TECH BRIEF
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ENGINEERED PAVEMENT FOUNDATIONS AND FIELD VERIFICATION OF DESIGN INPUTS

A Strategic Approach to Increased Pavement Performance and Lower Ownership Cost

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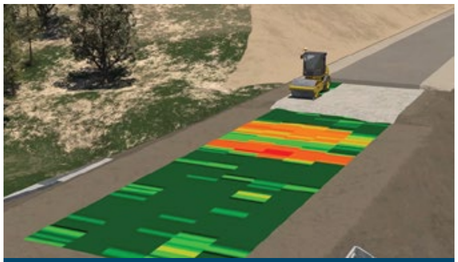
Introduction

The quality of the pavement foundation layers upon which pavement systems are constructed fundamentally influences their performance and longevity. A strategic approach to increasing pavement life is to ensure that pavement foundations meet engineering and design requirements for long life (ideally 100+ years) when they are constructed. Foundation engineering characteristics—such as strength, modulus, and uniformity—significantly affect the overall performance of the pavement. Ensuring that the foundation layers are properly engineered and constructed to meet the design requirements will consistently enable pavements to perform as intended, resulting in lower ownership costs and less disruption for motorists.

When the pavement foundation layers are of poor quality, the result can be several types of damage to the pavement, including cracking, nonuniform settlement, rutting, and structural failures (Figure 1). Simply increasing pavement thickness does not address the underlying foundation issues and is not a cost-effective or sustainable solution for poor foundations (White et al. 2021). To avoid pavement foundation issues, it is important to ensure that the foundation layers are correctly engineered, constructed, and verified before paving. Improvements to foundation practices will require a new emphasis on in situ measurement of the design input values for the foundation layers before the pavement is placed.


(a) Nonuniform foundation support identified during construction


(b) Undetected poor subgrade support


(c) Conceptualization of early pavement distress due to poor foundation support

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Figure 1. Poor pavement foundation support conditions leading to nonuniform pavement support and early pavement distress

In practice, pavement foundation layers are often assessed using an indirect geotechnical test representing less than 0.1% of the layer area. Traditional test methods measure parameters that are not directly used in engineering pavement design, resulting in a disconnect between pavement thickness design, engineered pavement foundation design, and field quality verification of the design values affecting performance.

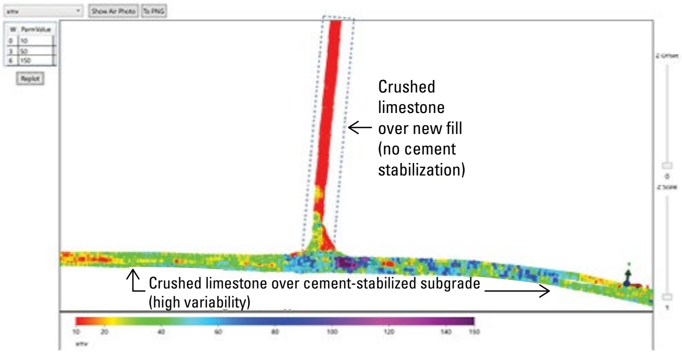

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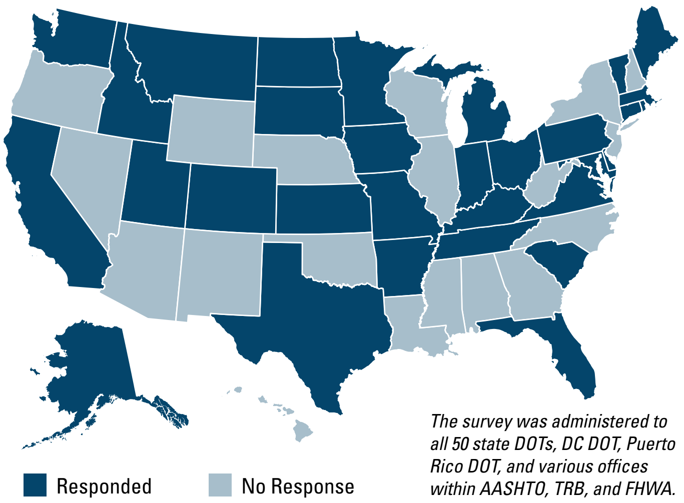
Figure 2. Example of variable pavement foundation subgrade layers after stabilization with cement

Because the important engineering parameters are not being measured, pavements are being constructed on poor foundations without documentation (see Figure 2), a practice that compromises the performance of the pavements before they are even open to traffic.

In 2020, the Iowa Department of Transportation (DOT) administered a national survey to all 50 states to assess their interest in improving pavement foundation practices and identify potential partner states that could collaborate with the agency as it transitioned to engineered foundations and direct modulus measurements for pavement foundations. The survey was administered as part of the Federal Highway Administration's (FHWA's) Accelerated Innovation Deployment (AID) Transportation Pooled Fund conducted in partnership with the Iowa DOT (Gieselman et al. 2021). The states responding to the survey are shown in Figure 3.

Of the 31 responding agencies,

- 97% want more effective quality acceptance for pavement foundation construction,
- 94% want to field verify the engineering properties used in pavement design for pavement foundation layers,
- 97% want real-time quality acceptance data to determine whether design and specification requirements are achieved,
- 94% want data reports to support field process controls during foundation layer construction, and
- 100% are interested in learning more about the Iowa DOT's AID implementation efforts to bring improved solutions to pavement foundation layers.



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

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Figure 3. State DOT respondents to the Iowa DOT survey addressing practices to increase pavement foundation performance

FHWA's Accelerated Implementation and Deployment of Pavement Technologies (AID-PT) program is focused on helping states implement innovative, proven technologies that have the potential to increase pavement performance significantly. FHWA has recognized the need to improve the quality of pavement foundations nationally and has identified this need as a focus area in its 2019/2020 annual report to Congress on the program (FHWA 2021):

> Improving pavement foundation design is a focus area for 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 be highly advantageous by expediting pavement rehabilitation.

Field measurements were conducted under an AID-PT project. Pilot projects were implemented in Iowa, and demonstration projects were conducted in Indiana, Minnesota, and Pennsylvania. The following key outcomes resulted from this implementation activity:

1. New mapping and data analysis technologies were successfully demonstrated to measure and report foundation layer modulus values in real time before paving.
2. With more than 1,000 modulus maps completed, it was learned that pavement foundation support values used in pavement thickness design are often not achieved during construction.
3. The engineering of pavement foundations and the verification of construction quality require new methods to meet the demand for delivering long-life, sustainable pavement systems.

The Pavement Foundation Challenge

The need for DOTs to increase the return on investment (ROI) from pavements has never been greater. The most recent report card (2021) on the condition of US infrastructure from the American Society of Civil Engineers (ASCE) gives the nation's 4.1 million mile roadway network a grade of D, with only 42% of the network in good condition and the balance in fair (15%), mediocre (23%), or poor (20%) condition. ASCE's analysis quantifies the cost of bringing the system into a good level of service at $786 billion. The magnitude of this problem compels agencies at all levels of government to look for solutions that will bring added value (reduced ownership cost) as they struggle to address the immense backlog of pavement needs.

Long-life pavement systems (which encompass pavement layers, subbase layers, and subgrade foundations) have not been achieved by most agencies due to the following:

1. Failure to design the pavement and foundation materials as an interrelated system whereby the foundation materials are designed to meet the pavement design requirements (e.g., resilient modulus for the life of the pavement)
2. Lack of a modern pavement foundation design methodology that enables the foundation layers to be engineered for optimal performance considering material selection, layer thicknesses, pavement design requirements, construction practices, carbon mitigation, cost, and durability of as-constructed layers
3. Lack of meaningful quality assurance sampling and measurement for field verification of as-constructed pavement foundation support, which is a leading cause of pavements being constructed over deficient and/or unoptimized foundations
4. Limited engineering relationships between traditional indirectly measured acceptance criteria and long-term performance, which creates a barrier to the continuous specification price adjustment provisions needed to incentivize quality material selection and construction

Although advancements in pavement layer design tools and software have emerged over the last two decades, practices for the design, construction quality control, and quality assurance verification of the pavement foundation materials (subbase, subgrade, embankment) have not advanced. As a result, most pavement foundations are specified, are not engineered for long life, and are not verified in the field prior to paving. Further, using (legacy) specified pavement foundation materials and thicknesses often results in thicker pavements with relatively thin, variable, unoptimized foundation layers subject to plastic deformation over time. Advancement in quality verification practices for pavement foundation design and construction is critical to achieving long-life pavement systems.

