

# **LARGE-SCALE LABORATORY TESTING OF GEOSYNTHETICS IN ROADWAY APPLICATIONS**

## Research Proposal

Submitted by:

**Steven Perkins, Ph.D., P.E.**

Professor

Department of Civil Engineering

College of Engineering

Montana State University

Bozeman, MT

**Eli Cuelho, P.E.**

Senior Engineer

Transportation Research, Testing and  
Services Division

TRI-Environmental, Inc.

Austin, TX

Submitted to:

**Montana Department of Transportation**

Research Programs

2701 Prospect Avenue

Helena, Montana 59620

December 2017

## Table of Contents

1	Problem Statement.....	1
2	Background.....	1
3	Objective.....	3
4	Business Case.....	3
5	Research Plan.....	3
	Task 0 – Project Management.....	4
	Task 1 – Literature Review.....	4
	Task 2 – Test Section Planning and Design.....	4
	Task 3 – Test Section Construction and Trafficking.....	8
	Task 4 – Analysis and Synthesis of Results.....	11
	Task 5 – Reporting.....	12
6	Products.....	12
7	Implementation.....	13
8	Staffing.....	13
	Dr. Steven Perkins, P.E.—Principal Investigator.....	13
	Mr. Eli Cuelho, P.E.—Co-Principal Investigator.....	14
	Staff Hours and Availability.....	14
9	Facilities.....	15
	Laboratories and Equipment.....	16
	Information Services.....	16
	Administrative Services.....	16
10	Schedule.....	17
11	Budget.....	17
	WTI Salaries and Benefits.....	18
	Testing Services (TRI).....	18
	Travel.....	18
	Contracted Services (TRI).....	19
12	References.....	19
	Appendix A: Two-Page Résumés.....	20

**List of Figures**

Figure 1: Test section conditions from studies summarized in Berg et al. (2000) and Perkins (2016). ..... 2

Figure 2: Illustration of proposed test section layout..... 5

Figure 3: Automated loading facility. .... 9

Figure 4: Illustration of typical instrumentation layout and calculation of strains. .... 10

**List of Tables**

Table 1: Comparison of Mix Design Properties for Montana and South Carolina HMA ..... 6

Table 2: General Characteristics of Proposed Test Sections ..... 7

Table 3: Summary of WTI Staff Person Hours by Task..... 14

Table 4: Project Schedule ..... 17

Table 5: Detailed Budget by State and Federal Fiscal Year ..... 17

Table 6: WTI Staff Salary and Benefit Information ..... 18

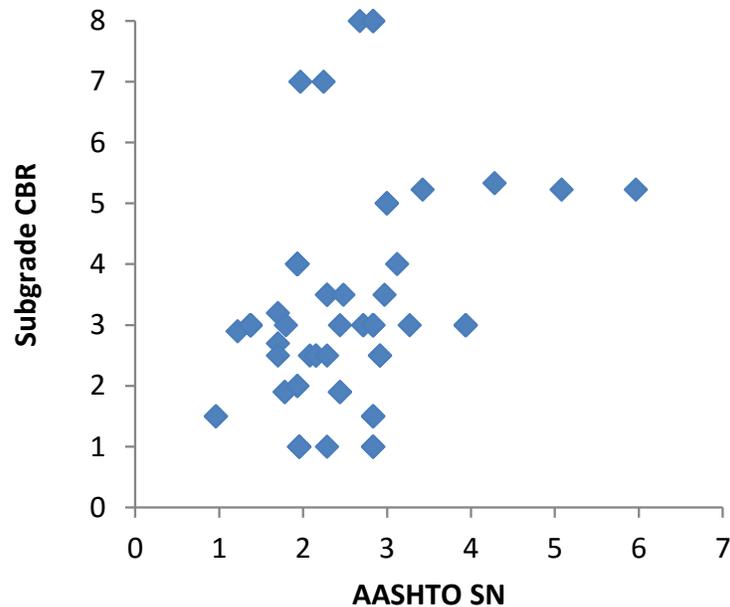
Table 7: Itemization of TRI Testing Services Costs ..... 18

## **1 Problem Statement**

The availability and quality of base course aggregates is becoming limited in many states, requiring departments of transportation to be even more innovative and efficient with their roadway designs. These limitations and requirements are even more acute in areas where low-volume roads are more prevalent, budgets are shrinking, user expectations are increasing, and commodities are under high demand. Geosynthetics are routinely used in transportation applications to facilitate construction, improve stability, and enhance longevity. Departments of transportation have generally had good experience with these products, although a robust and non-proprietary design process for geosynthetic reinforced paved roads is still lacking. Several proprietary design procedures have been developed by individual manufacturers, but are often based on a single product. Researchers at the Western Transportation Institute (WTI) at Montana State University (MSU) have been working on a non-proprietary road design procedure that incorporates generic material properties of the geosynthetic. Under certain conditions, it may be possible to reduce the cross-sectional thickness of the unbound structural layer using geosynthetics, thereby saving valuable resources. A program of study is being proposed to evaluate this procedure for the test conditions present in this project. Specifically, this study will conduct full-scale indoor testing of reinforced pavement test sections using a traffic simulator to provide performance data and to evaluate a spreadsheet-based design tool that can be used to augment current design procedures.

## **2 Background**

The Montana Department of Transportation has sponsored several projects conducted by WTI/MSU related to geosynthetic reinforcement of paved roadways. These projects include efforts to provide experimental evidence of performance of geosynthetic reinforced paved roads by the construction of test sections (Perkins, 1999, 2002) and those designed to provide design models for reinforced roads (Perkins 2001a,b, and Perkins et al. 2004). Test section work performed in the two studies noted above along with other studies reported in the literature was summarized by Berg et al. (2000) and more recently by Perkins (2016). The test conditions (asphalt and base thickness, subgrade strength, type of geosynthetic, number and position of geosynthetic layers) associated with these studies were summarized in a presentation delivered to MDT by the Principal Investigators in November 2015. These test conditions are summarized in Figure 1, where the subgrade strength, expressed in terms of CBR, is plotted against the pavement AASHTO structural number for each test section.



**Figure 1: Test section conditions from studies summarized in Berg et al. (2000) and Perkins (2016).**

Based on the work of these previous studies and their in-house experience, MDT believes that geosynthetics can be used responsibly to provide cost-savings on a number of upcoming highway construction projects in the state. Typical construction projects currently under consideration have, however, design conditions that differ from those contained in previous studies. MDT desires experimental evidence of performance for these typical projects in order to proceed with future designs. The design conditions of interest in these typical projects that differ from those in previous studies lead to the following questions.

- Do standard stabilization geotextiles used commonly as a construction expedient provide structural benefit to the pavement as seen by an increase in the number of traffic passes carried to reach a certain rut depth?
- What is the structural benefit of reinforcement geosynthetics for a pavement cross section having an asphalt and base course thickness moderately greater than those incorporated into previous studies?
- Does the addition of a layer of geogrid within the pavement cross section, when a stabilization geotextile is present, add significant benefit in terms of allowing for a reduction of base course thickness, and if so, where in the base aggregate layer should it be placed?

MDT is interested in a comprehensive testing plan that would answer all of the questions above. The current research funding capabilities of MDT requires, however, that this work be undertaken in a phased approach where the first phase will consist of the construction, testing and analysis of a single track of controlled pavement test sections. This first phase will involve elements addressing the first two bullet items listed above. A subsequent phase would address the third bullet item. The results from the single test track for this first phase have the potential to

significantly affect how geosynthetics are incorporated in typical highway pavement projects constructed by MDT.

