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Project Title

Enhancing the Resiliency of Pavement Infrastructure Built on Sulfate-Rich Expansive Soil Subjected to Climate Change

University

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Research Needs

Flexible pavement systems lie over a wide range of soil and terrain conditions and typically involve a foundation comprised of compacted granular material overlying compacted subgrade soil. While multiple failure modes may occur, the design of flexible pavement is primarily governed by fatigue cracking at the bottom of the surface layer and rutting failure from deformation at the top of the subgrade layer [1–3]. The 1993 and 1998 AASHTO guides for design of pavement structures and the AASHTO Mechanistic-Empirical Pavement Design Guide (M-EPDG) in 2004 recommend the use of resilient modulus for characterizing the subsoils [4–6]. Resilient modulus of the subsoil is thus a key design parameter for flexible pavement systems.

The resilient modulus (M_R) of a material is defined as the ratio of applied deviator stress (σ_d) to recoverable, elastic, or resilient strain (ε_r) from a repeated loading and unloading cycle of deviator stress [7]. Repeated load triaxial (RLT) testing is designed to simulate stress induced by traffic loading on base layer and subgrade material by applying a predefined cyclic loading sequence at different confining stresses that simulate the in-situ overburden pressure [5]. Significant research has been conducted on factors affecting M_R of soils. However, some essential factors have not been as comprehensively evaluated. Subgrades often exist in varying suction and corresponding moisture conditions resulting from diurnal and seasonal variations of temperature and precipitation. There have been issues due to the presence of expansive soils in pavement sections, as these soils undergo significant volume changes with varying soil suction states [8–11].

There is a need to analyze the behavior of the soil typically found in Region 8 which is derived from the Pierre shale formation. Fig. 1 shows the extent of presence of expansive soil in Region

8. Traditionally, subgrades in the region are typically stabilized using lime. However, there have been reports of issues from the local contractors that in some places the traditional stabilization techniques result in lower than expected strength and higher pavement distresses in the form of rutting.