Purpose

The purpose of this technical brief is to provide a roadmap for DOTs interested in implementing engineered pavement foundation designs and engineering verification of the as-constructed properties of the foundation layers. Aligning professional practice with currently available advanced measurement technologies enables DOTs to build long-life pavement foundations reliably. Examples of the pilot projects and field demonstrations conducted under Advancing Concrete Pavement Technology Solutions are included, along with a recommended five-step implementation process.

This technical brief explores the critical relationship between pavement foundation quality and long-life pavements, emphasizing the implications for design, construction quality verification, and overall pavement performance. Many technical papers, reports, workshop presentations, and special provisions have been developed separately as part of this overall pavement foundation program. And there is more work to do!

Pavement Foundation Materials Require Improved Verification Testing

Material properties, degree of compaction, shear strength, modulus, resistance to permanent deformation, volumetric stability, drainability, and other engineering parameters determine pavement foundation layer quality. Geomaterials used in pavement foundations are highly variable and complex materials that typically exhibit nonuniform plastic deformations over time. Soils with high plasticity, for example, tend to undergo significant volume changes and accompanying plastic deformation with fluctuations in moisture, leading to nonuniform support that contributes to pavement stress concentration and the accelerated formation of distresses such as cracking and uneven settlement. Conversely, well-compacted, moderately drained, granular soils with an optimized gravel-to-sand ratio provide a stable platform that minimizes the potential for movement under loads (near-elastic response), thus promoting a more durable pavement structure. Beyond compaction, various mechanical and chemical stabilizers are used to improve the engineering properties of geomaterials. Higher quality pavement foundations allow for the implementation of thinner pavement layers without compromising performance, which can reduce material costs and environmental impact while maintaining performance standards.

The design of a pavement system must consider the pavement foundation support capacity, which is the foundation's ability to uniformly support the applied loads without undergoing excessive deformation. As part of the pilot and demonstration projects summarized in this technical brief, engineers used automated plate load testing (APLT) (Figure 4) and e-roller mapping tools to field measure the modulus of subgrade reaction (k-value) and resilient modulus (M_r) to assess the pavement foundation support capacity. A robust pavement foundation should meet the minimum pavement modulus design requirements, be constructible, be reasonably uniform, and provide a high ROI to support long-life pavement systems.

In addition to the parameters describing pavement foundation structural support (e.g., k-value), the moisture conditions within the foundation play a pivotal role in pavement longevity. Insufficient drainage can lead to water accumulation, which saturates the underlying subgrade, diminishing its strength and increasing the likelihood of pavement surface distress. Effective drainage solutions, such as underdrains and effective surface water management, are essential in maintaining the integrity of the foundation layers and, consequently, the pavement above. After construction, monitoring foundation layer moisture levels and ensuring adequate drainage can help prevent deterioration.

Moreover, the sustainability benefits of long-life pavements are increasingly being recognized in modern engineering practices. Quality pavement foundations contribute not only to immediate pavement performance but also to life-cycle sustainability. By reducing the frequency of repairs and minimizing resource consumption through effective design and maintenance, a higher-quality foundation translates into a lower environmental footprint over the pavement's lifetime.

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Figure 4. APLT equipment to determine in situ modulus

In conclusion, the quality of the pavement foundation is a crucial determinant of the durability and longevity of a pavement structure. Its influence permeates various aspects of pavement engineering, from design considerations and material selection to maintenance strategies. Prioritizing foundation quality enhances pavement performance, reduces life-cycle costs, and supports sustainable infrastructure practices.

The question is, however, how can pavement foundations be engineered and constructed to deliver long-lasting support?

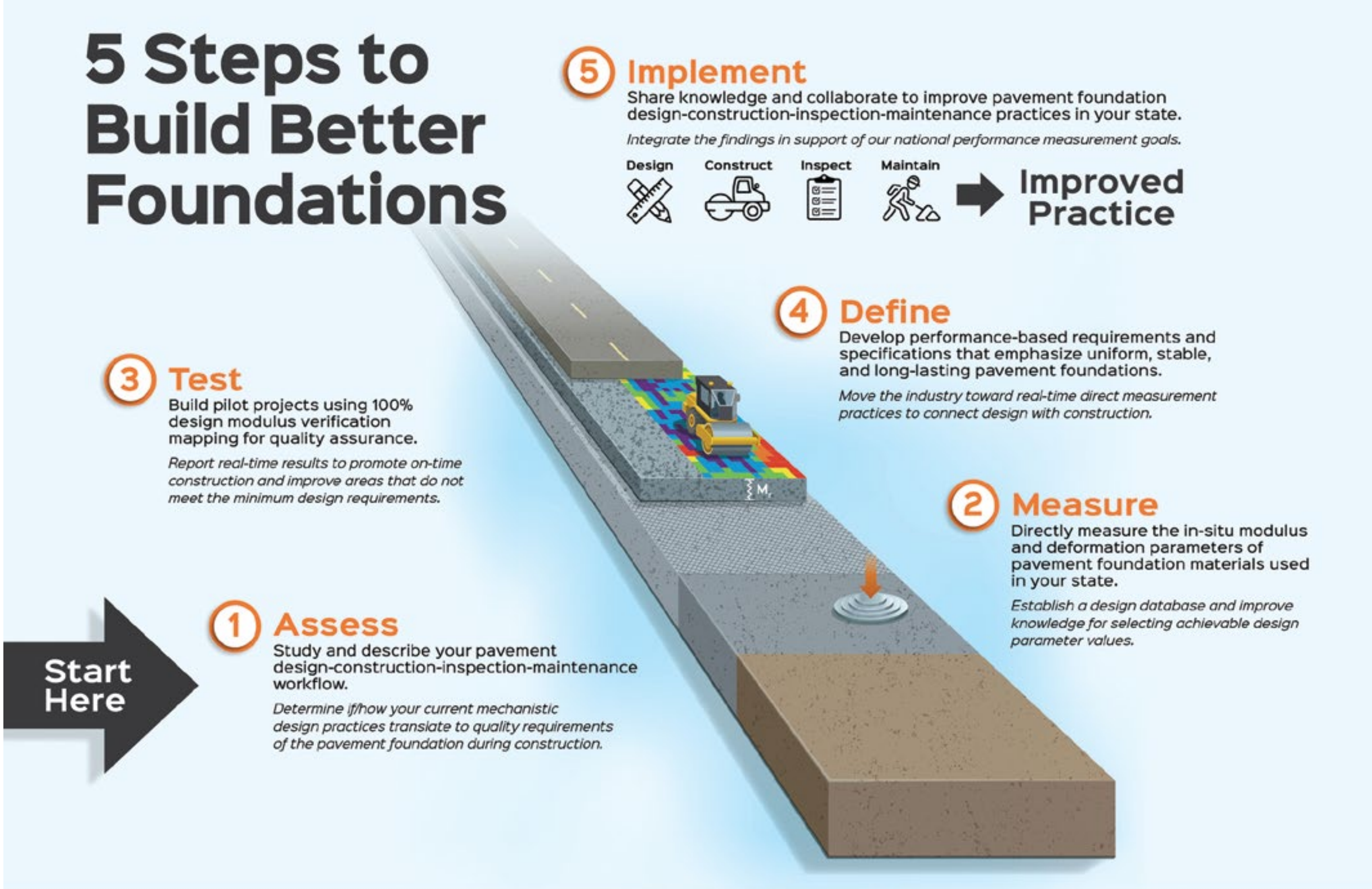
A Roadmap to Build Improved Pavement Foundations for Long-Life Pavements

Our nation needs pavements that last longer. Minimal investments in improved pavement foundations today can save millions in repair costs over pavements' service lives without jeopardizing construction productivity and quality. The engineering challenge is to deliver technically sound design solutions, achieve the maximum achievable quality, and increase the speed and efficiency of one of the most overlooked and critical construction processes on virtually all jobs—construction of the pavement foundation layers.

To accomplish the goal, a roadmap with the following five steps (see Figure 5) was developed to aid state DOTs in building better pavement foundations:

1. Assess Your Current Engineering Processes
2. Measure Design Engineering Parameters
3. Test Improved Pavement Foundation Solutions
4. Define Requirements for Building Improved Pavement Foundations
5. Implement Modulus Verification into Your Practices

Each of the five steps is elaborated below to present steps toward implementation.



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.

