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PROJECT TITLE

Improving the Foundation Layers for Concrete Pavements: Lessons Learned and a New Framework for Mechanistic Assessment

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Introduction

State Highway Agencies (SHAs) are facing a tremendous technical and financial challenge in how to not only improve the condition of their transportation infrastructure but modernize it for future needs with the constrained funding available. The disparity between need and available funding is not new, as funding historically has not been sufficient to keep up with the demands on the nation’s roadway network. As a result, many agencies have had to delay needed improvements on portions of their network as funding is channeled to address the most pressing infrastructure needs.

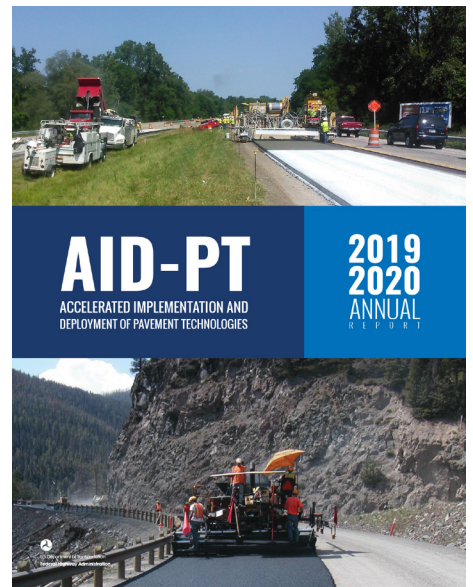
The American Society of Civil Engineers (ASCE) Committee on America’s Infrastructure recently released their 2021 infrastructure report card. Their cumulative grade for all infrastructure categories was C-, which was a modest improvement over the D and D+ scores of the past 20 years. Specifically for the roads category, however, the assessment continued to assign a D grade that has remained unchanged from the 2017 and 2013 report cards, was a D- in 2009, and was a D again in the 2005 report. The bottom line is that the nation is continuing to struggle just to maintain the condition of our roadway network.

What can be done to improve the condition of our roadways and address future needs? How do we get to a sustainable scenario where pavement condition can be consistently maintained with available funding? This is not an easy problem to solve. However, as a practical matter, there are two strategies that need to be addressed simultaneously to help address this dilemma. The first is to attempt to secure additional local, state, and federal funding for infrastructure.

This is currently a national focus area, in addition to ongoing efforts at local and state levels. It is unlikely, however, that sufficient additional investment will be secured to fully address the needs. Therefore, the second strategy that must be pursued concurrently with seeking additional infrastructure investment is to cost-effectively build roadways that will last longer, thus relieving the funding demand.

The second strategy is receiving significant attention from the engineering community. However, the budget gap is so large that instead of the traditional 20-to-40-year pavement design life, agencies are increasingly discussing what is needed to achieve very long-life pavement systems, in terms of double or triple present performance. This represents a tremendous engineering challenge.

Where do we start? Where are the opportunities to improve— not incrementally, but significantly—pavement performance? Many SHAs would identify two major causes of pavement performance problems



that result in pavements not achieving their potential service life. The first cause is some type of materials related distress (MRD). There has been and continues to be much progress on this topic. Improved material characterization and testing as well as improved mixture design procedures such as Performance-Engineered Mixtures (PEM) are addressing many of the historical MRD problems.

The second—and likely the most common—cause of pavement distress and failure is related to pavement foundations. This is complex and can be impacted by many factors, including nonuniform support, inadequate drainage, permanent deformation of the foundation layers under traffic, built-in construction defects, and selection of foundation layer materials that are not capable of achieving the foundation's design requirements.

The FHWA has recognized the need to improve pavement foundation design and construction practices in their most recent annual report (2019–2020) for the Accelerated Implementation and Deployment of Pavement Technologies (AID-PT) program.