### **3 Objective**

The main objective of this project is to characterize the performance of geosynthetic-reinforced test sections when compared to an unreinforced case in order to assess benefit in terms of a reduction in the base course thickness, an extension of the life of the pavement or the strengthening of the individual pavement layers. This objective will be achieved through the construction of a single test track containing three test sections, a detailed analysis and synthesis of the results, and the evaluation of an analytical design tool to be used by pavement engineers to design geosynthetic-reinforced pavements.

### **4 Business Case**

Geosynthetic reinforcement is used to reduce the amount of gravel used in construction of the roadway and/or to extend the life of the roadway. In Montana, gravel sources are becoming difficult to find and difficult to permit in densely populated areas. The Bakken oil development continues to place additional strain on aggregate sources in the Glendive district. There are areas in Eastern Montana where aggregates are hauled a significant distance. The Billings and Great Falls districts have areas where aggregate prices are relatively high because of lack of available sources. An extended service life of the roadway will reduce impacts from maintenance and construction operations on road users and surrounding businesses. Extending the pavement service life will lengthen the construction interval between major rehabilitation projects. This will cause fewer disruptions to traffic and thereby enhance route safety. The benefits and outcomes discussed above serve the core concepts in MDT's mission statement, namely quality, safety, cost effectiveness and sensitivity to the environment. Eastern Montana contains many miles of low volume roads and is experiencing tremendous infrastructure challenges due primarily to oil and gas development and increasing demands from the agricultural industry. These roads are in areas where gravel is scarce and contain design conditions for which data on the benefits of geosynthetic reinforcement is missing. MDT currently has scheduled two projects where geosynthetic reinforcement could be especially valuable. The conditions described above create a great urgency to provide documentation of performance and benefit.

### **5 Research Plan**

The objectives of this research will be accomplished through a comprehensive program that includes laboratory tests of geosynthetics; constructing, monitoring, and analyzing a single set of large-scale test sections in a newly constructed indoor testing lab; and calibration of a design tool for geosynthetic reinforced pavements. Information will be disseminated to the MDT Research Project Manager through detailed and timely quarterly reports, task reports, and regular project meetings. Deliverables for the project include Project Summary, Implementation and Performance Measures reports. A final presentation will be delivered to summarize the results of this research.

The major tasks associated with this work are detailed in the subsections that follow. Task 0 was added to outline project management activities.

### **Task 0 – Project Management**

The Principal Investigator (PI) for this project will manage the project in terms of contractual compliance, budget and schedule, administrative tasks, and communications with the MDT Research Project Manager. Dr. Steven Perkins of the Civil Engineering Department at Montana State University will serve as the PI for the project. He will be the primary contact and assume the majority of the project management responsibilities. Mr. Eli Cuelho will serve as Co-Principal Investigator (Co-PI) for the project, and will be involved in project planning, test section construction, trafficking, data collection, and analysis. Perkins and Cuelho constitute the research team for this project.

Project management is important to ensure that the work proposed herein is completed on time, on budget and high quality. Management will generally be achieved through regular communication between the PI, the MDT project manager, and the Co-PI. The PI will submit brief and concise quarterly progress reports to describe accomplishments, status of the project and future plans. Major deliverables will follow MDT reporting requirements and formats and will first be sent to the MDT Research Project Manager for review and comment.

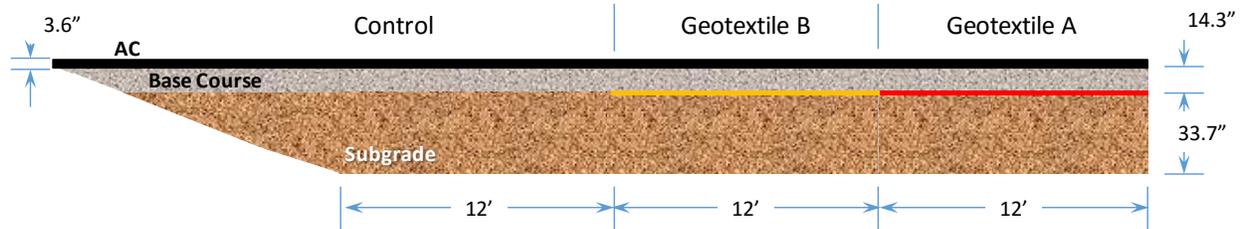
### **Task 1 – Literature Review**

A comprehensive literature search will be performed to determine appropriate practices related to geosynthetic reinforced pavements, base reinforcement, and base reduction. Current practices of geosynthetic reinforcement will be sought from journals, reports, databases, conference proceedings and other sources. This concise review will document design methods and specifications related to the use of geosynthetics as a reinforcement element within the base course. Montana State University provides sufficient access to a host of electronic and hardcopy databases in which to find information relevant to this project. Section 9 of this proposal describes in detail the information services available to the research team as part of the description of facilities. The wealth of literature available on this subject (including the literature contained in the background section) will be reviewed, summarized, and synthesized to extract information relevant to the challenges faced by Montana road designers. The final report will contain all pertinent literature available up to the date of the report.

### **Task 2 – Test Section Planning and Design**

A single large-scale paved test track containing three test sections is proposed. Experimental data from these test sections will be used to evaluate the structural benefit (based on rut) of a non-woven geotextile and a woven geotextile when used within a pavement cross-section. The testing will be conducted at TRI's laboratory facility in Greenville, South Carolina. A concrete-lined

trench 4 ft. deep by 11 ft. wide by 36 ft. long will be filled with subgrade, base aggregate and topped with asphalt to form a roadway that can be trafficked using an automated, rolling wheel load device. A side view of the trench with the proposed layout is shown in Figure 2. The subgrade soil will consist of a silty clay material whose strength is easily manipulated by water content. A subgrade material from South Carolina that resembles typical subgrades found in Montana will be sought for this project. Selection of the subgrade will be made in consultation with the MDT technical panel. The base course material will consist of a Montana crushed base course, Type 6A (1½-inch minus) and potentially topped with a thin layer of crushed top surfacing as a leveling course. The base materials will be obtained from a gravel pit located in Montana and trucked to South Carolina for use in this project. The source of this material will also be determined in consultation with the MDT technical panel.



**Figure 2: Illustration of proposed test section layout.**

The research team in consultation with the MDT technical panel has examined a number of possibilities for the hot-mix asphalt (HMA) material used in the test sections. The focus of this examination was to choose an option that resulted in a constructed material with engineering properties as close as possible to typical mixes used in Montana. Based on this examination, a HMA used for the pavement surface will be obtained from a commercial HMA plant located in Greenville, SC. There are several hot-mix plants near the testing facility in South Carolina that produce over 450 tons per hour.

To compare typical Montana mixes to those from plants around the Greenville, SC area, typical Superpave mix design reports were provided by MDT for each of the five districts in Montana except the Missoula District, which uses a ½-inch mix. A recent study of HMA mixtures in SC (Amirkhanian et al., 2017) provided data on materials from plants around Greenville, SC. Table 1 provides a comparison of mix design properties for the materials described above. The first four mixtures are from Montana. The fifth column gives a range of values from 19 mixtures from SC. Dynamic modulus  $|E^*|$  was estimated using the Hirsch model developed by Christensen et al. (2003), which has been shown to work well for many HMA mixtures. The model uses VMA, VFA and the binder dynamic shear modulus ( $G_b^*$ ) for input.  $G_b^*$  was estimated by equations derived from the Cox-Mertz rule (Kim et al., 2011) to have values at a comparable load frequency and temperature. Mixes provided by MDT used binders PG 70-28 and 64-28. SC uses either PG 64-22 or 76-22. The binder dynamic shear modulus ( $G_b^*$ ) is greater for the SC binders as

compared to the binders provided by MDT. The volumetrics are also different between MT and SC mixes, however SC mixes towards one end of the range have values comparable to MT mixes. The values of dynamic modulus  $|E^*|$  for MT mixes falls within the range of values for SC mixes. Dynamic modulus is considered the principle performance-related property for HMA mixes. Based on this examination, we believe a SC mix can be selected to have a comparable  $|E^*|$  value to typical mixes used in Montana and other properties that are not substantially different.