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Figure 5. Pavement foundation roadmap for long-life pavements

Step 1: Assess Your Current Engineering Processes

Pavement distresses and failures related to inadequate foundation designs, materials, and construction practices are significant reasons why the investments that state DOTs make in pavements are never fully realized. For many agencies, pavement foundations are specified and not designed. Further, the most important engineering parameters are not verified during construction or before paving. Innovative measurement technologies are needed and should be available to assist agencies in engineering and building foundation layers that meet the design intent. Each agency should develop a process that links design, construction, inspection, and maintenance in a workflow for efficient use of personnel, data sharing, and performance monitoring. Assessing an agency's current processes and developing a detailed flowchart identifying connections and gaps between design and construction verification is an important first step in identifying areas for improvement (Figure 6).

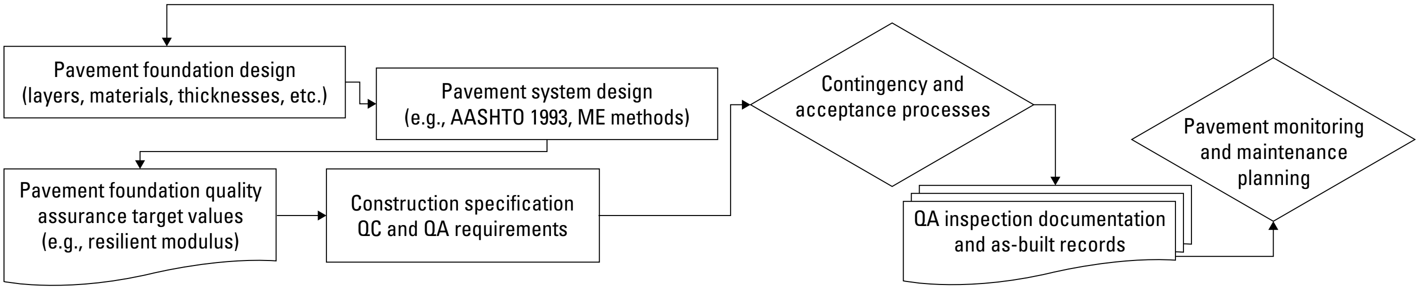

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Figure 6. Example agency flowchart to identify connections between design, construction, inspection, and maintenance

Step 2: Measure Design Engineering Parameters

Geomaterials used in pavement foundations are complex, and traditional practice is to rely upon indirect, index, or empirical methods. Experience shows that engineering quality pavement foundation layers requires a deeper understanding of the in situ (local) modulus and deformation parameters of the materials in your region. According to the results of the Iowa DOT's national survey of agencies presented above, modulus and deformation are not being measured.

More advanced field and laboratory material characterization is needed to rapidly and cost-effectively measure important design parameters. An example of a new test method used by the Iowa DOT employs large-scale testing equipment (3 ft diameter material molds, shown in Figure 7) to determine the support parameters of different foundation materials and combinations of layers, with high-volume loading simulations (up to 1 million loading cycles in a week) applied to determine how designs and materials will perform in terms of degradation/resiliency. Developing a database that documents the performance of your state's materials will improve your ability to select materials and stabilizers at the design phase, ensuring that quality target values (TVs) are achievable in the field.

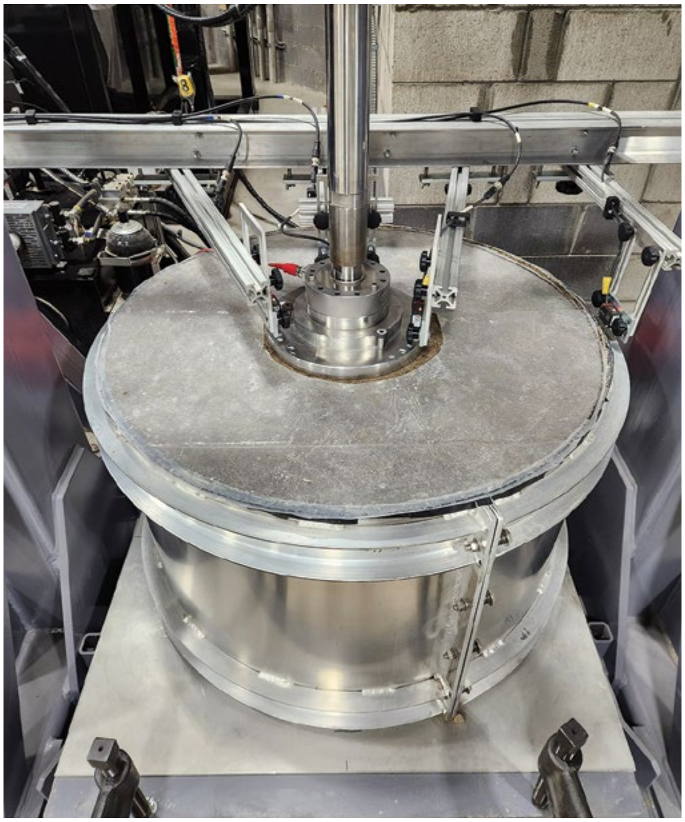

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Figure 7. Large-scale test samples used to determine modulus/deformation parameters during loading up to 1,000,000 cycles

APLT provides similar modulus/deformation data in situ via direct measurement (per American Association of State Highway and Transportation Officials [AASHTO] standards) of the modulus of subgrade reaction (k-value), stress-dependent resilient modulus (M_r), and permanent deformation (δ_p) (Figure 8). Static or cyclic testing is selected depending on the pavement design input requirements used in the mechanistic design. To develop a statewide pavement foundation database, about 200 tests are required depending on the range of materials across your region. APLT is performed on unbound or bound materials, subgrade, pavement layers, and combinations of layers. Testing is also performed through core holes on existing pavements.

Step 3: Test Improved Pavement Foundation Solutions

Building pilot projects using 100% design modulus verification mapping for quality assurance is an implementation strategy to test the design, construction, and inspection workflow using modulus. The pilot and demonstration projects summarized in this technical brief involved installing instrumentation packages on rollers that turn the roller into a testing machine that directly measures material modulus (Figure 9). Several layers of security are required on the instrumentation kits to provide unbiased engineering data. Data are transmitted to the cloud and processed, and results are shown in geospatial maps to agency inspectors and contractor personnel in real time to ensure compliance with project requirements.

During the roller mapping phase, the agency may share the resulting information with the contractor to help the latter meet the project's quality control requirements. Site-specific calibration is needed to determine the desired pavement foundation modulus parameter outputs, and the contractor's roller operators need operator training.

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Figure 8. APLT of the granular subbase layer for a portland cement concrete pavement

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Figure 9. Technician installing instrumentation kit for roller

The development of special provisions and specifications is needed during this implementation and pilot testing phase. Some states have elected to start by requiring contractors to map the foundation layers to become familiar with the control of their field operations and better achieve the project requirements without initial changes to existing acceptance criteria. This approach can increase knowledge among agency and contractor personnel and reduce unknowns/risks during the transition to the use of design performance requirements for the foundation materials.

Step 4: Define Requirements for Building Improved Pavement Foundations

The optimal value proposition for agencies is to develop modulus-based specification requirements, whereby the specification requires the achievement of specific engineering parameters for the foundation materials and the agency's quality assurance program ensures that these requirements are achieved. Agencies must develop specifications and procedures that comply with 23 C.F.R. Part 637 Subpart B (Quality Assurance Procedures for Construction). Roller mapping with independently calibrated engineering outputs (Figure 10) is a method to develop a continuous pay scale. FHWA encourages contracting agencies to establish a clear relationship to infrastructure performance in their price adjustment provisions (FHWA 2023).

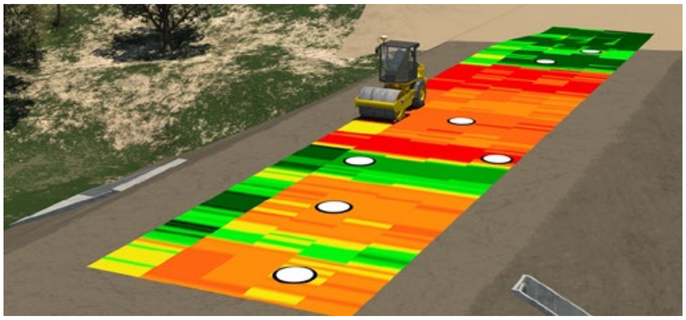

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Figure 10. Illustration of test section layout and test points for independent calibration

Step 5: Implement Modulus Verification into Your Practices

Implementing improved processes for design, construction, inspection, and maintenance will increase the performance of the single most costly investment agencies make: building and maintaining pavements.

Return on Investment for High-Quality Pavement Foundations

The ROI from building quality foundations under pavements can be very significant. However, it will vary depending on various factors, including initial construction costs, future maintenance costs, impact on public safety, and pavement lifespan. Investing in a stable and durable foundation reduces the ownership costs for the agency, protects motorists through better ride quality and a safer driving experience, and keeps roadways open with less disruption from reconstruction and patching of the pavement surface. The differential cost of building a quality foundation is relatively small compared to the value of extending the performance life of the pavement and reducing impacts on motorists.