Foundation design is a key aspect of pavement structural design that needs to be considered in the design processes. The basis of design in current mechanistic-empirical (ME) design procedures is pavement responses such as stresses, strains, and deflections. Because the stiffness of unbound base layers is significantly less than that of surface layers, foundation layers have a relatively minor impact on pavement response. Thus, the benefits of a good foundation are not adequately reflected in the ME design process. While fundamentally the ME design concept is sound, ME designs do not consider the effects of any deterioration or spatial variability in the foundation layers. Over time, the conditions of the foundation layers can degrade and deform under the influence of repeated heavy loads, leading to nonuniform support conditions and localized failures. **Thus, the principal role of a robust pavement foundation is ensuring the foundation layers retain their integrity throughout the pavement life.**

It is for this reason that improving pavement foundation design is a focus area for the FHWA. A pavement foundation that does not degrade over time does not need to be replaced, which may translate to significant sustainability benefits in environmental impact and costs. In congested areas, eliminating the need to replace the foundation could also be highly advantageous by expediting pavement rehabilitation.

This MAP brief will summarize the results of TPF-5(183) *Improving the Foundation Layers for Concrete Pavements*, which looked specifically at current practices related to pavement foundation design and construction. This report also presented a roadmap for improving the longevity and performance of foundation systems used under concrete pavements, although the principles are applicable to hot-mix asphalt (HMA) pavements as well.

Project Overview

The TPF-5(183) "Improving the Foundation Layers for Concrete Pavements" project was a pooled fund project led by the Iowa DOT, with the FHWA, California, Michigan, Pennsylvania, and Wisconsin as participating partners. Researchers on this project conducted extensive field and laboratory testing at 11 pavement foundation project sites that included new construction, reconstruction, and rehabilitation projects. The results from each of the field projects are published in individual site reports and are available at <https://cptechcenter.org/research/completed/improving-the-foundation-layers-for-concrete-pavements/>

In addition to the individual field reports, a summary report of key findings from the field, laboratory, and advanced numerical studies was provided. The summary report focused on the characterization of pavement foundation engineering properties and lessons learned from the field studies. The emphasis of the report is the measurement and characterization of design input values for pavement foundation layers. Through these studies, it was determined that current practices for pavement foundation quality inspection and mechanistic characterization are limited in terms of the methods of measurement and frequency of testing. A framework for a new type of performance-based workflow is therefore presented that outlines an approach for improved mechanistic assessment of pavement foundation layers. The goal of improving the measurement and performance of pavement foundation layers is to promote long-life (longer than 40 years) portland cement concrete (PCC) pavements.

As an integral component of concrete pavement systems, pavement foundations are relied upon by contractors to serve as a suitable construction platform and by pavement engineers to provide adequate long-term support for the

IMPROVING THE FOUNDATION LAYERS FOR CONCRETE PAVEMENTS:
 Lessons Learned and a Framework for Mechanistic Assessment of Pavement Foundations

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pavement. When pavement foundations are constructed in preparation for paving, there is a critical need to ensure the uniformity and adequate stiffness of the as-constructed pavement foundation. However, the series of field investigations undertaken during this project show that current in situ quality inspection practices do not directly measure the key geotechnical parameter values that are assumed during the design phase. Therefore, a disconnect exists between pavement design assumptions and construction inspection practices. This disconnect significantly limits the advancements

that can be made in understanding pavement foundations, hindering efforts to improve design practices and methods for verifying that pavement foundation systems are of sufficient quality to support long-life pavements.

A complicating factor is the breadth of materials, construction practices, and stabilization methods being used. Figure 1 highlights some of the geomaterials and conditions at selected project sites to illustrate the range of materials currently used in pavement foundation construction.



