanced systems like 3D-GPR. Furthermore, MnDOT is collaborating with local contractors to collect additional data from instrumented road sections across the state to validate the approach's effectiveness in diverse climatic regions and gain insights into the logistics of implementing this methodology on actual roads.

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Enhancing Pavement Durability

The Significance of Moisture Monitoring in Pavement Foundation

Ceren Aydin
Raul Velasquez
Minnesota Department of Transportation

The integrity and lifespan of pavement systems are profoundly influenced by moisture within the pavement foundation layers. It is widely recognized that the moisture varies due to factors like freeze-thaw cycles, seasonal shifts in groundwater levels, heavy rainfall-induced flooding, and condensation from moisture migration. Given the pivotal role of moisture in determining the stability and the varying environmental conditions, it is imperative to monitor the moisture of foundation layers, as their mechanical behavior (i.e., deformation characteristics) under traffic loading is closely tied to moisture variations.

The Minnesota Department of Transportation (MnDOT) continues to invest and work toward implementing research in the area of pavement foundations to enhance system performance and support its asset management program. One example is the 2022 construction project at the Minnesota Road Research Facility (MnROAD). This project placed significant emphasis on the comprehensive monitoring of moisture levels within the pavement foundation layers in the context of unsaturated soil mechanics (i.e., assessment of both volumetric water content and matric suction). Such dedication to moisture monitoring underscores its indispensable role in maintaining the structural integrity of pavements.

This section describes the significance of moisture monitoring in pavement foundation layers, drawing from existing literature and highlighting MnDOT's recent initiatives to enhance monitoring reliability from a transportation asset management perspective.

MOISTURE SUSCEPTIBILITY OF PAVEMENT FOUNDATION LAYERS

The susceptibility of geomaterials to moisture has prompted researchers to explore the correlation between existing moisture levels and fundamental mechanical properties (e.g., stiffness, strength). The stiffness of geomaterials in pavement foundations stands as a paramount design parameter in predicting the pavement response under traffic loading (*1*). While foundation materials are intentionally compacted during construction to a relative maximum dry density at a chosen moisture content to achieve an intended stiffness in unsaturated soil conditions (comprising a mixture of air, water, and soil solids), they are subject to continuous moisture level fluctuations due to changing environmental conditions**.** Figure 1 shows the possible moisture sources for pavement systems.

To this end, over the past several decades, researchers have investigated the impact of moisture on the stiffness of geomaterials (*3*-*9*). Overall, it is well understood that as stiffness values decrease with increasing moisture content, there is an associated increase in pore water pressure. This increase in pore water pressure can lead to diminished effective stress, resulting in further reductions in stiffness. It is widely recognized that moisture changes also affect the energy state of the existing water (matric suction, the difference between the pore air pressure and pore water pressure). Given that matric suction is a key variable governing the stress state and drainability of geomaterials, researchers also explored the relationship between matric suction and stiffness properties (*10*-*12*). Table 1 provides a summary of the existing literature findings.

MOISTURE MONITORING EFFORTS BY MnDOT

Considering the significant variations in the stiffness of pavement foundation layers due to even slight changes in moisture (both moisture content and matric suction), it is crucial for transportation agencies to ensure reliable moisture monitoring of these layers. MnPAVE, a mechanistic-empirical based design procedure adopted by MnDOT, possesses the capability to factor in moisture fluctuations that occur seasonally by using seasonal factors to modify the stiffness of pavement foundation layers (*13*). Thanks to the improvement in the sensor technologies, it becomes more feasible and affordable to monitor the field moisture trends within the foundation layers.

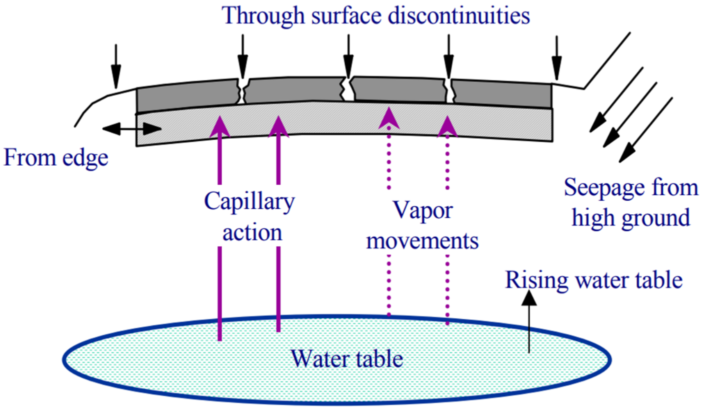

FIGURE 1 Sources of moisture in the subgrade and pavement systems (*2*).