**Table 1: Comparison of Mix Design Properties for Montana and South Carolina HMA**

Mix ID	165S000008CON	172S000001CON	174S000003CON	173S000003CON	SC Mixes Range of Values
<b>Binder Grade</b>	PG 70-28	PG 70-28	PG 70-28	PG 64-28	PG 64-22 or PG 76-22
<b>VTM (%)</b>	3.5	3.7	3.6	3.7	4.6 - 7.7
<b>VMA (%)</b>	13.4	13.4	14.5	14.1	15.8 - 20.2
<b>VFA (%)</b>	73.8	72.9	75.3	73.9	59.9 - 71.1
<b>G*<sub>b</sub> (psi)</b>	853	853	853	829	1408 or 1440
<b><math> E^* </math> (ksi)</b>	1036	1030	998	994	921 - 1151

The final SC HMA mixture will be chosen by first reviewing existing SuperPave mix designs from past production of candidate plants. From this review, three mixtures will be identified and material from each will be obtained. In addition, materials from at most three hot-mix plants in Montana will be obtained. These materials will be used to create gyratory-compacted samples that can be cored and trimmed for dynamic modulus testing. SuperPave Mix Design Reports summarizing volumetric properties will be issued for each mix. Bulk materials and additional gyratory samples of the selected mixture from SC will be sent to MDT to perform Hamburg wheel tracking tests to ensure the material passes MDT’s material specification. The results from these tests will be evaluated in consultation with the technical panel prior to making a final selection.

Subgrade strength and layer thickness of the asphalt concrete and base aggregate are based on typical sections that MDT anticipates for upcoming highway projects. The target subgrade strength will be CBR = 2.5. Lab CBR tests will be performed to determine the moisture content of the subgrade to yield a CBR of 2.5. Subgrade material will be sent to MDT for R-Value testing.

Dynamic modulus testing will be performed on the asphalt concrete to be used, which will be correlated to layer coefficient. CBR testing will be performed on the base aggregate material. This material will also be sent to MDT for R-Value testing. Test data will be correlated to a layer coefficient for the base course aggregate. In addition, light weight deflectometer (LWD) tests will be performed on both the subgrade and base aggregate. The LWD device owned by MDT and currently in WTI’s possession will be used for these tests and returned to WTI at the end of the project.

The asphalt concrete and base course thickness is scheduled to be 3.6 inch and 14.3 inch, respectively. The structural number for these test sections is 3.47, which assumes layer coefficients of 0.41 and 0.14 for the asphalt concrete and base aggregate layers, respectively. Should the layer coefficients differ from these values, the thickness of the asphalt concrete layer or the base aggregate layer will be adjusted accordingly to maintain the same overall structural number of 3.47. The final configuration will be decided by consultation with the MDT Technical Panel.

A summary of the proposed test section attributes is listed in Table 2. The anticipated ESALs for each test section are listed in Table 2. The test track proposed will answer the question of whether standard stabilization geotextiles used commonly to expedite construction will provide structural benefit to the pavement as seen by an increase in the number of traffic passes carried to reach a certain rut depth. Additional test tracks are needed to answer the remaining questions of interest detailed in Section 2. These additional tracks (Tracks 2 and 3) are also included in Table 2 to outline possible testing for future phases of this effort.

**Table 2: General Characteristics of Proposed Test Sections**

Test Track	AC Depth (in.)	Base Depth (in.)	Geosynthetic(s)	Geosynthetic Position	SN Expected ESALs
Track 1	3.6	14.3	Unreinforced	N/A	SN = 3.47 ESAL = 3.2x10 <sup>5</sup>
	3.6	14.3	Non-woven geotextile <sup>1</sup>	Subgrade/base interface	SN = 3.47 ESAL = 4.5x10 <sup>5</sup>
	3.6	14.3	Woven geotextile <sup>2</sup>	Subgrade/base interface	SN = 3.47 ESAL = 9.0x10 <sup>5</sup>
<b>Possible Future Test Tracks</b>					
Track 2	3.6	10.2	Composite (non-woven + geogrid)	Subgrade/Base Interface	SN = 2.91 ESAL = 3.3x10 <sup>5</sup>
	3.6	10.2	Non-woven textile <sup>1</sup> + geogrid <sup>3</sup>	Textile at subgrade/base interface, geogrid ½ way up into the base	SN = 2.91 ESAL = 8.8x10 <sup>5</sup>
	3.6	10.2	Textile <sup>1,2</sup> + geogrid <sup>3</sup>	Textile at subgrade/base interface, geogrid ½ way up into the base <sup>4</sup>	SN = 2.91 ESAL = 1.7x10 <sup>6</sup>
Track 3	3.6	16.9	Unreinforced	N/A	SN = 3.85 ESAL = 6.0x10 <sup>5</sup>
	3.6	19.7	Unreinforced	N/A	SN = 4.24 ESAL = 1.12x10 <sup>6</sup>
	3.6	22.5	Unreinforced	N/A	SN = 4.63 ESAL = 2.0x10 <sup>6</sup>

<sup>1</sup> Propex Geotex 801 or equivalent, final selection to be decided upon consultation with MDT Technical Panel

<sup>2</sup> Mirafi RS580i, final selection to be decided upon consultation with MDT Technical Panel

<sup>3</sup> BX Type 2 or equivalent

<sup>4</sup> alternatively, non-woven at subgrade/base interface + geogrid ½-way up into the base.

The test track will consist of three separate test sections, 12 ft. long and 11 ft. wide, constructed adjacent to one another in the concrete-lined trench. A six-inch overlap of the geosynthetics is

anticipated between adjacent reinforced test sections, leaving approximately 11 ft. of the test section by which to make longitudinal rut measurements.

### ***Material Characterization***

Wide-width tensile tests (ASTM D4595) or grab tensile strength tests (ASTM D4632) will be conducted on the geosynthetics to document their tensile strength properties in both principal strength directions. Subgrade properties will be verified by relating CBR to moisture content and a select hand-held device for the purposes of quality assurance and quality control during construction. The consistency and strength of the subgrade will be monitored during construction using a hand-held device that provides a quick and accurate measurement. Once the entire layer of subgrade is constructed, a dynamic cone penetrometer (DCP) will be used to measure the in-place strength, and LWD testing will be used to measure the dynamic stiffness. The base course aggregate will be characterized in the lab by sieve analysis, fractured face count and relative density. In-place strength and density of the base course will be assessed using DCP, LWD, sand cone and nuclear gauge testing. Characterization of the asphalt material will be done by dynamic modulus tests conducted on samples collected during the paving of the asphalt layer.

### **Task 3 – Test Section Construction and Trafficking**

Construction will begin by mixing the subgrade to a specific moisture content (indicative of a CBR strength = 2.5) and placing it in approximately 6-inch lifts bringing the total depth to the desired depth. At that point, the subgrade surface will be leveled, surveyed, and tested to document its in-place strength. Characterization of the subgrade will be made using a DCP, sand cone, LWD, a hand-held device, and moisture content. The DCP and LWD will be used only when the subgrade is fully constructed. The hand held device and/or moisture content will be primarily used during construction to ensure the subgrade is at the proper strength. A comprehensive topographic survey of the final surfaces of each of the pavement components will be taken to quantify the constructed thicknesses of each layer.