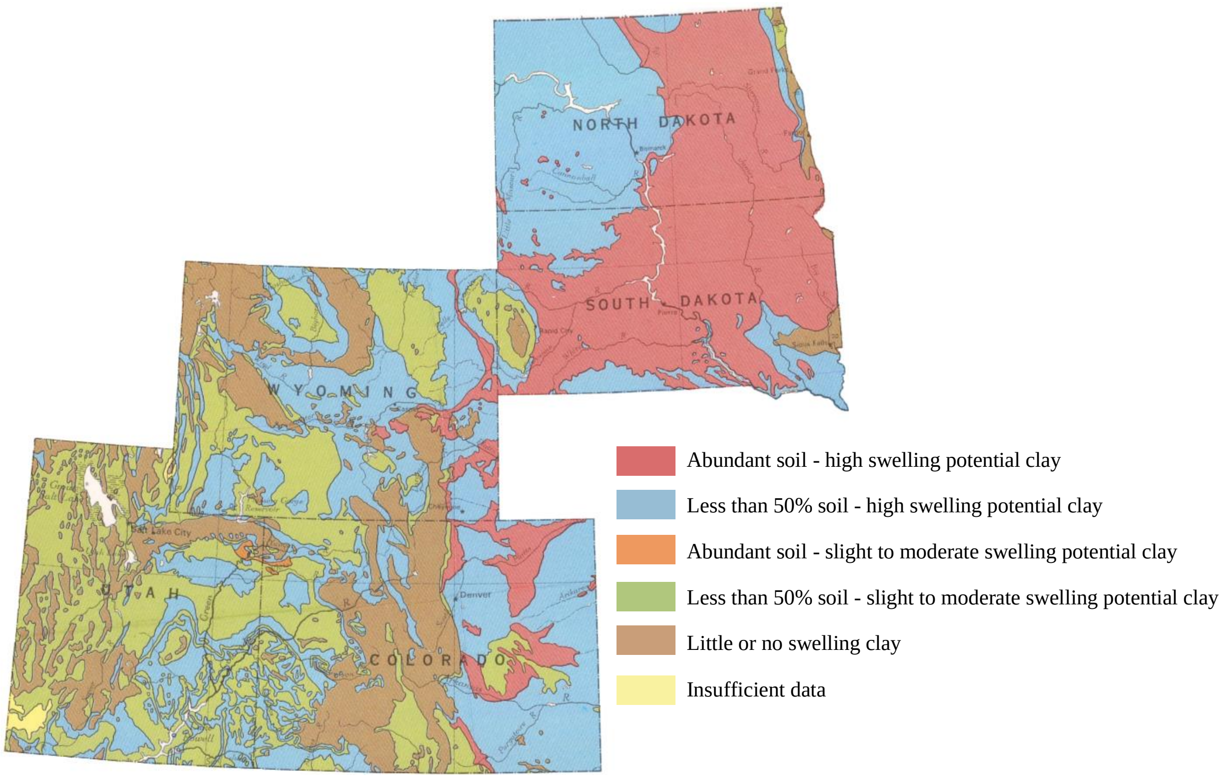


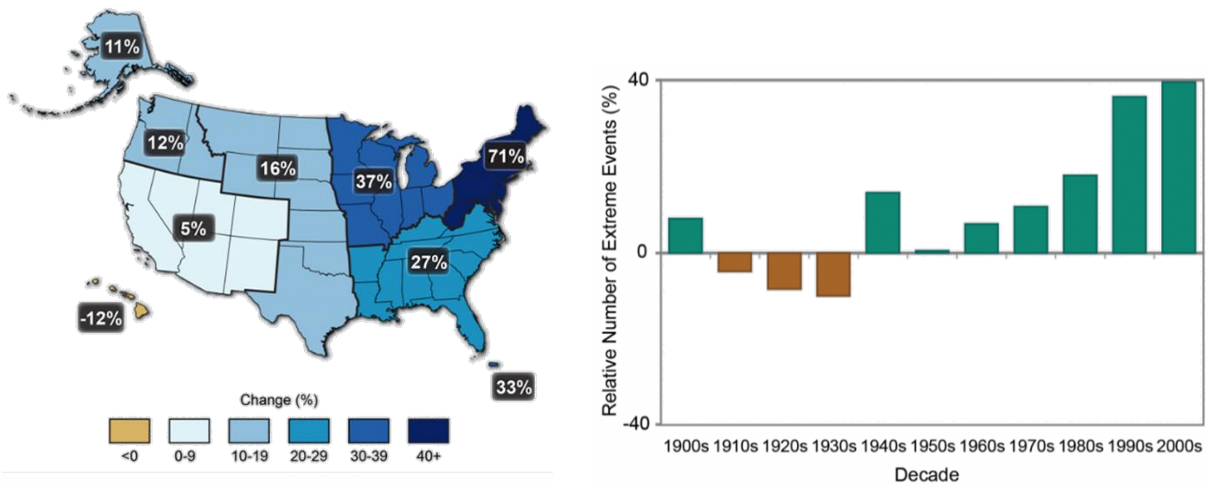
Fig. 1. Map of presence of expansive soils in Region 8 (modified from USGS 1989 (USGS))

Calcium-based stabilizers like lime and cement have been known to be counterproductive for stabilizing sulfate-rich soils like the clayey soils from the Pierre shale formation. It is known that the soils derived from Pierre shale have layers of gypsum, which is a rich source of sulfate as evidenced by a few local soil samples on the western part of the state. The layers of gypsum may cause local issues as they might not be well-distributed in the soil, as in the case of samples used in the laboratory. The calcium from stabilizers reacts with alumina and sulfate from such soils to form ettringite and thaumasite in presence of water. These are highly expansive minerals and have known to cause significant issues in different parts of the US due to its swell-shrink properties. This phenomenon is termed as “sulfate-induced heave” [12–17]. As more roads will be built on or near Pierre shale formation and with the effects of extreme weather conditions, the state agencies in Region 8 and contractors may start to face this problem on a regular basis.

In the life cycle of the pavement, the subgrade that may consist of expansive soil in native or treated form may undergo repeated cycles of swelling during heavy precipitation and later may be subjected to drought-like conditions wherein the subgrade may develop cracks. Eventually these cracks allow free movement of water and during winter may freeze and expand and cause severe distress to the pavement. During the life cycle of the pavement, such multiple cycles of wetting and drying along with freeze-thaw conditions may result in more frequent maintenance.