Key points when evaluating the ROI of building quality pavement foundations are as follows:

1. **Initial Construction Costs.** Quality foundations often require additional investment during the initial construction phase, which involves using better materials, stabilization materials, better compaction, and improved inspection. However, investing in high-quality materials and proper construction techniques can help ensure the long-term stability of pavements.
2. **Operational Considerations.** Transportation systems management and operations (TSMO) strategies, activities, and services maximize the performance of transportation systems. Investing in quality pavement foundations is part of a comprehensive and relatively low-cost TSMO strategy to keep traffic moving by avoiding lane closures for maintenance, thus protecting construction workers and the public while keeping roadways open.

3. **Extended Pavement Lifespan.** A durable, stable, and resilient foundation provides a solid base for the pavement surface, helping to reduce nonuniform settlement and cracking over time. This extends the pavement's lifespan and reduces the need for costly repairs and replacements. The most common reason for early pavement distress is failures in the foundation layers.
4. **Reduced Maintenance Costs.** Investing in a stable foundation lowers maintenance costs for repairing potholes, cracks, and other pavement damage. This can result in long-term cost savings and a higher ROI for the pavement project. Repairing poorly constructed pavement foundations after the pavement is placed can be over 10,000 times more costly than constructing a quality foundation during initial construction.
5. **Improved Performance.** A quality foundation improves a pavement's overall performance by providing a smooth and even surface throughout its design life. This can enhance safety, reduce vehicle wear and tear, and improve motorists' driving experience.
6. **Environmental Considerations.** Building a stable foundation can also have environmental benefits, such as reducing the need for frequent maintenance activities that generate waste and pollution. A longer-lasting pavement can help lower the environmental impact of road construction and maintenance. Quality foundations are also more durable and resilient to extreme weather events.
7. **Economic Benefits.** Investing in quality foundation infrastructure can have broader economic benefits by improving transportation efficiency, reducing traffic congestion, and supporting economic development in the surrounding area. This can lead to indirect ROI through increased property values, business activity, and overall quality of life for residents.

Although pavement foundations typically are the lowest-cost component of a pavement system, they play a critical role in maximizing pavement life. Pavement life can be extended significantly if future pavement foundations are built to ensure high quality through the use of 100% modulus verification documentation and real-time monitoring to address unstable work areas before the pavement is placed (Figure 11).

When a high-quality foundation supports the same pavement layer thickness as a low-quality foundation, the high-quality foundation results in a 20% to 50% extension of pavement life (see Figure 12). Therefore, the ROI for improved pavement foundations is realized by extending pavement life.

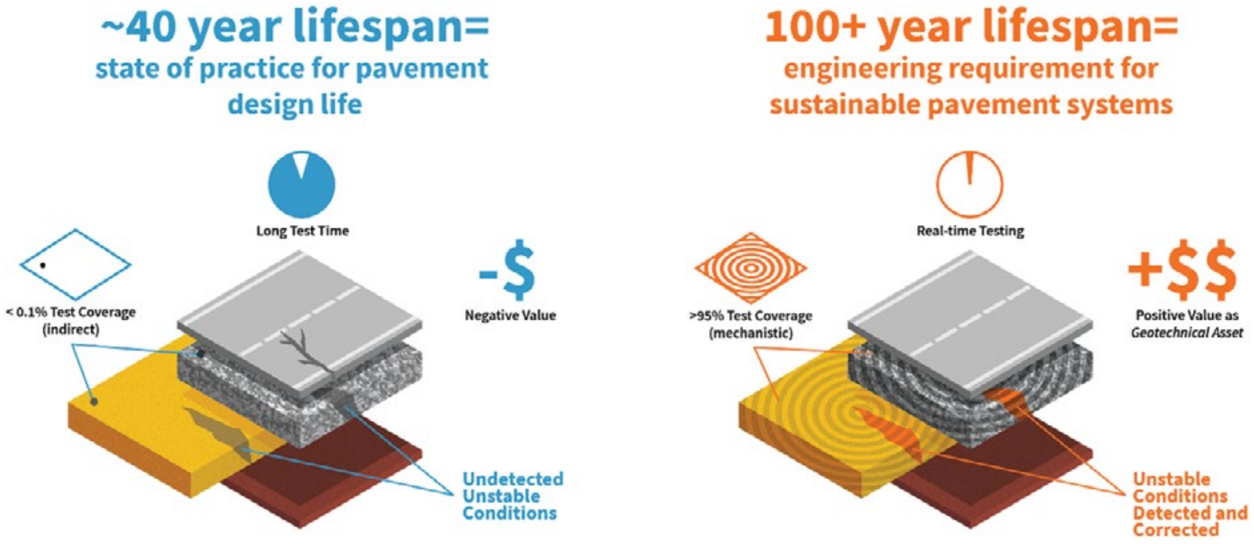

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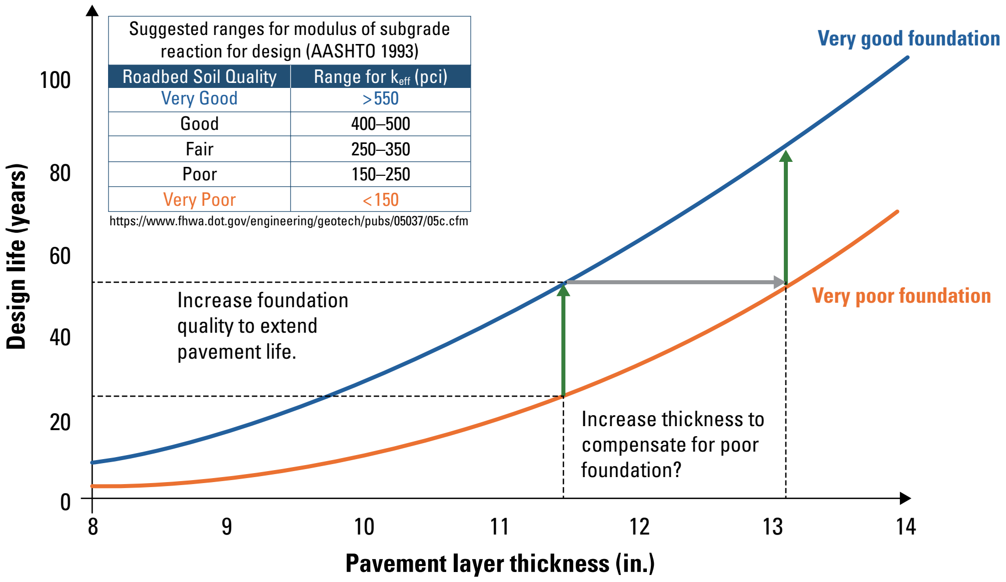
Figure 11. Comparison of the test area, testing time, and benefits of poor-quality (left) and high-quality (right) pavement foundations



Suggested ranges for modulus of subgrade reaction for design (AASHTO 1993)

Roadbed Soil Quality	Range for k_{eff} (pci)
Very Good	>550
Good	400–500
Fair	250–350
Poor	150–250
Very Poor	<150

https://www.fhwa.dot.gov/engineering/geotech/pubs/05037/05c.cfm

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Figure 12. Benefit of a high-quality pavement foundation in terms of pavement life for different pavement layer thicknesses

Pavement Foundation Demonstration Projects

In collaboration with FHWA, the CP Tech Center initiated six field demonstration projects in the 2023 and 2024 construction seasons. These projects aimed to disseminate advanced stiffness mapping technology for on-site verification of foundation layer design assumptions (i.e., k-value/resilient modulus) using specially instrumented soil compaction machines. Mapping was performed by trained operators using smooth drum vibratory rollers outfitted with a precalibrated measurement kit.

The demonstration project objectives included the following:

- Provide support to participating states for learning about modulus-based pavement foundation construction
- Initiate the development of a database of pavement foundation material properties to be used as input values in future Pavement ME Design (PMED) analysis
- Validate pavement foundation quality assurance procedures to assist participating DOTs in building longer-lasting pavement foundations
- Develop technical materials for future implementation of agency modulus verification

Six project demonstrations were completed between September 11, 2023, and October 1, 2024:

- I-494 Eastbound: Bloomington, Minnesota
- US 20: Elkhart County, Indiana
- I-465/I-69: Indianapolis, Indiana
- I-70 Eastbound: Westmoreland County, Pennsylvania
- I-94: MnROAD, Albertville, Minnesota
- I-70 Eastbound: Indianapolis, Indiana

A detailed project report was developed for each project. The following sections present a summary of findings and a link to the report for each project.