TABLE 1 Summary of the existing literature findings.

Reference	Material Type	Evaluation Criteria	Findings
Haynes and Yoder (*3*)	Gravel	Increase in moisture content	50% decrease in stiffness
Hicks and Monismith (*4*)	Crushed aggregates	Increase in moisture content	Consistent decrease in stiffness
Heydinger et al. (5)	Dense and open-graded aggregates	Reaching saturation	Significant drop in stiffness
Butalia et al. (6)	Cohesive soils	Reaching saturation	50% decrease in stiffness
Liang et al. (*7*)	Subgrade materials	2% increase in optimum moisture content	Significant drop in stiffness
Pacheco and Nazarian (*8*)	High-plasticity clay, clayey sand, and base materials	Increase in moisture content	Significant drop in stiffness
Tamrakar and Nazarian (*9*)	Base materials with varying fine contents	1% increase in optimum moisture content	Up to 53% decrease in stiffness
Yang et al. (2005) (*10*)	Fine-grained soils	Decrease in matric suction	Up to 83% decrease in stiffness
Khoury et al. (*11*)	Subgrade materials	Increase in matric suction increase	180% increase in stiffness
Ba et al. (*12*)	Base materials	Increase in matric suction	%140 increase in stiffness

While technological advancements have simplified installation and data collection, the inherent characteristics of geomaterials used in pavement foundation layers such as coarse-grained aggregate bases, open-graded aggregate bases and subbases, and recycled materials (such as recycled concrete aggregate and recycled asphalt pavement) can potentially compromise the reliability of the acquired moisture data by providing overestimated or underestimated values. Representative geomaterials used as pavement foundation layers are given in Figure 2.

Given the importance of obtaining the most accurate data representing the actual field conditions, MnDOT conducted a detailed investigation to understand the fundamentals of the volumetric water content and matric suction sensors used in the 2022 construction (*14*). According to the study, calibration equations, linking the sensor output (dielectric permittivity) to the target value (volumetric water content), were developed to accurately capture the moisture levels within the foundation layers. Figure 3 shows the relationship between sensor output and volumetric water content.

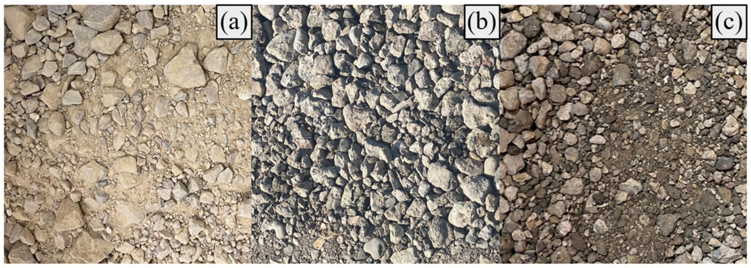

FIGURE 2 Some of the geomaterials used as pavement foundation layers: (a) virgin aggregate, (b) recycled concrete aggregate, and (c) recycled asphalt pavement.