If proper soil characterization is performed by evaluating the mechanical properties such as strength, stiffness, and resilient modulus and volumetric properties, such as those obtained from swell-shrink tests, the confidence on the design parameters will be higher. Upon implementation, this will result in more resilient pavement infrastructure in the region.

The effect of climate change on civil infrastructure has gained traction with each passing year [18]. There have been numerous studies that have predicted the influence of carbon emission on the climatic changes in the near future. The climate change is predicted to cause drought or excess precipitation in some areas (Fig. 2a); however, it is scientifically expected that the peak precipitation and storm intensity will increase in most regions [18]. Most of Region 8 and surrounding areas is expected to have almost 16% more rainfall on an average (Fig. 2a; Due to issues of climate change where extreme weather conditions, such as drought followed by extreme precipitation is expected to be more frequent in future, as evidenced in the data over the last century (Fig. 2b), the change in moisture regime can severely affect the pavement infrastructure in the region. Therefore, there is a need to characterize the behavior of sulfate-rich expansive soils in both native and stabilized forms with even more urgency.



(a) (b)

Fig. 2. Effect of climate change on precipitation. (a.) The percent increase in the amount of precipitation falling in very heavy events (defined as the top 1% of all daily events) from 1958 to 2012. (b.) Relative frequency of once-in-five-year precipitation events falling over a 2-day period, averaged over the continental U.S, 1901-2012. [18]

Research Objectives

The objectives of the proposed study are as follows:

1. Assemble an integrated suction-controlled repeated load triaxial setup that can determine the resilient modulus and the shear strength of saturated and unsaturated soils, including expansive soils.

2. Evaluate the behavior of native and treated sulfate-rich expansive soil that is imperative for designing pavement sections by determining the variation of resilient modulus with moisture content.

3. Establish the volumetric changes expected with wetting and drying of native and treated sulfate-rich expansive soils.

4. Recommend design guidelines for stabilizing sulfate-rich expansive soils for enhancing the performance of pavement structure that may include using new stabilization procedures.

Overall, the objectives of the proposed study are to characterize the behavior of sulfate-rich expansive soils and identify ways in which such soil can be stabilized to develop a resilient pavement infrastructure. All the objectives are measurable and at the conclusion of the project the success of each of these objectives will be identified.

Research Methods

The proposed study involves various aspects of soil characterization, stabilization, mechanical testing, and innovative stabilization procedure. The characterization of soil will be firstly involve setting up an integrated repeated load triaxial (RLT) system that is capable of determining the resilient modulus of soil in suction-controlled or suction-equilibrated condition (Fig. 3). This technique has been observed to enhance the repeatability of RLT testing of unsaturated soils [19]. For RLT testing, the loading sequence will be applied in accordance to AASHTO T-307 [20] where confining pressure will be replaced by mean net confining stress. The suction will be controlled using axis-translation technique.

State DOTs and local companies in the region will be contacted to identify the specific regions where high sulfate content and expansive soils has been encountered. The soil samples obtained from the site will be tested in the laboratory to determine the swell-shrink properties and their sulfate content. Subsequently the tests will be performed on a few select soils that are deemed to be highly problematic in the region. If high quantity of the same soil is not obtained, then the sulfate content of an expansive soil could be varied by adding laboratory-grade gypsum ($CaSO_4 \cdot 2H_2O$). The optimum dosages of calcium-based stabilizers will be determined by using the Eades and Grim test using the pH of soil as parameter [21]. The strength of the soil will be evaluated using unconfined compressive strength (UCS) test and suction-controlled consolidated drained and undrained tests under CTC stress path using axis translation technique [22]. The suction-controlled CD and CU triaxial will aid in determining the strength of the expansive soil which are required to evaluate the stability of embankments housing transportation infrastructure, like those for bridges and pavement sections.