I-494 Eastbound: Bloomington, Minnesota

The summary of findings presented in this section is drawn from the e-compaction report for I-494 eastbound in Bloomington, Minnesota.

Modulus mapping on this project occurred along the eastbound side of I-494 in Bloomington, Minnesota. Mapping was performed along and adjacent to the mainline roadway between Bush Lake Road and the Highway 100 interchange. A selected area within a map area was recompacted using repetitive passes. Compaction curves for k-value and M_r were developed in the areas mapped in Figure 13, where different colors indicate greater or lesser differences between in situ and target k-values (k-value delta).

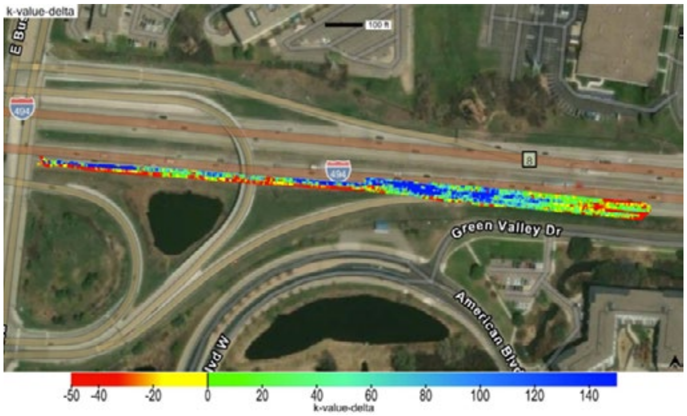

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Figure 13. I-494 roller mapping report

Key findings from this project include the following:

- A total of 97,800 ft² of pavement foundation area was mapped in approximately 1.5 hours.
- Three map reports were generated.
- All maps were generated on the unbound layer with Minnesota DOT (MnDOT) Aggregate Base Class 6 material.
- Blob maps identified spatially contiguous areas that did not meet this project's selected design k-value (k-TV = 200 psi/in.) and M_r (M_r-TV = 9,000 psi). The Global Positioning System (GPS) coordinates of the contiguous areas are documented within the reports for inspectors to investigate.
- Compaction curves on the Aggregate Base Class 6 material indicated increasing M_r and k-values with additional compaction passes.
- The measurements and improvements delivered from the compaction mapping process were recommended to be continued before paving to ensure that the pavement foundation modulus values achieved the pavement thickness design target values.

US 20: Elkhart County, Indiana

The summary of findings presented in this section is drawn from the e-compaction report for US 20 in Elkhart County, Indiana.

Mapping was performed along and adjacent to the mainline roadway between Highway 15 and Highway 27. The mapped area included three Indiana DOT (INDOT) research test sections. Two research test sections included layers of geogrid reinforcement within subgrade treatment layers, and the third section served as a control section without geogrid. Mapping was performed on the embankment borrow subgrade layer, the first lift of the subgrade treatment layer, and the second lift of the subgrade treatment layer. Production areas on the east and west sides of the research test sections were mapped before and four days after cement treatment was performed in the top 14 in. of the existing subgrade. Mapping results before and after cement modification are provided in Figure 14 and Figure 15.

Key findings from the US 20 project include the following:

- A total of 366,181 ft² of pavement foundation area was mapped in approximately 5.3 hours. A total of 21 mapping reports were generated.
- Mapping results showed that the modulus values increased on average about two times after cement treatment on the existing subgrade.
- Blob maps identified spatially contiguous areas that did not meet this project's selected design k-value (k-TV = 250 psi/in.) and M_r (M_r-TV = 10,000 psi). The GPS coordinates of the contiguous areas were provided.
- Mapping results indicated that both geogrid sections yielded similar k-values and M_r, while the control section yielded, on average, about 17% lower modulus values than the geogrid sections.
- Mapping results indicated that modulus values increased from the subgrade to the first lift of the No. 53 aggregate layer and the second lift of the No. 53 aggregate layer.

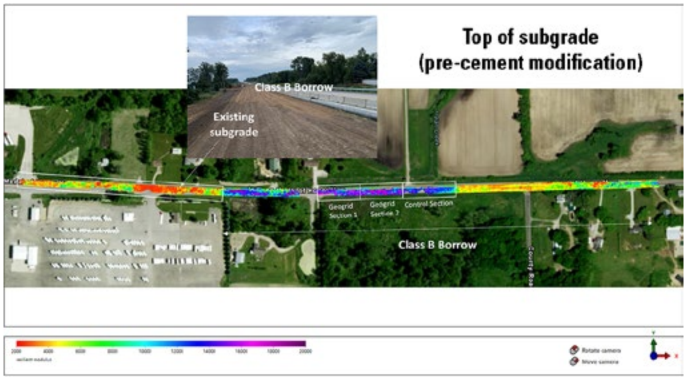

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Figure 14. US 20 mapping results before cement modification

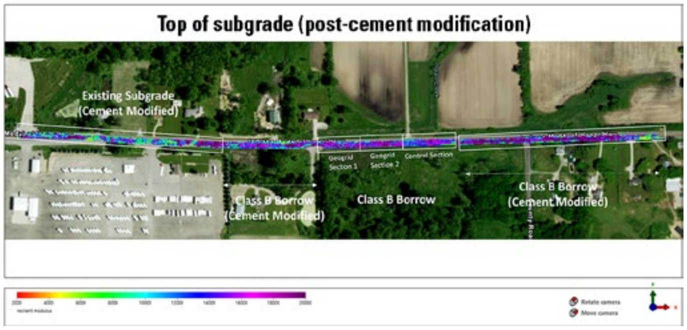

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Figure 15. US 20 mapping results after cement modification

I-465/I-69: Indianapolis, Indiana

The summary of findings presented in this section is drawn from the e-compaction report for I-465/I-69 in Indianapolis, Indiana.

Modulus mapping on this project occurred along an interchange ramp as part of the I-465/I-69 project in Indianapolis, Indiana (Figure 16). Only one ramp area was available for mapping at the time of this project. Mapping was performed using the CAT CS56B vibratory smooth drum roller.

The pavement foundation at the map location consisted of 6 in. of Aggregate No. 53 base layer over Indiana DOT Type IBC stabilized layer with 14 in. of cement modification over lime-stabilized embankment.

Key findings from the mapping report completed at the I-465/I-69 project include the following:

- A total of 15,492 ft² of pavement foundation area was mapped in approximately 20 minutes. One mapping report was generated.
- Mapping results indicated very stiff conditions, with the measured M_r and k-values near the upper limit of the calibration model (20,000 psi for M_r and 550 psi/in for k-value). These modulus values far exceeded the pavement design targets.
- An underlying culvert showed weaker support conditions.

I-70 Eastbound: Westmoreland County, Pennsylvania

The summary of findings presented in this section is drawn from the e-compaction report for I-70 eastbound in Westmoreland County, Pennsylvania.

Mapping on this project occurred along I-70 just west of the Pennsylvania Route PA 51 interchange in Westmoreland County, Pennsylvania (Figure 17). Mapping was performed using the contractor's Caterpillar CS56B vibratory smooth drum roller, which was outfitted on the project site with the instrumented roller kit. All mapping was performed by the contractor's operator, who was provided on-site training.

Key findings from the e-compaction report completed at the I-70 project include the following:

- A total of 281,688 ft² of pavement foundation area was mapped in approximately 21.8 hours.
- All production passes were recorded during mapping.
- A total of nine modulus reports were generated.
- Two material layers (subgrade and subbase) and two materials (cement-stabilized subgrade and Subbase 2A) were mapped.
- Mapping results indicated that the average k-value on the cement-stabilized subgrade layer was 1.25 times higher than that measured on the Subbase 2A layer. Similarly, the average M_r value of the cement-stabilized subgrade layer was 1.35 times higher than that measured on the Subbase 2A layer.
- All production compaction passes were recorded on Subbase 2A layer by the operator on this project, allowing for advanced compactibility analysis of the material. The material compactibility assessment maps highlighted areas that were being decompacted with additional compaction, areas that had achieved adequate compaction, and areas that can potentially achieve the target value with additional compaction. Compactibility assessment and visualization in real time can be valuable for optimizing contractors' compaction operations in the field.