After completion of the subgrade, a geosynthetic will be placed on the subgrade surface in the reinforced sections and pulled taut by hand. The base course aggregate will be placed on top of the subgrade or geosynthetic, screeded to ensure uniform depth across each test section, and compacted with a roller to at least 95 percent of maximum dry density using a vibratory roller. The base layer will consist of a crushed base course from Montana that meets Montana specifications. Construction of the base course on top of the geosynthetic stabilized test sections will be accomplished using lightweight equipment to minimize distresses prior to trafficking. It is anticipated that the base course will be placed in two lifts. Final grading of the base course will be accomplished by screeding the material to a consistent depth and possible addition of a leveling course. An equal number of roller passes will be used to compact each layer of the base course. Construction and final grading of the base course will be done in such a way that the test sections

will be in a virgin state prior to trafficking. In-place strength and density of the base course will be assessed using the DCP and sand cone.

Consistent strength, thickness and quality of the asphalt are vital to ensure direct comparisons between test sections. It is anticipated that the asphalt layer will be placed in two lifts using an asphalt paving machine. A vibratory roller compactor will be used to densify the asphalt mixture once it has been placed by the paving machine. The material properties of the asphalt pavement will be quantified using traditional asphalt testing procedures, and mix design reports will be documented.

### ***Trafficking***

Trafficking of the test sections will be accomplished using an automated loading facility. This device (Figure 3) can apply a rolling wheel load across all three test sections. A 9-kip load will be applied to the dual-wheel assembly, and the tires will be inflated to 90 psi representing 1 ESAL per pass. Application of the load is accomplished through two 12-inch pneumatic cylinders that react against a stiff frame. The wheel carriage assembly is pulled back and forth across the test panels using a cable and winch assembly at a speed of 4 to 6 mph. Trafficking will be applied in both directions (i.e., bi-directionally) until 0.5 inches of rut is reached or the loading device has made the predicted number of passes (refer to Table 2, Track 1).



**Figure 3: Automated loading facility.**

### ***Instrumentation and Monitoring***

Instrumentation within the test sections will consist of linear variable differential transducers (LVDTs) to determine displacements at the interface between the subgrade and base course, and at the interface between the base course and asphalt. Having these two measurements, plus the

surface rut, will allow strain in the asphalt and base course layers to be determined. The datum for each of the LVDT displacement measurements will be the bottom of the concrete trench (as illustrated in Figure 4). This will be accomplished by driving a solid metal rod through the base course and subgrade until it bears on the bottom of the trench. The stem of the LVDT will be attached to this rod, and the backside of the LVDT will be positioned at the measurement point of interest. Three replicate measurements will be made in each test section for a total of six LVDT displacement measurements in each test section. Measurements will be concentrated near the center of the test sections in the wheel path. Dynamic measurements will be made periodically during trafficking, likely to be coincident with rut measurements on the road surface. Data will be automatically collected during trafficking to provide a semi-continuous measure of displacement and strain as a function of traffic passes. The applied wheel load will also be included in this data set.

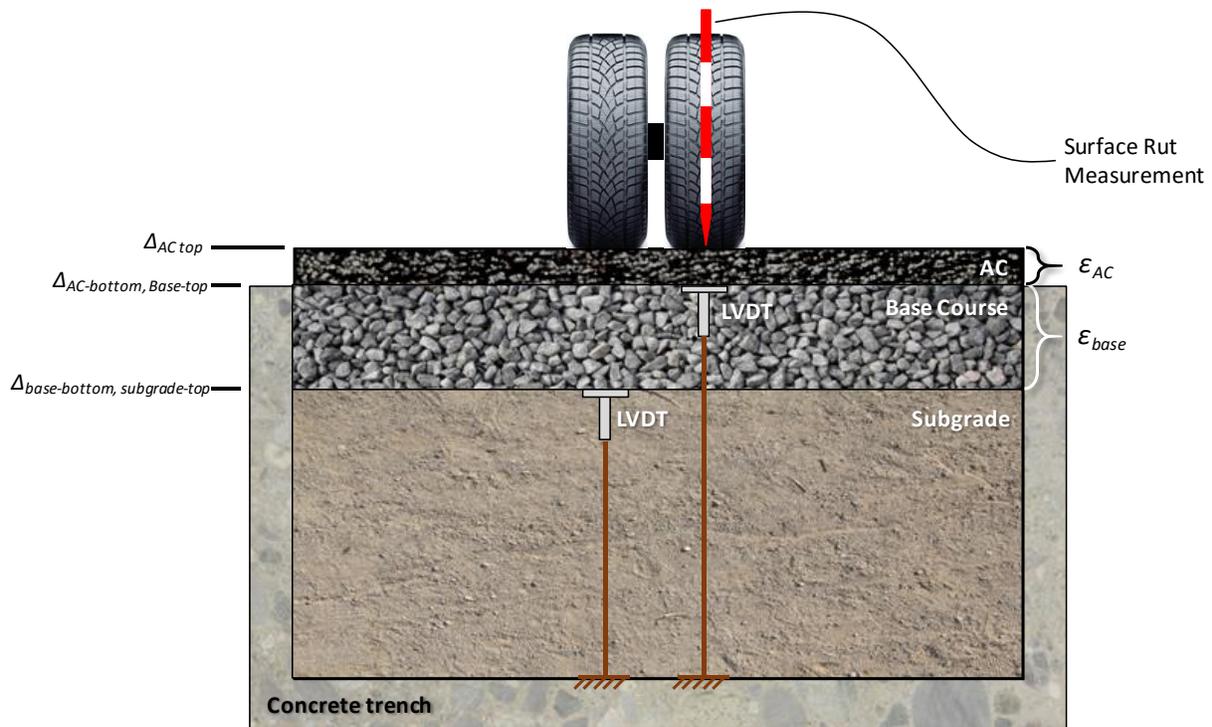


Figure 4: Illustration of typical instrumentation layout and calculation of strains.

Longitudinal rut depth measurements in the wheel path and transverse rut profile of the pavement surface will be made periodically during trafficking to quantify the performance of the individual test sections. Longitudinal rut measurements will be made at one-foot intervals along the length of each test section; however, a 1-foot area between adjacent test sections will be ignored to avoid the transition zone. Transverse rut profiles will also be taken at two locations in each test section. Baseline measurements of the surface of the base course will be taken prior to trafficking. A suggested schedule for the remaining measurements is after passes 100, 200, 400, 800, 1600, 2500, 5000, 7500, 10,000, 15,000, 20,000, 25,000, 30,000, 35,000, 40,000, 50,000, and every 100,000

passes until failure (defined as 1- inch of elevation rut) or the predicted number of passes shown in Table 2 is reached. Additional rut measurements may be necessary to capture early behaviors in sections that fail more rapidly.