I-15 near Ontario, California, CTB layer after removal of pavement



I-29 in Monona and Harrison Counties, Iowa, recycled pavement special backfill material over compacted subgrade



I-94 in St. Clair and Macomb Counties, Michigan, woven geotextile separator installed on top of the subgrade



SR-22 near Clyde in Indiana County, Pennsylvania, construction of drainage ATB layer



US Highway 422 in Indiana County, Pennsylvania, injected HDP foam into OGB under the pavement surface



US Highway 10 just north of Junction City, Wisconsin, variable clay subgrade material

Figure 1. Selected field test projects showing the wide range of materials used in pavement foundation construction

Key Findings

- A wide range of geomaterials with variable engineering properties are used for pavement foundations, with virtually no field verification of the design engineering parameter values (e.g., modulus of subgrade reaction, resilient modulus, drainability, deformation behavior). Construction acceptance of pavement foundation layers was sometimes approved based on in situ moisture and relative compaction measurements.
- Parametric studies conducted using AASHTOWare Pavement ME Design show that pavement performance has a low sensitivity to changes in the type and stiffness of foundation materials for selected slab thicknesses. However, the sensitivity of pavement performance to poor support conditions (nonuniformity, stiffness, permanent deformation) is well documented in the literature, indicating that these foundation layer properties affect the long-term field performance of rigid pavement systems.
- Substantial spatial variability (nonuniformity) exists in the engineering values of newly constructed pavement foundations, setting the conditions for the development of increased tensile stresses in the pavement layer (as verified using finite element [FE] modeling) for certain loading conditions. Uniformity of support is an important characteristic of pavement foundation systems.
- Loss of support (LOS) due to irreversible plastic deformation or erosion beneath the pavement significantly decreases the fatigue life of the pavement. A gap as small as 1.3 mm (0.05 in.) between the pavement and the foundation layer can lead to a loss of support.
- Permanent (irreversible) deformation of the pavement foundation layers (including the embankment, subgrade, and base layers) is currently not considered in pavement design and is not measured as part of the construction verification process.
- Overall, limited geotechnical testing (amounting to less than 1 percent of the area of the foundation layers) is used to characterize pavement foundation engineering values; as a result, testing has had a low reliability in detecting conditions that do not meet the assumed design requirements.
- Constructed pavement foundation layers often have isolated areas of poor quality that are believed to contribute to localized pavement performance issues.
- Limited technology is currently available to help earthwork and paving contractors improve the field control of the subgrade and subbase layers and thereby improve the construction of the foundation layers.
- Even with modern laboratory testing to determine the stress-dependent resilient moduli of foundation materials, various challenges limit understanding of in situ conditions, including nonrepresentative boundary conditions

and the lack of consideration of either stress transfer or the interactions between multiple foundation layers.

- In practice, the frost heave and thaw softening behavior of foundation layer materials is assessed mostly using soil classification, but the findings from this research show that soil classification is not always a reliable indicator. A broader program of laboratory testing and characterization is needed to assess frost heave and thaw softening behavior but is not often performed during pavement foundation design.
- The current state of the practice in selecting design input parameters (e.g., modulus) is largely based on historically convenient values or empirical relationships with surrogate or indirect test measurements. Empirical approaches offer much lower up-front costs than direct measurement approaches but introduce greater risks because of the (largely unquantified) uncertainties associated with the possibility that the predicted values will not match the actual field conditions. Some empirical procedures (e.g., calculating the composite modulus of subgrade reaction using a method developed by the American Association of State Highway and Transportation Officials [AASHTO] [1993]) can result in unrealistic values that do not represent field conditions.
- Although a variety of in situ test methods are available that allow for the rapid evaluation of foundation layer mechanistic properties, most tests do not qualify as direct determinations of the values of design input parameters. Without direct measurement, agencies must rely on local calibrations to design input parameters.

Recommendations

The ideal support conditions for concrete pavement foundation layers include the following:

- Uniform support
- Balance between excessive softness and stiffness
- Adequate drainage
- No irreversible plastic deformation
- Use of sustainable methods and materials

Building long-life pavements with design lives of 40 or more years will require sustainable solutions and pavement foundation systems that not only support pavements uniformly during their service lives but also support rehabilitation design solutions after the pavements' initial service lives. The problem with poor support conditions is that defects cannot be overcome by increasing the thickness of the pavement layer. To economically construct optimal foundation layers and ensure that they are long lasting, new inspection workflows and specifications are required to promote the field verification of the design assumptions used for the foundation layer design as well as the pavement structural design. If credible field measurements are taken during construction, appropriate

corrective actions can be taken to fix problematic areas prior to paving. Better measurement technologies are critical to making significant advances in this area.