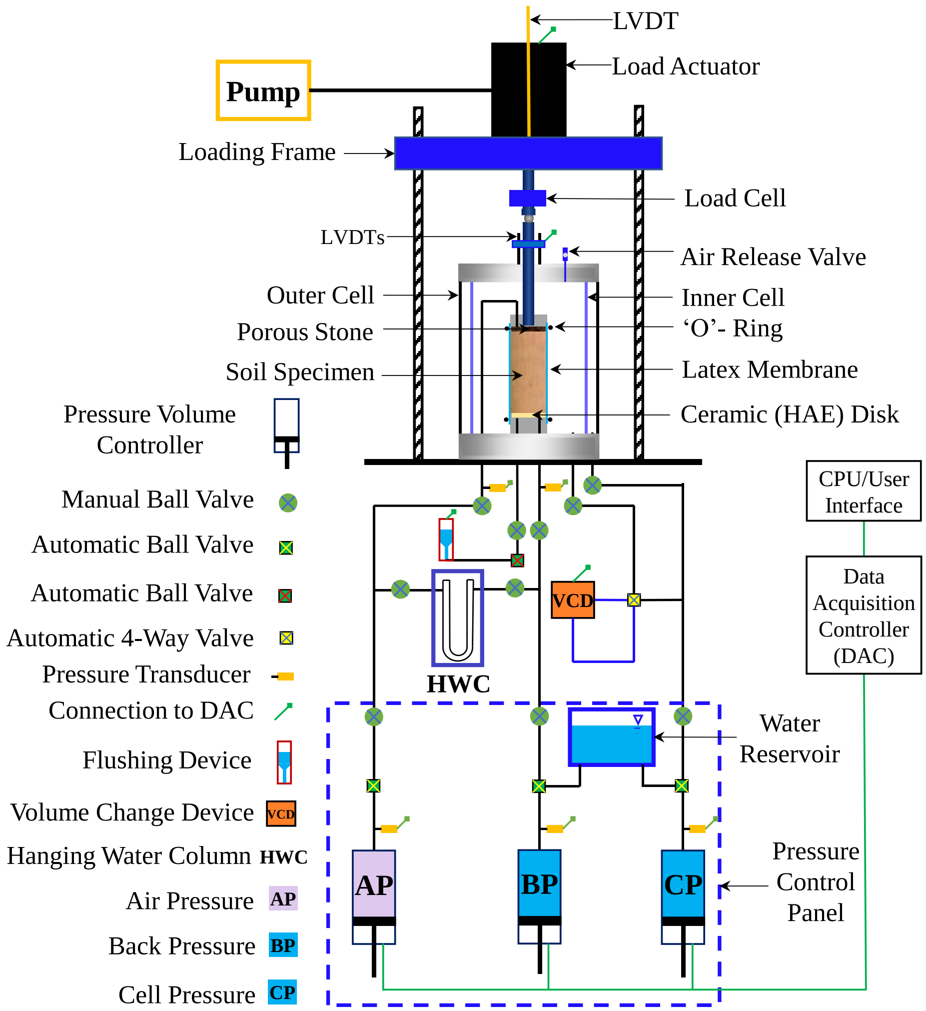


Figure 3. Schematic layout of the setup for conducting suction-controlled RLT tests on soils using axis-translation technique

Expected Outcomes

The proposed study is expected to provide a better understanding of the variation of resilient modulus and shear strength of sulfate-rich expansive soils. Guidelines will assist the practitioners in estimating the resilient modulus and shear strength of such soil with sulfate content and moisture content. This will help in designing pavement systems in the region with more confidence and will be more resilient during repeated wetting and drying cycles and freeze-thaw cycles. This would be first study for the soils in this region where the resilient modulus has been evaluated using the more repeatable RLT testing. If required a change in the procedure followed to stabilize sulfate-rich soils using calcium-based stabilizer will be identified and guidelines will be provided to handle such problems.