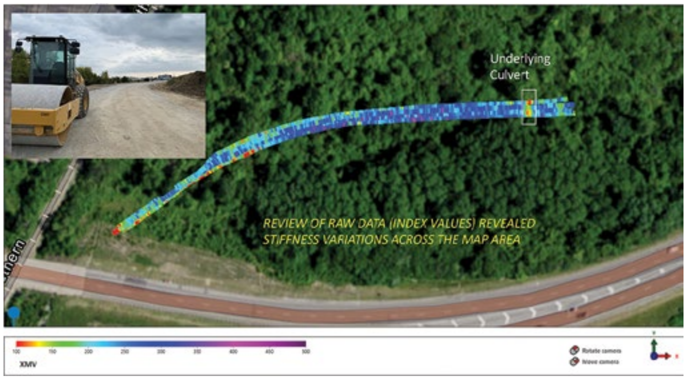

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Figure 16. I-465/I-69 stabilized pavement foundation showing stiff conditions

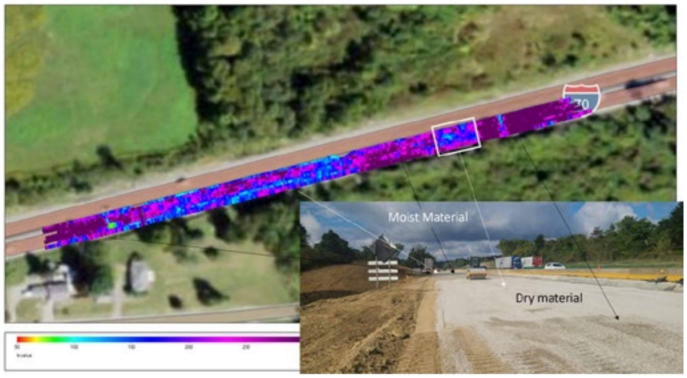

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Figure 17. I-70 map results indicating changes in modulus related to subbase moisture content

I-94: MnROAD, Albertville, Minnesota

The summary of findings presented in this section is drawn from the [e-compaction report for the I-94 MnROAD facility in Albertville, Minnesota](#).

The MnROAD demonstration was performed at the research test track facility in Albertville, Minnesota, from August 13 to 29, 2024. Reconstruction efforts at the MnROAD facility included constructing eight new test sections with rigid pavement materials consisting of cement alternatives, including reclaimed or harvested fly ash, microspheres, and other sustainable materials.

Modulus mapping was performed using a precalibrated vibratory smooth roller equipped with advanced hardware technology (Figure 18). The roller was precalibrated to measure the composite modulus of subgrade reaction (k-value) at a contact stress of 10 psi using 30 in. diameter APLT loading plates, the composite resilient modulus (M_r) using 18 in. diameter APLT loading plates at a cyclic stress of 70 psi, and the permanent deformation (δ_p) predicted at 100,000 loading cycles using 18 in. diameter APLT loading plates at 70 psi.

Generating the modulus reports and analyzing the data from the reports involved selecting an appropriate TV for each of the engineering parameters to analyze contiguous areas of noncompliance, defined as blobs. TVs were explicitly developed for this project using the guidance in the MnPAVE rigid pavement design manual and typical values assumed for each layer.

MnPAVE uses an online k-value calculator provided by the American Concrete Pavement Association (ACPA) to calculate the composite k-value on a layered profile. The composite M_r-TVs were estimated by modeling the layered system using KENLAYER layered elastic analysis to determine the peak deformation under the selected stress and by calculating the composite M_r-value using Boussinesq's equation.

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Figure 18. Caterpillar CS56 vibratory smooth drum roller outfitted with e-compaction hardware kit

Static plate load testing was conducted using APLT to verify the reported k-values using the AASHTO T 222 test procedure. The test equipment and setup are shown in Figure 19 for tests performed on the Class 5Q layer in Cells 2403 and 2404.

Modulus mapping was performed on the three foundation layers in Cells 2401 to 2408. Ten e-compaction reports were generated, which included a total mapping area of 216,841 sq. ft. Modulus of subgrade reaction k-value maps from three map runs performed in Cells 2401 to 2404 are presented in Figure 20. Results show that the average k-value decreased from 120 pci on the Class 3 layer to 112 pci on the overlain Class 5 layer, then increased to 176 pci on the Class 5Q layer. Results on the Class 5Q layer showed lower k-values in Cell 2404 and the eastern portion of Cell 2403 compared to the remainder of the cells in the mapping run. Blob analysis using a k-TV of 140 pci for the mapping run delineated the lowest k-value areas, noted as (1) in Figure 20.

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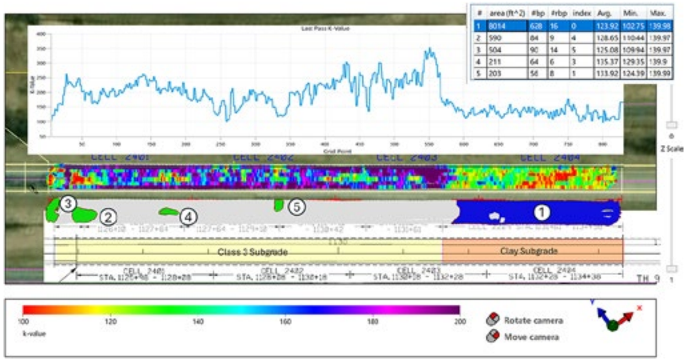
Figure 19. APLT setup with a 30 in. diameter loading plate to verify e-compaction measurements in Cell 2404



#	area (ft^2)	#bp	#rbp	index	Avg.	Min.	Max.
1	8014	628	16	0	123.92	102.75	139.98
2	590	84	9	4	128.65	110.44	139.97
3	504	90	14	5	125.08	109.94	139.97
4	211	64	6	3	135.37	129.35	139.9
5	203	56	8	1	133.92	124.39	139.99

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Figure 20. I-94 MnROAD k-value map and blob map (assuming k-TV = 140 psi/in.), overlaid with a line plot of k-value and the variations in the subgrade layer between Cells 2401 and 2404

I-70 Eastbound: Indianapolis, Indiana

The summary of findings presented in this section is drawn from the demonstration project report for I-70 eastbound near Indianapolis, Indiana.

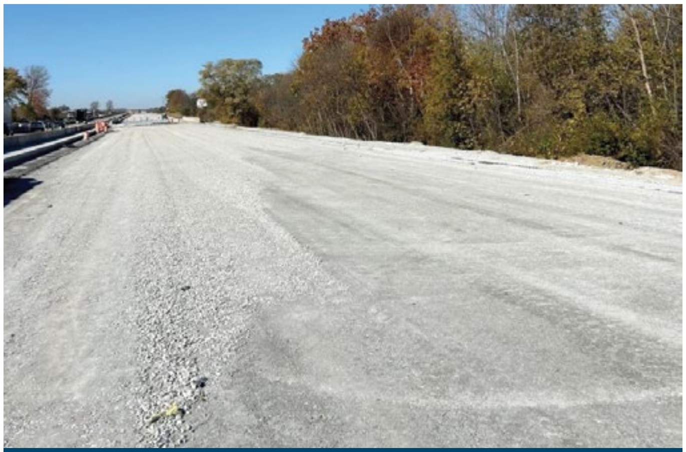
This demonstration project was located on I-70 in Hancock County, Indiana, approximately 10 miles east of Indianapolis, where I-70 crosses Sugar Creek. At the time of the demonstration project, the westbound lanes of I-70 were being reconstructed. Approximately 1,500 ft were mapped along I-70 west of Sugar Creek. Approximately 1,100 ft were mapped along I-70 east of Sugar Creek.

Mapping was performed using a precalibrated vibratory smooth roller to measure the composite modulus of subgrade reaction (k-value) at a contact stress of 10 psi using 30 in. diameter APLT loading plates and the composite resilient modulus (M_r) using 18 in. diameter APLT loading plates at a cyclic stress of 70 psi. Figure 21 shows project photographs.

Figure 22 shows the variability of M_r along the length of Lane 1 west of Sugar Creek, where 18% of the values are less than the M_r-TV of 14,500 psi. East of Sugar Creek, 39% of the values are less than the M_r-TV.

This analysis shows that most of the lanes west of Sugar Creek meet or exceed the design target values. East of Sugar Creek, significant portions of the travel lanes do not meet the design target value, including approximately half of the M_r values in Lanes 2 and 3. This difference is likely due to the differences in cement treatment between the two sections.

(a) Top of cement-treated subgrade layer on October 21, 2024, looking east from the west end of the project



(b) Top of AASHTO 53 subbase on October 27, 2024, looking west from the east end of the project

(c) Caterpillar CS56 vibratory smooth drum roller outfitted with mapping hardware kit

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Figure 21. I-70 Eastbound project photographs

2024 MnROAD/International Concrete Pavements Conference Open House Demonstration

In addition to the demonstration projects summarized in the previous section, an open house field demonstration was conducted at the MnROAD facility on August 29, 2024, as part of the 13th International Concrete Pavements Conference. Approximately 80 meeting attendees, including participants from multiple state/federal agencies and research institutions, visited the facility. Figure 23 provides pictures of the conference demonstration event. Observers learned about APLT methods and ways to integrate modulus values into compaction verification for pavement foundations.