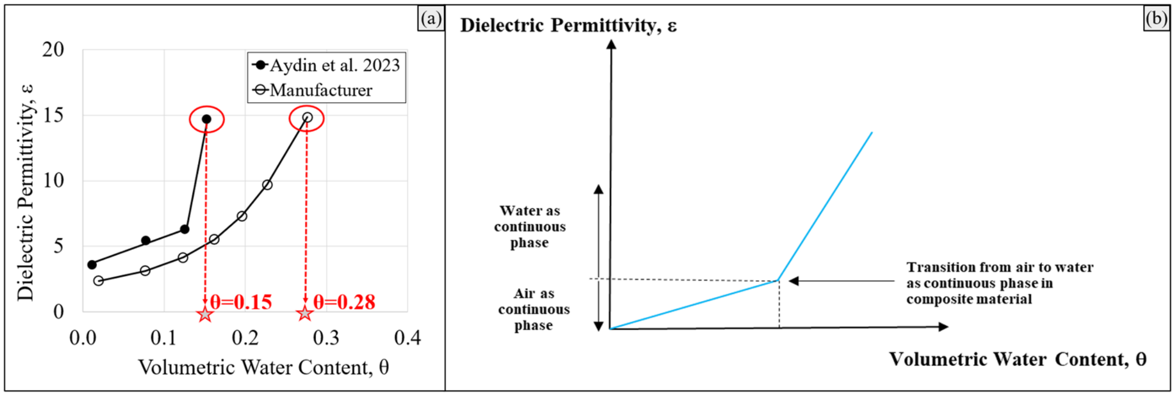

FIGURE 3 The relationship between dielectric permittivity (sensor output) and volumetric water content: (a) Aydin et al. (*14*) and manufacturer (*15*), (b) simplified relationship.

As can be seen from Figure 3a for the same sensor output (dielectric permittivity=15), the calibration equation developed by Aydin et al. (*14*) indicates a volumetric water content of 0.15. In contrast, the manufacturer's equation (*15*), specific to agricultural fine-grained soils, suggests a significantly higher volumetric water content of 0.28. These findings underscore the importance of utilizing an appropriate calibration relationship to avoid overestimating the volumetric water content. Figure 3b shows the simplified version of the obtained bilinear relationship. As can be seen from the figure, the relationship is governed by two distinct rates of dielectric change. The efforts are still ongoing to investigate the fundamentals of this relationship aiming to understand the mechanism controlling this transition.

Moreover, for the matric suction sensor, the authors developed a unique installation technique to ensure hydraulic contact between the sensor head and surrounding soil to obtain reliable results for granular and recycled geomaterials. Figure 4 shows the sensor along with the sensor with soil packed around the sensor head to achieve hydraulic conductivity.

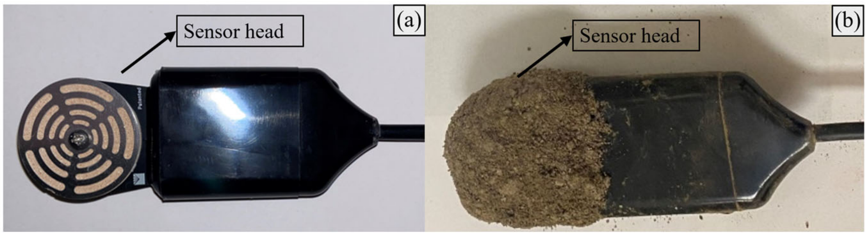

FIGURE 4 Matric suction sensor: (a) sensor head without soil, (b) sensor head with soil.

Preliminary field data, collected from both moisture sensors, was analyzed to derive the in situ soil water characteristics curve (SWCC) and soil water freezing curve (SWFC). The curves given in Figure 5 illustrate the relationship between volumetric water content and matric suction for the first 100 days of 2023. Obtaining these curves helps engineers to predict the geomaterial stiffness characteristics and better assess unsaturated flow within the pavement foundation.

INSIGHTS

Monitoring the moisture of geomaterials consistently throughout the lifespan of pavements is vital for asset management by transportation agencies, given the critical role geomaterials play in maintaining structural integrity. Figure 6 shows the key actions to improve the lifespan of the pavement systems from the viewpoint of moisture monitoring.

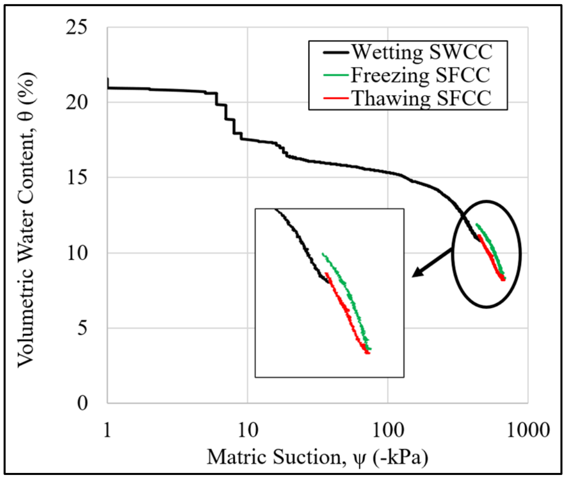

FIGURE 5 Wetting SWCC and freezing/thawing soil freezing characteristic curves (SFCCs) for the subgrade layer at MnROAD.