#### ***Post-trafficking Forensic Investigations***

Post-trafficking, forensic investigations will be conducted to evaluate damage to the geosynthetics during construction and from trafficking, as well as to re-evaluate pertinent soil strength characteristics. Intensive evaluations will take place in the area within each test section where the transverse rut profile measurements were made. The asphalt layer will be saw-cut out and carefully removed from an area approximately 3 ft. wide (in the direction of traffic) by the width of the test site to carefully expose the base course. Thickness measurements of the asphalt layer after trafficking will be made on samples removed during these investigations to quantify the total strain within the AC layer. The original thickness will be based on baseline measurements taken during construction. Removal of the base course aggregate will be accomplished using a high-flow compressed air nozzle to minimize disturbance and damage to the geosynthetic during excavation. The geotextiles will then be carefully removed from the area to analyze damage. Several DCP and moisture measurements will be taken during these investigations on the exposed subgrade surface within each test section. Additionally, the depth of the base course aggregate layer will be measured. The transverse rut profile of the base and subgrade will be measured on each side of the excavated area to determine strain in the base course aggregate and characterize movement of the subgrade due to trafficking. Finally, the base and subgrade will be sampled from this area to comprehensively evaluate soil mixing between the subgrade and base course in the rutted areas and to facilitate a visual evaluation of the rutted area.

#### **Task 4 – Analysis and Synthesis of Results**

The results from these test sections will be analyzed and synthesized by the team members and summarized in a final report. The analysis of the respective performance of the test sections will be based largely on longitudinal rut depth and the displacement measurements. The rut measurements will be averaged in each test section to be able to make direct comparisons of rutting performance. Quantitative comparisons between test sections will be made using a two-sample t-test to evaluate the statistical significance of any differences in the mean rut depth over time.

The proposed test sections will be monitored to provide an assessment of performance in terms of pavement rutting. Information from these test sections will provide a measure of the additional structural life (TBR) achieved when a stabilization geotextile is placed for construction purposes. The spreadsheet design model developed by Perkins (2001a) will be used for the test sections constructed to comment on the ability of the model to predict performance as measured by TBR. This piece of software will also be updated to operate within Office 16 as a xlsx/xlsm format.

A cost/benefit analysis will be conducted using the results obtained and cost information provided by MDT. The results of this analysis will be included in the Performance Measures report.

### **Task 5 – Reporting**

A comprehensive final report that includes all data, analyses and recommendations will be written in conformance with MDT’s standard research report format to thoroughly document the findings of this project. The report will be concise and include all pertinent information to aid state MDT in adopting an efficient, effective, and reliable tool for geosynthetics used to reduce the thickness of the base course layer in flexible pavements. A draft report will be sent to the MDT Research Project Manager for review and comment. The results of the project will also be disseminated, as appropriate, to the professional community through presentations at various conferences and/or through journal papers. A four-page “Project Summary Report” will be written and submitted to the MDT Research Project Manager near the end of the project to summarize the background, methodology, results and recommendations of this research. After the final report is accepted, the Principal Investigator will formally present the methodology and findings of the project to all interested parties, including the Technical Panel. In conjunction with the final presentation, an implementation meeting will be held to discuss content to be placed in the Implementation Report. Following this meeting, an Implementation Report will be written to summarize how the researcher’s recommendations and MDT’s response as to how the recommendations will be implemented into practice. A “Performance Measures” report will be written to summarize the benefit of this research in terms of cost savings to the department.

Three task reports will be written during this project. Task Report 1 will summarize the literature review. Task Report 2 will describe test section planning and design. Task Report 3 will summarize the accelerated testing. Quarterly progress reports will be submitted to provide updates on the administrative aspects of the project, such as progress regarding the schedule and budget.

## **6 Products**

The products to be delivered during this project include the following items.

- Quarterly progress reports.
- Three task reports.
- A draft final report and executive summary describing the research methodology, findings, conclusions, and recommendations, followed by a final report addressing comments and suggestions from the Technical Panel.
- A four-page draft project summary report.
- An implementation report.
- A performance measures report.
- Excel spreadsheet program updated to operate within Office 16 as a xlsx/xlsm format
- An executive presentation to all interested parties and including the Technical Panel at the conclusion of the project.

## 7 Implementation

The results from this study can be directly implemented into future MDT highway construction designs having similar conditions to the test sections. These recommendations will pertain most directly to operational conditions where a stable construction platform is established over relatively weak subgrade when it is advantageous to reduce base course thickness in order to save both time and money. Designers will be able to use TBR values to design the reinforced road within the context of the AASHTO '93 pavement design.

## 8 Staffing

Dr. Steve Perkins will be the Principal Investigator and Mr. Eli Cuelho will be the co-Principal Investigator for this research project. As Principal Investigator, Dr. Perkins will be the primary manager and sole point of contact with the MDT project manager. Both Principal Investigators will be responsible for ensuring that the objectives of the study are accomplished, executing the project tasks, and preparing the final report.

The research team is well qualified, experienced and available to conduct this research, and, to the best of its ability, will deliver a high-quality finished product in a timely and efficient manner. The scope of work proposed for principal and professional members of the research team will not be changed without prior consent of the MDT Research Project Manager. The following paragraphs describe some of the qualifications and experience of key project personnel in addition to each person's role in this study. Additional information for key personnel can be found in Appendix A.

### **Dr. Steven Perkins, P.E.—Principal Investigator**

Dr. Steven Perkins is a Professor in the Civil Engineering Department at Montana State University and has over 25 years of experience working on projects related to geosynthetics and, in particular, projects related to geosynthetic reinforcement of pavements. Dr. Perkins has been the Principal Investigator of 10 research projects focused on aspects of reinforced pavements ranging from the measurement of field performance of reinforced pavements to the development of design methods. In these projects, work components have included the development of material testing methods and the use of instrumentation for the measurement of material response. Dr. Perkins has written over 40 articles, reports and book chapters and has given over 50 presentations related to geosynthetics. Dr. Perkins has been involved in the preparation of several synthesis reports for NCHRP and AASHTO on research and practice of geosynthetics in pavements. He has assisted with the development and delivery of several short courses and workshops on pavement design with geosynthetics sponsored by industry and agency groups and delivered to practicing engineers and DOTs.

As Principal Investigator, Dr. Perkins will participate in and provide oversight for all the components of this research project. He will meet with the Technical Panel at the various times

specified in the research plan, and will write and review the task reports and final report. Dr. Perkins will also be chiefly in charge of the analysis of the data collected from the test sections.

**Mr. Eli Cuelho, P.E.—Co-Principal Investigator**

Mr. Eli Cuelho is a Senior Engineer with TRI-Environmental, Inc. leading the Transportation Research, Testing and Services division. Mr. Cuelho is a licensed professional engineer in the state of Montana and is currently involved with a number of projects related to the design and testing of transportation infrastructure. He has over 20 years of experience on a variety of research topics including geotechnical engineering, geosynthetic design, pavement design and analysis, subgrade stabilization, cost-effectiveness and cost-benefit analyses, large-scale laboratory and field tests, and remote sensing and data acquisition equipment. Eli has extensive experience testing geosynthetic materials and is the chair of an ASTM task group dedicated to developing new test procedures for geosynthetics used as pavement and subgrade reinforcement. He also currently serves as an active member of the Geosynthetics committee at TRB.

Mr. Cuelho will be the Co-Principal Investigator, and will support the management needs of the project. He will be chiefly in charge of the construction, trafficking and monitoring of these test sections based on his related and extensive experience with full-scale laboratory experimentation. Finally, he will also provide assistance with the analysis of the data.

**Staff Hours and Availability**

It is anticipated that the proposed work associated with this research project will take 2,229 person hours to complete. The number of hours committed to the project by each person during this time period is shown in Table 3. Key personnel assigned to accomplish the work associated with this project are available throughout the duration of this project. In the event that the level of effort proposed for any member of the research team requires significant modification, written consent will be sought from the MDT Research Project Manager to justify and approve this change.