Furthermore, although pavement design is increasingly becoming more sophisticated, selection of the input parameter values for pavement foundation design still often relies upon limited test data and empirical estimations from indirect measurements. Reliance on limited information to assess critical engineering performance characteristics, neglecting to control materials and quality inspection practices related to foundation uniformity, and failing to account for potential degradation of support due to poor drainage, erosion, and changes in soil volume all introduce substantial risks that the pavement system will not perform in a way that meets the requirements of long-term pavement design.

The findings from this research and prior literature indicate that little emphasis is currently placed on the in-situ verification of the values of design input parameters. Without the information on what is being built, it is difficult to accurately understand how the geotechnical properties of the foundation layers influence the long-term performance of PCC pavements. New technologies for the in situ assessment of parameters such as modulus and strength are expected to improve both materials selection and field process control through geospatial documentation that can verify design parameters in the field during construction.

Building on the field test results, new analyses, and a study of the origins of current practices for selecting pavement foundation parameters, a performance-based workflow for mechanistic pavement foundation testing has been proposed. The next major steps toward improving pavement foundation longevity will be to improve the uniformity of the foundation layers, ensure the as-constructed condition meets the minimum mechanistic design requirements, and provide geospatial documentation of the foundation layers. These improvements will offer a new understanding of the relationships between the support conditions provided by the foundation layers and the ride quality and structural performance of the pavement. The most important next steps are to measure modulus in situ, limit the reliance on empiricism, and document foundation layer conditions using reliable tests. The following measures are recommended:

- Encourage stakeholders to build on the proposed workflow within their organizations and to study how pavement design assumptions can be translated into field target values for use during construction.
- Establish field test protocols to directly measure the important mechanistic parameters. This will ensure uniformity of foundation layer construction and verification that the design requirements are achieved.
- Enable inspectors and contractors to use real-time measure-

ment technologies to implement improved moisture control, compaction, and stabilization practices for pavement foundation materials.

- Build robust databases of results that can be used to improve the selection of materials and processes that deliver the needed results in the field.
- Develop performance-based requirements and specifications that minimize methods-based process controls and emphasize the delivery of uniform, stable, and long-lasting pavement foundation support conditions. Moving the industry in this direction will require vastly different practices than those that currently exist.
- Share the knowledge gained through these processes on each new project to improve subsequent projects.

Roadmap for Improvement

1. Framework for Mechanistic Pavement Foundation Specifications

Current specifications for pavement foundation layers are a combination of construction method requirements (e.g., lift thickness, roller passes) and end results requirements (e.g., minimum relative compaction). These processes serve a practical function but limit advancement in terms of pavement foundation improvement. In moving to a performance-based specification approach, the support conditions for the pavement foundation layer are specified in terms of the pavement designers' requirements (e.g., resilient modulus or modulus of subgrade reaction), including a new requirement for uniformity (e.g., coefficient of variation [COV] of resilient modulus). Key features of a performance-based construction specification should include the following:

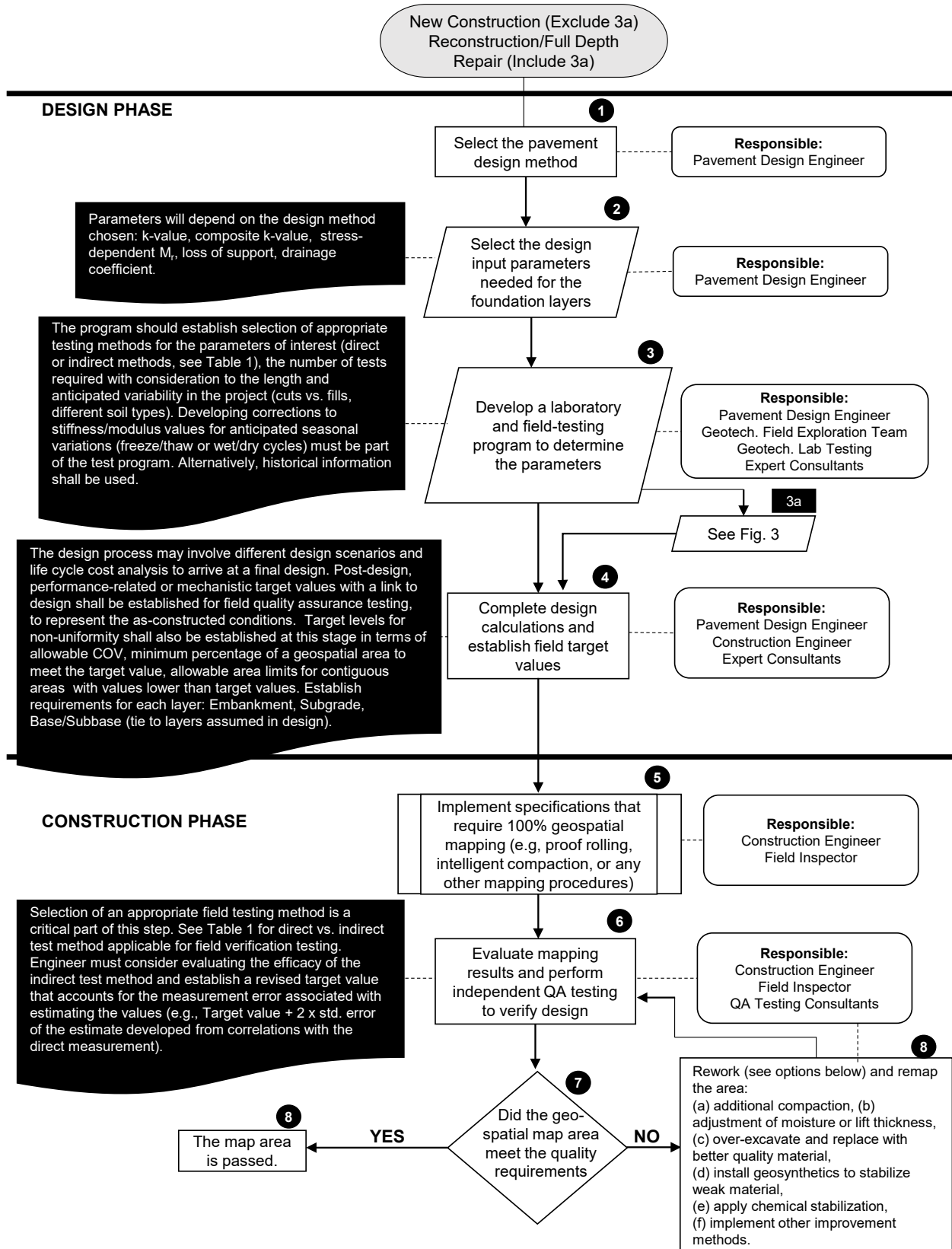
- Measurement technologies that provide near 100% sampling coverage
- Acceptance and verification testing procedures that measure the performance-related parameters that are relevant to the mechanistic design inputs
- Protocols for establishing target values for acceptance based on design
- Quality statements that require achievement of spatial uniformity
- Protocols for data analysis and reporting that ensure that the construction process is field controlled in an efficient manner

2. Framework for Performance-Based Mechanistic Pavement Foundation Testing

The starting point for moving toward a performance-based specification is to develop an entirely new quality inspection workflow involving communication between the designer,

engineer, contractor, and inspector. This new framework focuses on linking the design inputs assumed by the pavement designer to what is achieved during construction through performance-based mechanistic verification testing. This framework is outlined as a workflow for new construc-

tion and reconstruction (rehabilitation with full-depth repair) projects. Figure 2 and Figure 3 illustrate the key components of the workflow process and requirements. Table 1 summarizes testing methods to determine the mechanistic properties of geomaterials.



