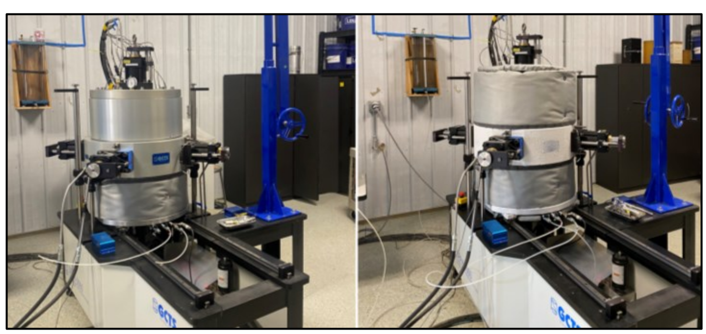
Advanced Testing and Characterization of Iowa Soils and Geomaterials

tech transfer summary

This project evaluated the fundamental cross-anisotropic mechanical properties of ten Iowa soils and geomaterials collected from various sources in Iowa along with evaluation of the freeze-thaw effect on these properties.

Objectives

- Evaluating the cross-anisotropic stiffness characteristics of Iowa soils and geomaterials through advanced cyclic true triaxial tests.
- Evaluating the cross-anisotropic permanent deformation characteristics of Iowa soils and geomaterials through advanced cyclic true triaxial tests.
- Determining the effect of freeze-thaw action on stiffness and permanent deformation of geomaterials under field similar stress states through advanced cyclic true triaxial test setup.
- Determining the effect of fine content on the freeze-thaw performance of geomaterials.



Advanced cyclic true triaxial equipment: prismatic testing and freeze-thaw testing

MICHIGAN STATE UNIVERSITY

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RESEARCH PROJECT TITLE

Advanced Testing and Characterization of Iowa Soils and Geomaterials

SPONSORS

Iowa Department of Transportation
Iowa Highway Research Board
(IHRB Project TR-780)

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Background

The structural performance of the roadway systems is strongly dependent on the foundation layers (i.e., base, subbase, and subgrade) and their properties. These layers serve as a support system to the overlaying asphalt or concrete layers that are constantly exposed to traffic loading so their properties play an important role in determining the longevity and overall performance of the pavement systems.

To ensure reliable pavement performance predictions, the complex behavior of geomaterials under traffic loading necessitates specialized tools like advanced laboratory testing systems.

Damages to the flexible pavements due to weak geomaterial and soil characterizations

Problem Statement

Most pavement designs and road infrastructure performance predictions are made based on the laboratory characterization of the materials that are used during pavement construction. However, these designs made with material properties tested with standard test methodologies do not typically fulfill their predicted service life and often require early and more frequent maintenance practices. Moreover, the field and laboratory performance of pavement materials do not usually agree well with each other. The main reason for these problems is the standard test methods used to characterize the strength and stiffness of materials used in pavement designs. Standard testing methods do not incorporate the anisotropic behavior and stress dependency of materials and do not simulate climate conditions (cold and hot temperatures) on materials.

In this project, advanced cyclic true triaxial equipment was employed to replicate field stress conditions and assess the cross-anisotropic mechanical properties of geomaterials, while also examining their freeze-thaw performance under stress states mimicking field conditions using the environmental chamber feature of the testing equipment.

Damages to the rigid pavements due to weak geomaterial and soil characterizations

Materials

Ten materials (Ames Mine, Bethany Falls Limestone, Crocker Pit, Oneota Formation Dolomite, Plano Quarry, Weber Quarry, Shambaugh Quarry, Stone City Quarry, Pottawattamie County CBIS (Council Bluffs Interstate System), Plymouth County (95) sourced from various regions of Iowa were gathered.

Examples of the tested soils and geomaterials

Research Description

The comprehensive experimental program was designed to characterize the cross-anisotropic stiffness and permanent deformation characteristics of Iowa base, subbase, and subgrade materials under field-similar stress states and environmental conditions.