Name or Title	Role in Study	Task						Total
		0	1	2	3	4	5	
Steve Perkins (MSU)	Principal Investigator	160	40	40	40	180	240	700
Eli Cuelho (TRI)	Co-Principal Investigator	80	4	80	203	80	160	607
Jay Sprague (TRI)	Testing Lab Manager	0	0	0	248	0	0	248
Lab Tech 1 (TRI)	Lab Technician	0	0	0	311	0	0	311
Lab Tech 2 (TRI)	Lab Technician	0	0	0	304	0	0	304
Jeralyn Brodowy (WTI)	Administration	60	0	0	0	0	0	60
<b>Total</b>		<b>300</b>	<b>44</b>	<b>120</b>	<b>1105</b>	<b>260</b>	<b>400</b>	<b>2,229</b>

**Table 3: Summary of WTI Staff Person Hours by Task**

## 9 Facilities

The Western Transportation Institute (WTI) is a university-based research center focusing on rural transportation issues. The Institute was established in 1994 by the Montana and California departments of transportation, in cooperation with Montana State University–Bozeman. WTI is part of the College of Engineering at MSU and has an extensive multidisciplinary research staff of professionals, students, and associated faculty from the fields of engineering (civil-mechanical-industrial-electrical), computer science, psychology, fish and wildlife, business, biology and economics.

WTI has an annual budget of approximately \$7 million, which is obtained from a diverse sponsor base including many state departments of transportation, the U.S. Department of Transportation, and other federal agencies such as the National Science Foundation, Department of Homeland Security, Transportation Research Board, National Park Service, and the Forest Service. WTI also receives funding from private foundations, Parks Canada and several private companies.

WTI integrates expertise from six research areas: Road Ecology, Safety and Operations, Winter Maintenance and Effects, Logistics and Freight Management, Mobility and Public Transportation, and Transportation Planning and Economics. Additional information on WTI can be obtained from our web site at [www.WesternTransportationInstitute.org](http://www.WesternTransportationInstitute.org).

WTI is partnering with TRI-Environmental, Inc. (TRI) to conduct the full-scale testing. TRI is a full-service independent laboratory serving a variety of related polymer-centric industries around the world. TRI staff has a deep understanding of polymeric materials and the characteristics critical to performance. TRI tests, certifies, performs research, develops equipment and provides consulting on plastic materials used in civil, environmental and geotechnical engineering as well as protective clothing.

Materials including geomembranes, geosynthetic clay liners, geotextiles, geogrids, geocells, plastic pipe, rolled erosion control products, protective clothing, and more have been tested by TRI for over three decades. TRI also performs research, develops test equipment, develops standards and provides education for each of the industries it serves. TRI's personnel are active throughout the world's standards development organizations and routinely provide short courses, seminars and tailor-made training services.

TRI is unaffiliated with any manufacturer or engineering firm, and thus provides services to regulators, manufacturer, engineering firms, contractors and installers. Laboratories perform testing in accordance with ASTM, ISO, BS, DIN and GRI test methods. TRI is GAI-LAP Accredited and is an official provider of testing services to NTPEP, USACE, AASHTO and other government and regulatory agencies.

### **Laboratories and Equipment**

TRI's Transportation Research, Testing and Services Division is an internationally-recognized research, development and testing facility that focuses on providing high quality data to users, manufacturers, and researchers within the transportation sector. This unique program covers geotechnical, geosynthetic and pavements testing along a broad spectrum of project sizes and budgets – from bench-top to full scale roadways. TRI-Transportation is a multi-acre facility that includes an outdoor test track and extensive indoor laboratory space to do controlled, full-scale pavement simulations on a variety of roadway configurations and designs, creating an environment of virtually limitless possibilities. TRI's laboratory facilities can accommodate a wide variety of products/technologies, configurations, sizes, and environments to better answer questions related to product performance, system behavior, or innovative designs of transportation infrastructure.

The rolling wheel load test is being proposed as the method to determine traffic benefit from the use of geosynthetics. The test facility that will be used for this effort includes a concrete lined trench 4 ft. deep by 11 ft. wide that can simultaneously accommodate three 12 ft. long test sections. Trafficking will be applied using an automated rolling wheel load capable of applying up to 30 kips of force on dual-wheel semi tires. TRI has access to all the construction and testing equipment necessary to build and monitor the test associated with this project.

### **Information Services**

The PI regularly conducts literature and information gathering through the Carnegie Research Level 1 Library (Renne Library) on the MSU campus. In addition to an extensive collection of printed material, the library subscribes to dozens of databases and hundreds of refereed journals in print and electronic format. Specific items not accessible through these sources can be located and retrieved by the Interlibrary Loan service, which is affiliated with other research libraries across the United States. Typical sources used to aid literature searches include TRID (Transport Research International Documentation), E-Science Server, Transportation Research Board Research Records, Google Scholar, Google, and Montana Local Technical Assistance Program library.

### **Administrative Services**

The researchers at WTI are assisted by a highly qualified group of experienced support staff. Administrative staff members assist with budgeting, procurement, contracts, and accounting. Communications staff provides technical editing, layout, graphic design, and web page support. Information Technology staff maintains network servers and individual computers, software and hardware.



### WTI Salaries and Benefits

An itemization of salaries, benefit rates and total cost per person is provided in Table 6 for WTI staff. Percent time is calculated based on a 2,080 hour work-year.

**Table 6: WTI Staff Salary and Benefit Information**

<b>Staff Person</b>	<b>Hourly Rate</b>	<b>Benefit Rate</b>	<b>Total Hours</b>	<b>Total Cost</b>	<b>Percent Time</b>
Steve Perkins	\$65.64	20%	700	\$55,138	17%
Business Manager	\$41.55	35%	60	\$3,366	1%

### Testing Services (TRI)

The budget for testing services is to compensate TRI-Environmental, Inc. for conducting the rolling wheel load tests and providing the data to WTI for analysis. The total cost for this service is \$184,400, which includes all labor, supplies, construction materials acquisition, shipping, equipment rental costs, APT testing fees, instrumentation, and materials testing. A detailed itemization of these costs is provided in Table 7.

<b>Budget Item</b>	<b>Cost</b>
Labor	\$79,800
Eli Cuelho - Co-Principal Investigator	\$30,375
Jay Sprague - Testing Lab Manager	\$32,175
Lab Technician 1	\$9,960
Lab Technician 2	\$7,290
Expendable Supplies	\$8,856
Construction Materials Acquisition	\$32,921
Equipment Rental	\$8,323
APT Testing Fees	\$26,460
Instrumentation	\$21,793
Materials Testing	\$6,247
<b>Total</b>	<b>\$184,400</b>

**Table 7: Itemization of TRI Testing Services Costs**

### Travel

The travel budget will cover two trips to Helena at \$111 per trip, which includes vehicle rental, fuel, and per diem. Two trips to Helena are planned: one at the beginning of the project for the kick-off meeting and a second at the end of the project for the final presentation.

### **Contracted Services (TRI)**

Contracted services in the amount of \$60,600 are to cover sub-consultant fees for TRI-Environmental, Inc for Eli Cuelho's time to manage the project as Co-Principal Investigator, review documentation and task reports, develop the testing plan and design of experiments, assist with the analysis, and help write the final report (Tasks 0, 1, 2, 4 and 5). Mr. Cuelho's hourly rate is \$150/hr.