6 Figure 2. Workflow for field verification of pavement foundation design input parameters

EVALUATION OF SUPPORT CONDITIONS UNDER EXISTING PAVEMENTS

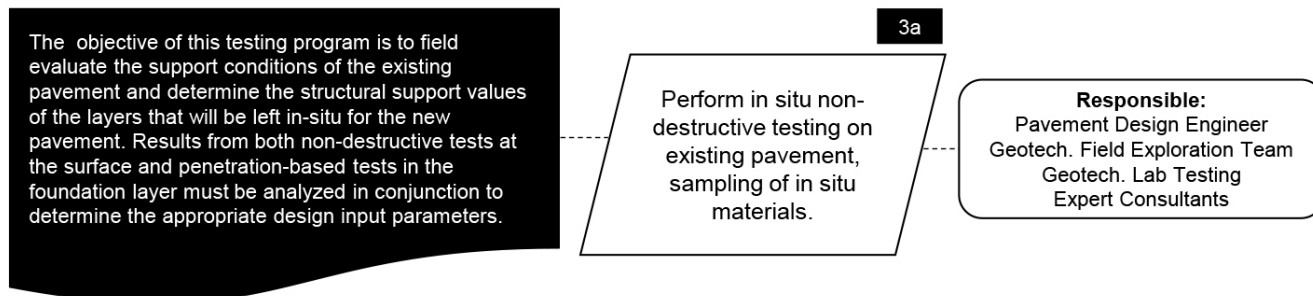


Figure 3. Step 3a of workflow for field verification of pavement foundation design input parameters (for evaluation of support conditions under existing pavements prior to rehabilitation)

Table 1. Summary of testing methods to determine mechanistic properties of geomaterials

Mechanical Property	Lab/Field	Direct/Indirect	Test Method/Reference	Measurement Device	Comments
Modulus of subgrade reaction (k)	Field	Direct	AASHTO T 22 USACE (1995) ASTM D1196	APLT	Can be determined using 30 in., 18 in., 12 in., and 8 in. diameter plates
	Field	Indirect	ASTM D4694	FWD	Backcalculation analysis assumes static loading, but FWD applies dynamic loading. Empirical corrections are made. Very limited data directly comparing dynamic and static values.
	Lab	Indirect	ASTM D1883	CBR test device	Well-established test method, but source of correlations and the uncertainties associated with the relationship to k value are not well understood. Sample is compacted in lab. Differences in field versus lab compaction and boundary conditions can influence results.
	Lab	Indirect	ASTM D6951	DCP	Used to empirically estimate CBR or elastic modulus and convert to k value. Can determine individual layer CBR in situ, but variations in penetration resistance with depth complicates interpretation.
Resilient Modulus (M _r) or Elastic Modulus (E)	Lab	Indirect	AASHTO T 307 Witczak (2003)	Repetitive triaxial test device	Sample is compacted in lab. Differences in field versus lab compaction and boundary conditions can influence results.
	Field	Direct	ASTM E1196 AASHTO T 307	APLT	Can directly measure confining stress-dependent M _r values to determine k ₁ , k ₂ , and k ₃ values. Test measures composite moduli values, but layered moduli can be determined based on layered analysis.
		Indirect	ASTM D4694	FWD	Layered analysis can be performed to estimate individual layer moduli values.
		Indirect	ASTM E2583 ASTM E2835	LWD	Results can be empirically correlated to M _r (Nazarian et al. 2014)
		Indirect	Nazarian et al. (1995)	Seismic pavement analyzer (SPA)	
	Lab	Indirect	ASTM D1883	CBR test device	Well-established test method, but source of correlations and the uncertainties associated with the relationships to M _r or E values are not well understood in practice. Sample is compacted in lab. Differences in field versus lab compaction and boundary conditions can influence results.
	Field	Indirect	ASTM D6951	DCP	Used to empirically estimate CBR or elastic modulus. Can determine individual layer CBR in situ, but variations in penetration resistance with depth complicates interpretation.