The experimental data will help in the development of more accurate prediction models based on the already existing models [23–28] for soils in the region and the variation of resilient modulus with different moisture contents may be predicted without going through a rigorous experimental plan. This will help to lower the cost of experimental program required before designing pavement systems on sulfate-rich expansive soils. The pavement systems when designed based on the guidelines provided from the study will lead to lower maintenance costs and better ride quality over the life of the pavement. Additional socio-economic and environmental benefits will be derived from the development of resilient pavement systems in the form of (a) lower man-hours lost due to traffic delays during the expected lower number of maintenance and pavement rehabilitation, (b) lesser environmental impact due to fewer maintenance programs, and (c) lower cost of maintenance of vehicles due to better pavement condition. The proposed project will help reduce the crack formation with the expansive subgrade due to moisture fluctuations. This will aid in mitigating issues faced during freeze-thaw cycles, where lesser volume of cracks means lower possibility of water accumulation and resulting pavement distress due to crack propagation after volume expansion of water upon freezing and crack exposure upon thawing. Overall life cycle cost of pavement infrastructure is expected to decrease.

The research findings will be disseminated among the practitioners and other researchers by means of journal publications and conference proceedings and presentations. At least one peer-reviewed journal article and one conference paper is expected from the findings of the proposed study.

Relevance to Strategic Goals

The expected outcomes of the proposed project are directly related to the strategic goals, such as State of Good Repair and Economic Competitiveness, which were identified by the FAST Act. From the proposed project, the enhanced material behavior response prediction when subjected to extreme climatic conditions like floods and drought-like conditions, will aid in the design of resilient pavements. This increased quality of the pavements that will cater to the conditions of Region 8 will result in better rehabilitated pavements that will have better ride quality for the users and increase the life of the pavement between repairs. Addressing the issues of sulfate-induced heave and effect of extreme climatic conditions will result in fewer maintenance activities during the life of the pavement. This will lead to higher savings and decreased user cost in the form of loss of time due to slower traffic during construction and less vehicle maintenance cost due to better ride quality. The life-cycle-cost analysis (LCCA) is expected to show significant savings over a typical pavement design life of 20 years thereby highlighting the economic competitiveness of the approach.

Educational Benefits

The proposed project would have immense educational benefits wherein both undergraduate and graduate students can learn about the issues faced by sulfate-rich expansive soils. The graduate student working on the project will eventually write a PhD dissertation on this topic. Undergraduate students will be hired and will be working along the graduate student, where he/she will learn the fundamentals of how experimental research is conducted. The PI (Banerjee) will be guiding the undergraduate researcher and ensure that he/she learns not only about soil mechanics and geotechnical testing but also about teamwork, planning, and work ethics. The findings from the study will be incorporated into new courses on Ground Improvement and Soil Behavior and Minerology that is planned to be offered to undergraduate and graduate students as a Technical Elective. The triaxial equipment will be used to demonstrate the working of traditional and advanced triaxial unit in the laboratory course for undergraduate students (CEE 346L: Geotechnical Engineering Lab). The graduate students will be offered a revised course on

CEE 749: Geotechnical Testing, where they will learn about RLT testing to determine resilient modulus and triaxial testing. The unsaturated triaxial setup will be used to demonstrate the experimental program in a new course on Unsaturated and Expansive Soils.

Overall, one undergraduate student and one graduate student will be working on the project and gain direct experience. The findings from the proposed project and equipment purchased through the project will be used to demonstrate laboratory sessions in CEE 346: Geotechnical Engineering and in advanced courses like CEE 749: Geotechnical Testing.

Technology Transfer

The project has been proposed based on the discussions at the SDDOT Research Ideas Workshop in October 2021. Various agencies and companies are interested in this topic. The findings of the proposed project will assist the SDDOT personnel and other stakeholders in Region 8. Research papers will be published, and presentations will be delivered at national conferences to disseminate the findings from the study as quickly and effectively as possible. The target conferences include the ASCE annual Geo-Congress and Transportation Research Board (TRB) Annual Meetings in Washington, DC. The latter has a broader participation and includes personnel from various universities, FHWA, various state DOTs, and private agencies. These presentations and classroom teaching will aid in building a stronger transportation workforce which is a major portion of MPC mission and vision.

Work Plan

Task 1: Construct testing facility and conduct calibration tests

The integrated suction-controlled RLT and triaxial setup will be assembled in the laboratory to create a state-of-the-art facility at SDSU. Setups for shrinkage tests and swell tests will be purchased and set up in the laboratory to compressively study the behavior of soil at varying weather conditions.