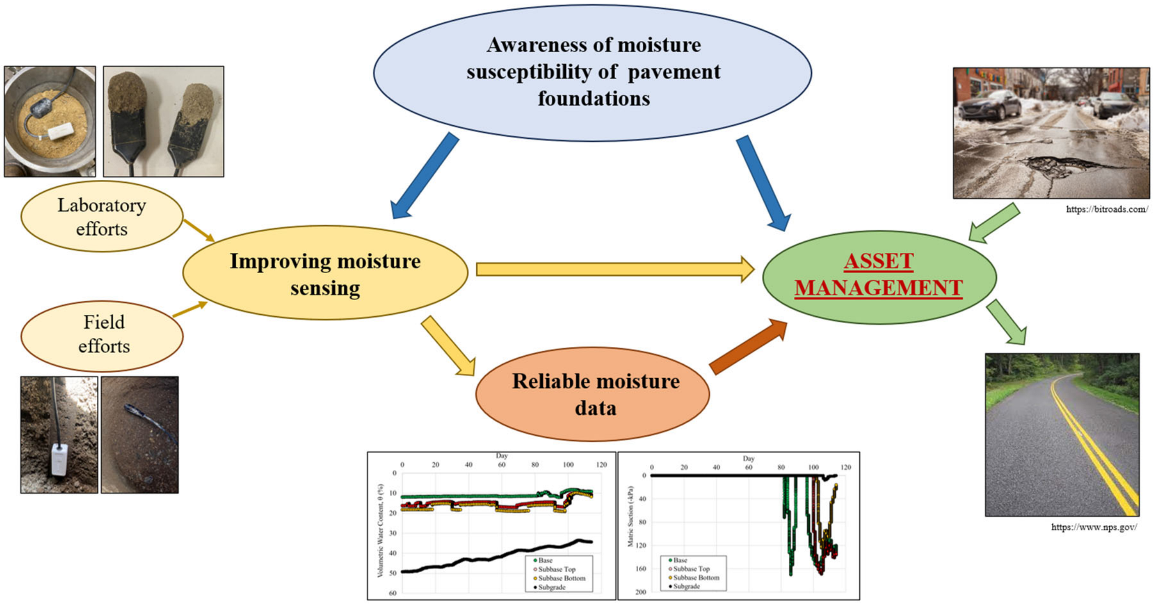

FIGURE 6 Moisture sensing asset management flow chart.

Looking ahead, transportation agencies, researchers, and industry must continue to collaborate and share a significant responsibility to enhance our knowledge of moisture in pavement systems. This involves:

- Enhancing the durability and accuracy of moisture sensors.
- Conducting both long-term and short-term life-cycle cost assessments.
- Including foundation moisture effects during pavement system design.
- Utilizing moisture data to diagnose issues in failing pavements.
- Decreasing the cost and improving the accessibility of sensors.

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Key Points from Breakout Group Discussions

Encourage the FHWA, state DOTs, and local agencies to consider the following:

- Evaluate projects for increased sustainability and resiliency by designing and constructing the pavement foundation for its critical role in achieving long-term performance.
- Encourage decision makers to fully consider subsurface drainage, moisture conditions, and geomaterial durability during pavement system design, construction, and maintenance.
- Collaborate with the construction and technology industries to implement effective and automated measurement of critical engineering parameters while increasing safety for human activities during construction.
- Increase collection and use of pavement foundation test data to assure design requirements are achieved and create as-built records for long-term asset management.
- Emphasize that successful pavement system construction is a team effort that combines the skills of contractor personnel, state DOT specialty offices, local agencies, and the FHWA.
- Increase understanding of technical solutions and eliminate barriers to deploying beneficial technologies. Encourage academia to emphasize the importance of quality pavement foundation materials and methods so that graduates have greater understanding.