Collaboration Opportunities

There appears to be broad national interest in modernizing pavement foundation design requirements, specifications, and construction practices in recognition of the positive impact this can have on increasing pavement performance. Since the conclusion of this study, several opportunities to collaborate in this effort have been initiated.

The Iowa DOT has implemented a 5-year plan to transition from methods-based specifications to modulus-based specifications and construction requirements for pavement foundations. The implementation plan, which is beginning with pilot projects in 2021 and will transition to full implementation in 2025, is a culmination of recent foundation-related studies and an AID grant under the FHWA Every Day Counts program entitled *Increasing Pavement Performance through Pavement Foundation Design Modulus Verification and Construction Quality Monitoring*. As part of the outreach effort under the AID project, in 2019 the Iowa DOT conducted a survey of all 50 states, the DC DOT, and the Puerto Rico DOT to determine current practices and interest in partnerships to work together to improve pavement foundations (Figure 4).

Responses from 31 states have indicated the following:

1. 21 states have indicated that their pavement performance is being compromised because of foundation related issues.
2. 27 states have indicated they do not currently have acceptance requirements for the foundation layers based upon the engineering parameters assumed by the pavement design.

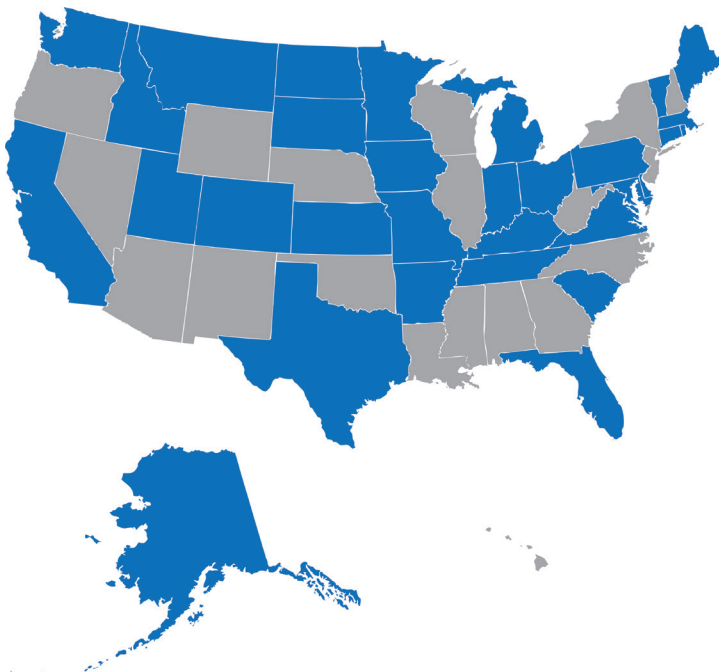


Figure 4. States responding to survey on current foundation practices (states that responded are indicated in blue)

3. 30 states have indicated they are interested in more effective and efficient alternatives to the acceptance of embankments and pavement foundation layers.
4. 30 states have indicated that it is important to field-verify the in situ engineering properties used in the pavement design of the various foundation layers.
5. 30 states have indicated that they are interested in knowing in real time during construction if field outcomes are meeting the design and specification requirements.
6. 31 states have indicated that they are interested in learning more about the Iowa DOT's implementation efforts.

Another opportunity to collaborate on advancing pavement foundation quality and performance requirements is by participating in the FHWA-led TPF-5(478) "Demonstration to Advance New Pavement Technologies Pooled Fund." This project is part of the FHWA's continuing effort under the AID-PT program to support SHAs with implementing innovative technologies, products, and processes by providing financial and technical support. Pavement foundations is an interest area that has been identified.

For more information on these opportunities contact:

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- Tom Yu, FHWA, tom.yu@dot.gov
- Dr. Peter Taylor, National CP Tech Center, ptaylor@iastate.edu

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