## **12 References**

- Amirkhanian, S., Xiao, F. and Corley, M., (2017) *Characterization of Asphalt Concrete Dynamic Modulus in South Carolina*, Report No. FHWA-SC-17-06, 612 p.
- Christensen, D.W., Pellinen, T.K., Bonaquist, R.F., (2003) "Hirsch Model for Estimating the Modulus of Asphalt Concrete," *Journal of the Association of Asphalt Paving Technologies*, Vol. 72, p. 97-121.
- Berg, R.R., Christopher, B.R. and Perkins, S.W., (2000) *Geosynthetic Reinforcement of the Aggregate Base/Subbase Courses of Flexible Pavement Structures – GMA White Paper II*, Geosynthetic Materials Association, Roseville, MN, USA, 176 p.
- Kim, Y.R., Underwood, B., Sakhaei Far, M., Jackson, N. and Puccinelli, J., (2011) *LTPP Computed Parameter: Dynamic Modulus*, Report No., FHWA-HRT-10-035, 263 p.
- Perkins, S.W., (2016) "Evaluation of a Finite Element Based Model for Base Reinforcement", *Proceedings of the 3rd Pan American Geosynthetics Conference and Exhibition GeoAmericas 2016*, Vol. 2, pp. 1850-1860, Miami, Florida.
- Perkins, S.W., Christopher, B.R., Cuelho, E.V., Eiksund, G.R., Hoff, I., Schwartz, C.W., Svanø, G., and Watn, A., (2004) *Development of Design Methods for Geosynthetic Reinforced Flexible Pavements*, U.S. Department of Transportation, Federal Highway Administration, Washington, DC, FHWA Report Reference Number DTFH61-01-X-00068, 263p.
- Perkins, S.W. (2002) *Evaluation of Geosynthetic Reinforced Flexible Pavement Systems Using Two Pavement Test Facilities*, U.S. Department of Transportation, Federal Highway Administration, Washington, DC, Report No. FHWA/MT-02-008/20040, 120 p.
- Perkins, S.W. (2001b) *Mechanistic-Empirical Modeling and Design Model Development of Geosynthetic Reinforced Flexible Pavements*, U.S. Department of Transportation, Federal Highway Administration, Washington, DC, Report No. FHWA/MT-01-002/99160-1, 170 p.
- Perkins, S.W. (2001a) *Numerical Modeling of Geosynthetic Reinforced Flexible Pavements*, U.S. Department of Transportation, Federal Highway Administration, Washington, DC, Report No. FHWA/MT-01-003/99160-2, 97 p.
- Perkins, S.W. (1999) *Geosynthetic Reinforcement of Flexible Pavements: Laboratory Based Pavement Test Sections*, U.S. Department of Transportation, Federal Highway Administration, Washington, DC, Report No. FHWA/MT-99/8106-1, 140 p.

## **Appendix A: Two-Page Résumés**

# STEVEN W. PERKINS, PhD, P.E.

Professor  
Civil Engineering Department  
Montana State University–Bozeman  
Bozeman, MT 59717  
(406) 994-6119  
stevep@montana.edu

## EDUCATION

Ph.D., Civil Engineering, University of Colorado, Boulder, 1991

M.S., Civil Engineering, University of Colorado, Boulder, 1985

B.S., Civil Engineering, Virginia Polytechnic Institute and State Univ., Blacksburg, Cum Laude

## PROFESSIONAL REGISTRATION

1993, Licensed Professional Engineer, State of Montana

## RELEVANT PROFESSIONAL EXPERIENCE

1991–Present Professor, Montana State University, Department of Civil Engineering, Bozeman, Montana

2007–2011 Co-Instructor, National Highway Institute, Short Courses on Geosynthetics Engineering Workshop and Geotechnical Aspects of Pavements

2006–2007 Visiting Research Engineer; Norwegian Geotechnical Institute (NGI), Oslo, Norway

1986–1988 Engineer; Kleinfelder and Associates, Geotechnical Engineers, Fairfield, California

## RELEVANT WORKSHOPS, SHORT COURSES, AND TRAINING PRESENTATIONS

"Design of Geosynthetic Reinforced Flexible Pavements", 1-day training course delivered to Montana Department of Transportation, May 30, 2017.

"Geosynthetics in Transportation Infrastructure Applications," A Half-Day Training Course for the Montana Department of Transportation, Bozeman, Montana, January 7–8, 2003.

"Design of Geosynthetic Reinforced Flexible Pavements Using the MSU-GRFP Design Model," Montana Department of Transportation, Helena, Montana, November 2002.

"Geosynthetics in Pavement Systems," Invited presentation at the Idaho Asphalt Conference, Moscow, Idaho, October 22, 2009.

Geosynthetics in Roadway Systems, Perkins, S.W., A Half-Day Workshop, Geosynthetics Conference 2009, Salt Lake City, Utah, February 27, 2009.

Geotechnical Aspects of Pavements, Berg, R.R., Perkins, S.W. and Schwartz, C.S., NHI short course, Columbus, OH, September 18-20, 2007.

Geosynthetics in Roadway Systems, Schwartz, C.S. and Perkins, S.W., Full-Day Workshop, Geosynthetics Conference 2007, Washington, DC, USA, January 18, 2007.

Pavement Design with Geosynthetics, Christopher, B.R., Berg, R.R. and Perkins, S.W., Full-Day Workshop, Geosynthetics Conference 2001, Portland, OR, USA, February 11, 2001.

Workshop on Flexible Pavement Design, Invited Feature Speaker, Lund Institute of Technology, Lund Sweden, March 2004.

New Trends in Pavement Structures, Invited Participant, Fourth International Conference and Exhibition on Road and Airfield Pavement Technology, Kunming China, April 2002.

## **RELEVANT TEACHING EXPERIENCE**

ETCC 302 Soils and Foundations

ECIV 320 Geotechnical Engineering

ECIV451 Highway Pavements

## **RELEVANT PUBLICATIONS**

"Evaluation of a Finite Element Based Model for Base Reinforcement", Perkins, S.W., Proceedings of the 3rd Pan American Geosynthetics Conference and Exhibition GeoAmericas 2016, Vol. 2, pp. 1850-1860, Miami, Florida, 2016.

Synthesis of Warm Mix Asphalt Paving Strategies for Use in Montana Highway Construction, Perkins, S.W., Montana Department of Transportation, U.S. Department of Transportation, Federal Highway Administration, Washington, DC, Report No. FHWA/MT-09-009/8117-38, 209 p., November, 2009

Geosynthetic Reinforcement of the Aggregate Base/Subbase Courses of Flexible Pavement Structures – GMA White Paper II, Berg, R.R., Christopher, B.R. and Perkins, S.W., Geosynthetic Materials Association, Roseville, MN, USA, 176 p., 2000.

"A Mechanistic-Empirical Model for Base-Reinforced Flexible Pavements," Perkins, S.W., Christopher, B.R., Cuelho, E.V., Eiksund, G.R., Schwartz, C.S. and Svanø, G., International Journal of Pavement Engineering, Vol. 10, No. 2, pp. 101-114, 2009.

"Mechanistic-Empirical Design Model Predictions for Base-Reinforced Pavements," Perkins, S.W. and Cuelho, E.V., Transportation Research Record 1989, Transportation Research Board, National Research Council, Low-Volume Roads, Vol. 2, pp. 121-128, 2007.

"Evaluation of Base-Reinforced Pavements Using a Heavy Vehicle Simulator," Perkins, S.W. and Cortez, E.R., Geosynthetics International, Vol. 12, No. 2, pp. 86-98, 2005.

"Pore Water Pressure Influence on Geosynthetic Stabilized Subgrade Performance," Christopher, B.R., Perkins, S.W., Lacina, B.A. and Marr, W.A., Proceedings of the Conference Geosynthetics 2009, Salt Lake City, Utah, USA, 2009.