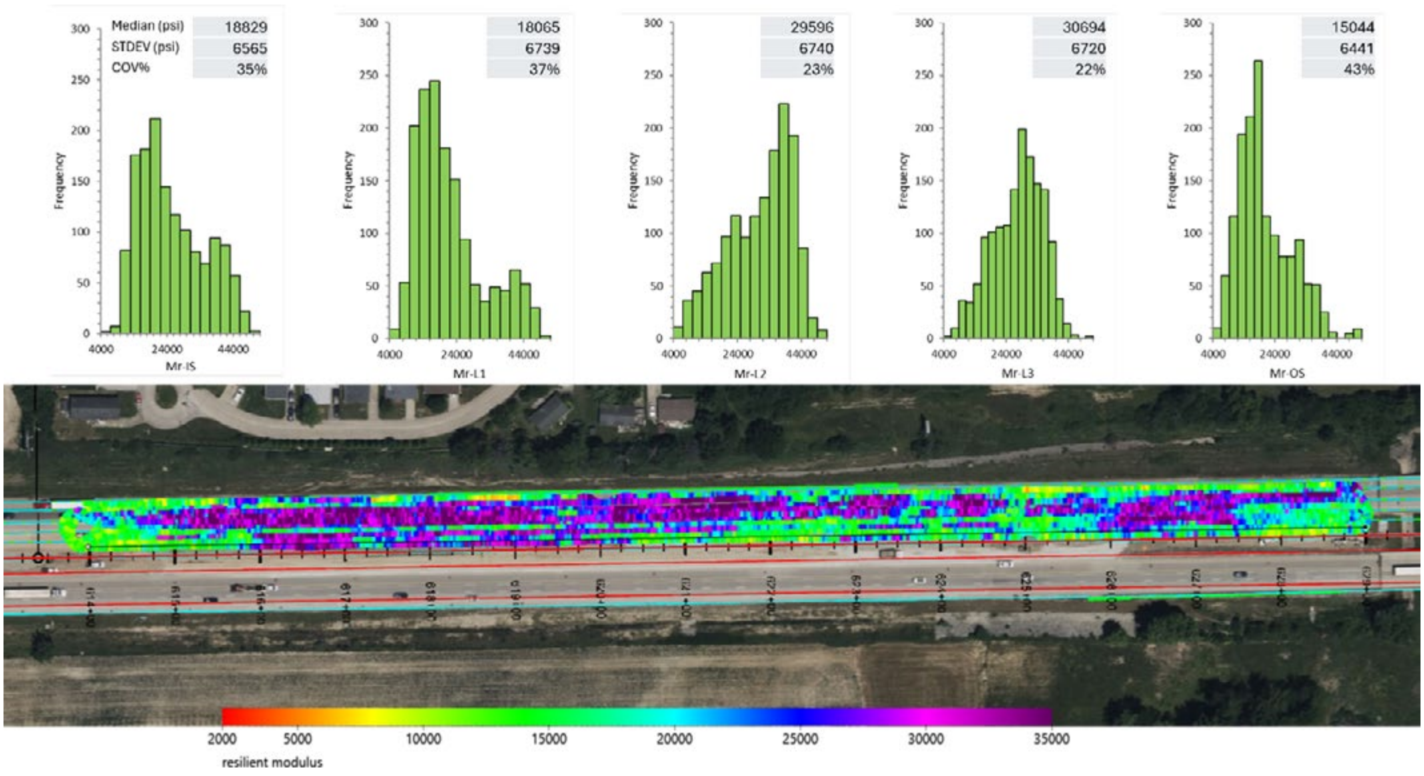

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Figure 22. Histograms showing distribution of M_r values for each travel lane and shoulder west of Sugar Creek

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Figure 23. Photographs of (a) e-compaction roller and (b) conference attendees at the e-compaction field demonstration

Iowa DOT Pilot Projects

The Iowa DOT has recognized that the current level of performance of its pavement infrastructure is not financially sustainable. Current and anticipated funding levels will require pavements to last two or three times longer than their current service lives to maintain the system at an acceptable level of service. This disparity has motivated the Iowa DOT to develop practical steps that will lower ownership costs for its pavement infrastructure and increase the level of service that the system provides to the public.

The Iowa DOT is in the fourth year of an implementation plan to move from method specifications (e.g., roller equipment type and pass limitations) to an end-result quality specification that uses modulus verification for mechanistic quality assurance of pavement foundations (k-value or resilient modulus). Using modulus as the compaction quality requirement will ensure that the foundation support values assumed during pavement design are achieved during construction. Workflow processes are also being evaluated to ensure that design, material selection, and construction requirements are established that achieve organizational efficiency and maximum value.

Roller mapping was performed on 10 pilot projects to evaluate and demonstrate the use of the technology for mechanistic quality assurance of pavement foundations. Field measurements of foundation support values obtained from about 150 plate load tests (per AASHTO T 222) on a variety of foundation treatments across the state indicate that under current design and construction requirements, only about 30% of the locations tested meet the minimum modulus values assumed in design. These data were generated under FHWA-sponsored State Transportation Improvement Council (STIC) and AID projects from 2017 to 2022 (White et al. 2019, White et al. 2022, Gieselman et al. 2021, Gieselman et al. 2023).

Key outcomes from the pilot projects included the following:

- Field-calibrated modulus mapping results were found to provide a high degree of confidence in delivering k-value and M_r value maps, with R^2 values above 0.90.
- Detailed roller calibration records were developed for different material types across Iowa for several contractor-owned machines.
- k-value tests revealed that about 70% of the measurements do not meet the current minimum modulus values assumed in design.
- Roller mapping identified “weak” areas in the underlying subgrade that were reflected in the overlying subbase layers.
- New emphasis is needed to engineer improved pavement foundation layers to meet pavement design requirements.
- A web application was developed to provide real-time results and digital reports to the Iowa DOT.

Future pilot projects aim to learn from these results to improve pavement foundation performance.

Figure 24 shows the developed web application’s use to provide real-time data during the Iowa DOT pilot projects. Figures 25 and 26 show examples of pavement foundation modulus variation related to material selection, poor compaction, and variable cement stabilization.

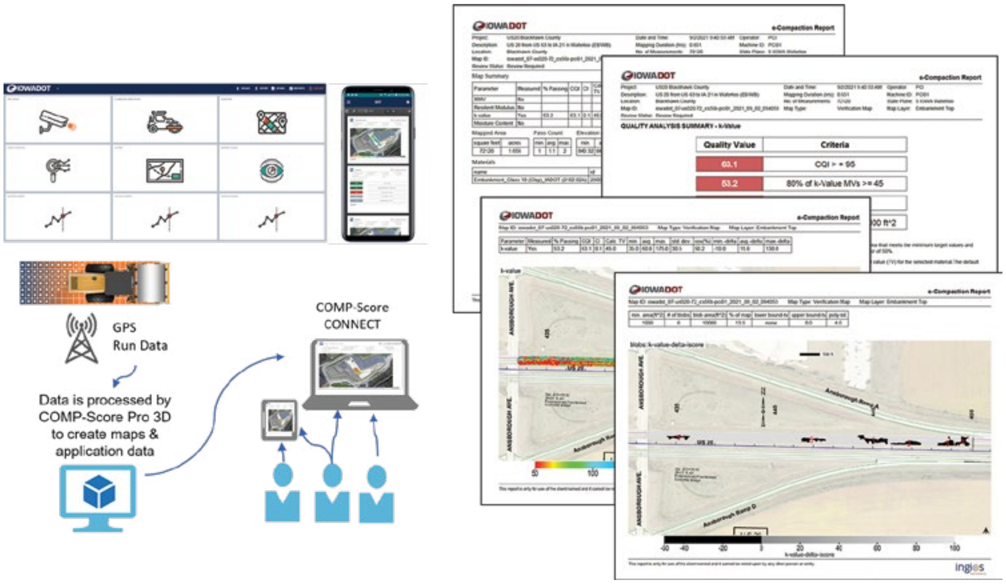

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Figure 24. Overview of the web application developed to provide real-time results and digital reports to the Iowa DOT