Task 2: Literature Review

Literature review will be conducted on variation of resilient modulus with moisture, suction and degree of saturation for various soil types. The stabilization of sulfate-rich expansive soils will be also conducted.

Task 3: Material selection

The appropriate soil will be procured after discussing with SDDOT and private agencies that have experienced problems while handling soils in specific locations. A redundancy will be kept where if large portions of the same sulfate-rich expansive soil is not obtained, any expansive soil can be selected and by adding gypsum and bentonite, the sulfate content and plasticity of the soil can be increased.

Task 4: Material characterization and selection of stabilizer dosage and curing period

A series of basic geotechnical testing including grain size distribution, Atterberg limit, and compaction curve determination will be conducted. The sulfate content will be measured. Using Eades and Grim pH test, the stabilizer like lime and its dosage will be selected. Pilot studies will be conducted to arrive at the most optimum curing period. Advanced test would include the determination of soil-water-characteristic curve (SWCC) for untreated and treated soils.

Task 5: Study the volumetric changes during swelling and shrinkage of untreated and treated soils

The volumetric changes during swelling and shrinkage will be determined using the 1D-swell test and shrinkage bar test to determine the effectiveness of soil stabilization. If sulfate-induced heave is observed, suitable mitigation measures will be used, and their efficacy verified.

Task 6: Study of shear strength of untreated and treated soil and its variation with moisture

A series of suction-controlled monotonic consolidated undrained or drained tests will be conducted on untreated and treated soils to determine the variation of strength with confining pressure, moisture content and suction. Unconfined compressive strength will be conducted on both untreated and treated soils to establish the increase in strength due to stabilization and any measures taken to mitigate sulfate-induced-heave.

Task 7: Study the variation of resilient modulus of untreated and treated soil with moisture

A series of suction-equilibrated repeated-load-triaxial (RLT) tests will be conducted to determine the variation of resilient modulus with moisture content and suction. Similar series of tests will be conducted on stabilized soils. This will aid in designing pavement systems as per AASHTO MEPDG.

Task 8: Analyze test results, summarize findings, and report findings

Compare the experimental results to evaluate the effectiveness of soil stabilizer and sulfate-induced heave mitigation procedure. Develop guidelines to aid the pavement design procedure where sulfate-rich expansive soils are used as subgrade. Finally, the findings will be summarized, and a final report will be prepared.

Task 9: Outreach and technology transfer initiatives

The research findings will be disseminated by publishing them in journals and conference proceedings. The findings will be shared with the research division of SDDOT and other private agencies who are interested in the solution so that it can be implemented in the field as soon as possible. The primarily form of dissemination among a wider audience will be aimed by presenting the findings at the Transportation Research Board (TRB) Annual Meetings in Washington, DC which is attended by more than 13,000 people and also at the annual ASCE Geo-Congress. The findings will be incorporated within the course work to train current and future transportation workforce.

Table 1 Time Schedule of Tasks

TASK YEAR/ MONTH	YEAR 1												YEAR 2											
	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
1. Construct testing facility and conduct calibration tests	■	■	■	■	■	■	■	■	■															
2. Literature review	■	■	■																					
3. Material selection		■	■	■	■	■	■	■	■															
4. Material characterization and selection of stabilizer dosage and curing period					■	■	■	■	■	■	■	■	■	■										
5. Study the volumetric changes during swelling and shrinkage of untreated and treated soils						■	■	■	■	■	■	■												
6. Study of shear strength of untreated and treated soil and its variation with moisture								■	■	■	■	■	■	■	■	■	■	■	■	■				
7. Study the variation of resilient modulus of untreated and treated soil with moisture									■	■	■	■	■	■	■	■	■	■	■	■	■	■		
8. Analyze test results, summarize findings, and report findings																	■	■	■	■	■	■	■	■
9. Outreach and technology transfer initiatives																			■	■	■	■	■	■

Project Cost

Total Project Costs: $310,527
MPC Funds Requested: $151,404
Matching Funds: $159,123
Source of Matching Funds: South Dakota State University

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