Encourage the FHWA, state DOTs, and local agencies to develop training materials, which could improve understanding of the following:

- Seasonal pavement foundation moisture changes and their influence on design, construction, maintenance, and long-term performance.
- Long-term pavement system solutions that optimize total life-cycle costs and minimize environmental impacts.
- Currently available technical information that justifies new product deployment.
- Surface roughness resulting from subsurface moisture conditions, drainage effectiveness, and geomaterial durability.

Encourage the FHWA, state DOTs, and local agencies to develop performance-based guidelines which could support implementation of the following:

- Incentivize quality construction through return-on-investment analysis, which quantifies long-term benefits compared to initial investment.
- Develop better measures to assure design requirements are achieved during construction and implement better monitoring during the expected long-term performance period.
- Deploy technical solutions that drive quality and construction efficiency. Identify barriers that are slowing deployment of technical solutions.
- Increase collaboration between design, construction, and maintenance offices to enhance long-term maintenance operations, which keep the public safe and roadways open to traffic.
- Measure design parameter values for compaction, modulus, and moisture content during construction to quantify pavement performance impacts (negative and positive).
- Pavement foundation design using durable and resilient geomaterials including improved control of moisture variation to increase the long-term performance.
- Quantify the benefits and costs of constructing and maintaining durable foundations with effective drainage during the expected long-term performance period of the pavement foundation asset.
- Improve moisture test methods and specifications requiring more accurate, precise, and reliable moisture testing during construction.
- Consider the needs for long-term maintenance of drainage systems during their design. Develop video logging policies and procedures to improve long-term performance.
- Quantify the benefits and costs of geomaterial stabilization materials, such as geosynthetics, cement, lime, and others, which deliver long-term pavement foundation performance and develop performance-based mechanistic guidelines for stabilization.

Key Workshop Suggestions

- Recognize that the total life-cycle costs and environmental impacts of pavement systems will be reduced when defects in pavement foundations are corrected before the asphalt or concrete surface layer is placed. An appropriate number of well-trained construction inspection personnel will help to ensure that defects are corrected effectively.
- Recognize that resiliency and sustainability will be enhanced when seasonal moisture changes and proper drainage are fully considered during pavement system design, construction, and maintenance.
- Recognize that moisture monitoring of the pavement foundation layers provides valuable information that will improve data-driven decision-making and long-term asset management.
- Recognize that pavement foundations will fulfill their critical role in achieving long-term pavement system performance when technically sound solutions, such as full coverage measurement during construction, are accompanied by agency quality assurance using standardized devices that verify design inputs.
- Recognize that collaboration with the construction industry, more effective communication, and greater agency support are essential during the deployment of innovative technologies.
- Recognize that safety and optimizing agency activities during construction are synergistic while assuring design intent, creating accurate as-built project records, and facilitating effective long-term asset management.
- Recognize that implementing policies and organizational structures that improve collaboration, workflow, and decision-making during design, construction, and maintenance will increase pavement system resilience and sustainability.

In addition, individual workshop participants identified the following actions that some thought FHWA could consider regarding guidance and expectations for the state DOTs.

- Analyze performance data to determine the service life currently being achieved for all pavement system configurations using modern and robust evaluation techniques.
- Include life-cycle assessment and return on investment in all state DOT transportation and geotechnical asset management plans.

- Encourage and fully support AASHTO development of pavement foundation performance specifications for the design and construction of 100-year pavement systems.
- Encourage and fully support demonstration projects that accelerate innovation deployment and provide contractors, engineers, and inspectors with additional construction experience.
- Examine existing moisture data and encourage the use of monitoring tools, particularly considering climate change scenarios, to establish correlations between structural capacity and moisture levels.
- Deploy geosynthetics and other stabilizing materials to provide sustainable and effective solutions for long-term durability, adequate support, and pavement foundation uniformity.
- Implement pavement foundation design criteria that improve the long-term durability and uniformity of the foundation materials and layer thicknesses.
- Implement a minimum service life performance measure for overlays using surface roughness. For example, federal funding would not be allowed if the overlay service life estimated using an FHWA-approved design method is less than a prescribed number of years.
- Implement a minimum service life performance measure for pavement foundations. For example, federal funding would be limited if the pavement foundation service life estimated using an FHWA-approved design method is less than 100 years (Life Cycle Design and Performance, USACE, 1997).