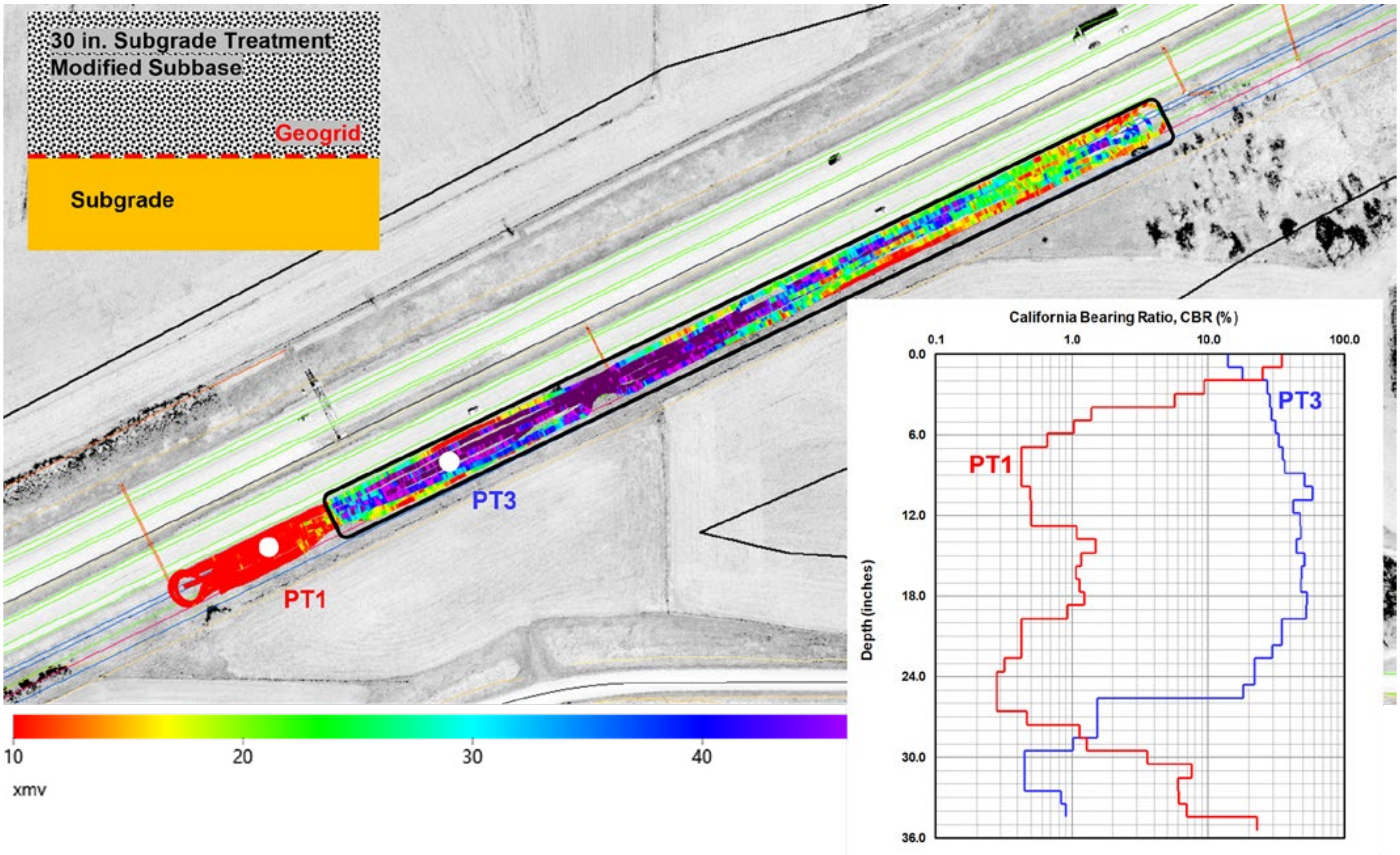

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Figure 25. Results of testing on I-80 in Jasper County, Iowa, showing weak support conditions confirmed with spot testing

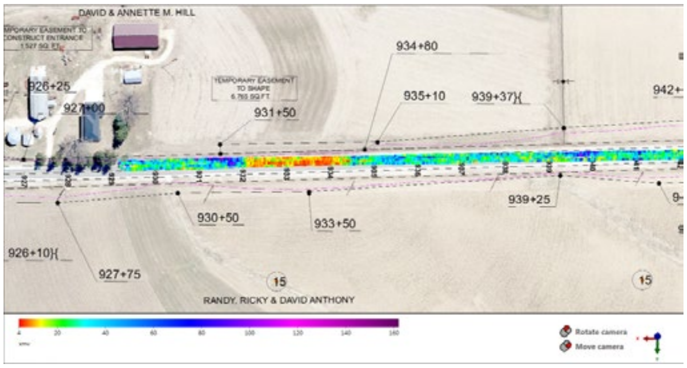

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Figure 26. Modulus mapping of cement-stabilized subgrade on US 52 in Dubuque County, Iowa, showing that the foundation is not stabilized

The Iowa DOT’s current implementation plan for modulus mapping and specification changes builds upon the key findings and lessons learned from the pilot projects. Improving compaction quality for pavement foundations is a complex issue requiring significant effort and resources. Specific challenges involve the inadequacy of current field measurement practices, organizations’ lack of time for field inspection, and the short-term focus on completing projects quickly and achieving immediate cost reductions rather than investing in quality improvements that may not pay off for years.

Working Toward Engineered Pavement Foundations

Designing pavement foundation layers involves considering several factors, such as soil properties, traffic loads, climate, and materials. Unlike pavement thickness design, current foundation design methods lack robust standardization, and foundations are typically only specified without engineering analysis for support life and durability. New design tools are needed and must consider the following key engineering inputs at a minimum:

1. **Layer Characteristics.** It is crucial to assess the properties of the layered pavement foundation materials, such as bearing capacity, compaction characteristics, stress-deformation relationship, and moisture content.
2. **Traffic Loads.** Understanding the type, volume, and weight of traffic expected on the pavement helps determine the required stresses and, therefore, the thickness and strength of the foundation layers.
3. **Climate Conditions.** Climate influences the design by affecting factors that impact the pavement foundation layers' durability and structure, such as freeze-thaw cycles and moisture variation.
4. **Materials Properties.** Evaluating the properties of materials used, such as subgrade, aggregates, geosynthetics, and stabilizers, is essential for achieving the desired strength, modulus, and durability of the pavement foundation layers.
5. **Geotechnical Investigations.** Conducting site-specific geotechnical investigations, including deep soil tests (>1 m) and subsurface exploration, provides essential data for designing the foundation layers.
6. **Environmental Considerations.** Assessing environmental factors, like the potential for erosion or the presence of soluble materials, helps inform the selection of materials that can withstand these conditions for the design life of the pavement.
7. **Design Standards and Codes.** Following relevant engineering standards and codes will ensure that the pavement foundation meets performance requirements. New standards are needed.
8. **Water Drainage.** An adequate drainage design prevents water accumulation, which can weaken the foundation layers. Proper slope and drainage structures are essential considerations.
9. **Layer Thickness Design.** The appropriate thickness of each layer (subgrade, subbase, base) should be calculated based on load-bearing requirements and support capacity (i.e., modulus).
10. **Quality Control and Assurance.** Implementing quality control measures during construction, including design value compaction testing and material quality checks, ensures that the pavement foundation meets design specifications.

Integrating these inputs will help engineers develop a pavement foundation design that can withstand anticipated loads and environmental conditions.

Key Findings and Recommendations

This technical brief addresses the need to implement approaches and technologies for designing, specifying, and accepting pavement foundations. Current and anticipated funding levels at highway agencies underscore the need for a twofold to threefold extension of pavement service life to maintain the transportation system at an acceptable operational standard. There is growing recognition among highway agencies of the significance of enhancing the sustainability of their pavements by improving the quality of the pavement foundations through verification of design input parameters in situ.

While building quality pavement foundations may require higher upfront costs, the long-term benefits in terms of reduced maintenance costs, extended pavement lifespan, improved performance, improved safety for construction workers and the public, environmental sustainability, and economic growth can result in a favorable ROI over time. It is essential to evaluate these factors holistically when weighing the upfront cost versus the ROI of investing in stable foundations under pavements.

Building on the success of the pilot and demonstration projects summarized in this technical brief, additional pilot projects will be conducted utilizing modulus verification to develop experience for future implementation and specification development.

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About the National Concrete Pavement Technology Center

The mission of the National Concrete Pavement Technology Center (CP Tech Center) at Iowa State University is to unite key transportation stakeholders around the central goal of developing and implementing innovative technology and best practices for sustainable concrete pavement construction and maintenance.