"Field Construction and Trafficking of an Unsurfaced Geosynthetic-Stabilized Road," Cuelho, E.V., Perkins, S.W., Hauck, J., Akin, M.R. and von Maubeuge, K., Proceedings of the Conference Geosynthetics 2009, Salt Lake City, Utah, USA, 2009.

# ELI V. CUELHO, P.E.

Senior Engineer  
TRI-Environmental, Inc.  
Transportation Research, Testing and Services Division  
Austin, TX 78733  
(406) 600-3947  
ecuelho@tri-env.com

## EDUCATION

1998, Master's of Science in Civil Engineering, Montana State University – Bozeman  
1995, Bachelor's of Science in Civil Engineering, Montana State University – Bozeman

## PROFESSIONAL REGISTRATION

2002, Professional Engineering License, State of Montana

## PROFESSIONAL AFFILIATIONS

2000–present International Geosynthetics Society (IGS)  
2001–present American Society of Civil Engineers (ASCE)  
2005–present American Society for Testing and Materials (ASTM)  
2006–present Transportation Research Board Committee Member – Committee on Geosynthetics (AFS70)

## PROFESSIONAL EXPERIENCE

2017–present Senior Engineer, TRI-Environmental, Inc., Austin, TX  
1998–2017 Research Engineer, Western Transportation Institute, Montana State University – Bozeman  
2015–2017 Adjunct Instructor, Civil Engineering Department, Montana State University – Bozeman  
2006–2007 Adjunct Instructor, Civil Engineering Department, Montana State University – Bozeman  
1995–1998 Research Assistant, Civil Engineering Department, Montana State University – Bozeman  
Summer 1995 Research Aide, Western Transportation Institute, Montana State University – Bozeman

## RELEVANT PROJECT EXPERIENCE

**Validation of Polyester Concrete Rehabilitation Strategy to Extend the Service Life of Concrete Bridge Decks**, Eli Cuelho – PI with Jerry Stephens, Caltrans, \$157,565, July 2013 to June 2016.

**Unstable Slope Management Program for Federal Land Management Agencies: Phase II**, Eli Cuelho – PI, Western Federal Lands Highway Division, \$315,898, September 2014 to December 2017.

**Deep Patch, Phase II – Design Validation**, Eli Cuelho – PI with Steve Perkins, Western Federal Lands Highway Division, \$182,600, September 2012 to June 2016.

**Deep Patch, Phase III – Field Instrumentation**, Eli Cuelho – PI, Western Federal Lands Highway Division, \$64,000, August 2014 to April 2016.

**Development of a ¾-Inch Minus Base Course Type A Specification for Montana**, Eli Cuelho – PI, Montana Department of Transportation, \$95,155, January 2015 to August 2016.

**Mitigation of Expansive Soils in South Dakota**, Eli Cuelho – PI with Michelle Akin, South Dakota Department of Transportation, \$80,000, April 2015 to October 2016.

**Relative Operational Performance of Geosynthetics Used as Subgrade Stabilization**, Eli Cuelho – PI with Steve Perkins, Montana Department of Transportation – Pooled Fund Study, \$598,469, December 2011 to July 2014.

**Validation of Rehabilitation Strategies to Extend the Service Life of Concrete Bridge Decks**, Eli Cuelho – PI with Jerry Stephens, Caltrans and the Western Transportation Institute, \$619,339, July 2008 to June 2013.

**Geosynthetic Design Guidelines and Construction Specifications Review and Update**, Eli Cuelho – PI with Steve Perkins, Alaska Department of Transportation and Public Facilities, \$70,000, June 2011 to December 2012.

**Geosynthetic Biaxial Testing Machine Design and Protocol Development**, Eli Cuelho – PI, Propex Geosynthetics, \$20,000, November 2011 to August 2012.

**Developing a Standard Test Method for Measuring Geosynthetic-Soil Resilient Interface Shear Stiffness**, Eli Cuelho – PI with Steve Perkins, the Western Transportation Institute, \$46,760, June 2007 to September 2010.

## RELEVANT PUBLICATIONS

- Cuelho, E.V. and Perkins, S. (2015) “Field Performance of Geosynthetics Used as Subgrade Stabilization,” Proceedings: Geosynthetics 2015 Conference, Portland, Oregon.
- Cuelho, Eli and Perkins, Steve. “Field Investigation of Geosynthetics Used for Subgrade Stabilization,” Final report to the Montana Department of Transportation, FHWA/MT-09-003/8193, July 2009.
- Cuelho, Eli; Mokwa, Robert and Obert, Keely. “Comparative Analysis of Coarse Surfacing Aggregate Using Micro-Deval, L.A. Abrasion and Sodium Sulfate Soundness Tests,” Final report to the Montana Department of Transportation, FHWA/MT-06-016/8117-27, January 2007.
- Cuelho, Eli; Mokwa, Robert and Akin, Michelle. “Preventive Maintenance Treatments of Flexible Pavements: A Synthesis of Highway Practice,” Final report to the Montana Department of Transportation, FHWA/MT-06-009/8117-26, October 2006.
- Cuelho, Eli; Smolenski, Peter; Stephens, Jerry and Johnson, Jeff. “Evaluating Concrete Bridge Deck Performance – Final Project Report,” Final report to the Montana Department of Transportation, FHWA/MT-06-006/8156-002, June 2006.
- Perkins, S. W., Christopher, B. R., Cuelho, E. L., Eiksund, G. R., Schwartz, C. S. and Svanø, G. (2009) “A mechanistic-empirical model for base-reinforced flexible pavements,” International Journal of Pavement Engineering, 10:2, 101-114.
- Cuelho, E.V., S.W. Perkins, J. Hauck, M.R. Akin and K. von Maubeuge (2009) “Field Construction and Trafficking of an Unsurfaced Geosynthetic-Stabilized Road,” Proceedings: Geosynthetics 2009 Conference, Salt Lake City, Utah.
- Christopher, B.R.; E.V. Cuelho and S.W. Perkins, (2008) “Development of Geogrid Junction Strength Requirements for Reinforced Roadway Base Design,” Proceedings: Geoamericas 2008 Conference, Cancun, Mexico.
- Cuelho, E.V.; B. Mokwa, K. Obert and A. Miller, (2008) “Comparative Analysis of Micro-Deval, L.A. Abrasion and Sulfate Soundness Tests,” Proceedings of the Transportation Research Board 2008 Annual Conference, Washington, D.C.
- Mokwa, B.; E. Cuelho and M. Browne (2008) “Laboratory Testing of Soil Using the Superpave Gyratory Compactor,” Proceedings of the Transportation Research Board 2008 Annual Conference, Washington, D.C.
- Perkins, S. W. and E. V. Cuelho, (2005) “Comparison of a Mechanistic-Empirical Design Model to Measured Performance for Base-Reinforced Pavements,” Proceedings, NAGS 2005/ GRI 19 Conference, Las Vegas, NV.
- Perkins, S.W., Ismeik, M., Cuelho, E.V., Fogelson, M. and Wang, Y. (1998), “Geosynthetic-Reinforced Pavements: Overview and Preliminary Results,” Proceedings: 6th International Conference on Geosynthetics, Vol. 2, Atlanta, Georgia, pp. 951-958.
- Cuelho, Eli (1998), “Determination of Geosynthetic Constitutive Parameters and Soil/Geosynthetic Interaction by In-Air and In-Soil Experiments,” M.S. Thesis, Montana State University – Bozeman.