- ***Standard Mechanical Characterization of Geomaterials:*** Cylindrical specimens (6 inches by 12 inches) were prepared to be tested through conventional testing methods for standard characterization. Model parameters of the commonly adopted model developed by Mossadegh and Witczak (1981) were determined for the tested materials.
- ***Advanced Mechanical Characterization of Geomaterials:*** Prismatic specimens (6 inches by 6 inches by 12 inches) were prepared to investigate the cross-anisotropic stiffness and permanent deformation characteristics. To this end, stiffness and permanent deformation tests were performed in both vertical (standard) and horizontal directions. The effect of the stress history in addition to stress dependency was investigated. Moreover, cross-anisotropy under a moving wheel load was evaluated by conducting stress path sweep tests.
- ***Evaluation of Actual Freeze-Thaw Performance of Geomaterials:*** The effect of freeze-thaw on the stiffness of base material (Ames Mine) with increasing fines content was investigated. The environmental chamber feature of the testing equipment allowed for the replication of field stress conditions in the laboratory during the freeze-thaw process, and it also facilitated the collection of heave and settlement data throughout this phase.

Cylindrical specimen

Prismatic specimen

Prismatic specimen in the testing chamber

Key Findings

- All six base materials were classified as well-graded (GW) and A-1-a, according to the USCS and AASHTO, respectively.
- The two subbase materials were classified as poorly graded (GP) and A-1-a, according to the USCS and AASHTO, respectively.

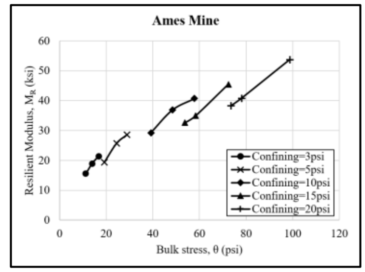
- CBIS, the subgrade, was classified as silty sand (SM) and A-2-4, according to the USCS and AASHTO, respectively. Meanwhile, Plymouth was classified as low plasticity silt (ML) and A-6, according to the USCS and AASHTO, respectively

According to standard mechanical characterization test results:

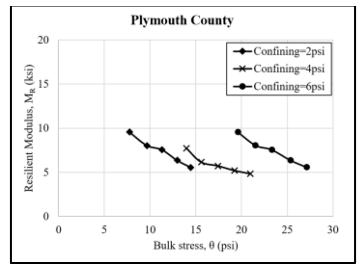
- The interlocking mechanism in granular materials contributed significantly to base materials' stiffness.
- Base materials exhibited the highest stiffness (10-54 ksi), while subgrade materials had the lowest stiffness (4-12 ksi). Subgrade materials had low stiffness due to their lack of internal structural capacity.
- Subbase materials had higher stiffness (15-45 ksi) compared to subgrade due to granular particle size distribution.
- Unbound materials demonstrated stress-dependent behavior for confining and cyclic pressure. Stress dependency in base, subbase, and subgrade materials was nonlinear, impacting stiffness variations.
- Moossazadeh and Witczak (1981) model was used to determine model constants (k_1, k_2) and R^2. The observations revealed that the values of k_1 ranged from 2.75 to 6.49, while the values of k_2 ranged between 0.36 and 0.55. Additionally, the R^2 values were observed to fall within the range of 0.93 to 0.99.

According to advanced mechanical characterization test results:

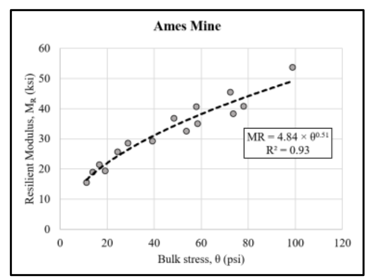
- Ames Mine exhibited nonlinear stress-dependent characteristics in all directions: vertical z-axis, horizontal x-axis, and horizontal y-axis. The vertical direction displayed the highest stiffness values (24-90 ksi), while the other two horizontal directions showed similar stiffness values, ranging between 3-22 ksi for the horizontal x-axis and 3-21 ksi for the horizontal y-axis.
- Crocker Pit displayed nonlinear stress-dependent characteristics in all directions: z-axis, x-axis, and y-axis. The vertical direction had the highest stiffness values (17-59 ksi), while the other two horizontal directions exhibited similar stiffness values, ranging between 3-18 ksi for the x-axis and 3-16 ksi for the y-axis.



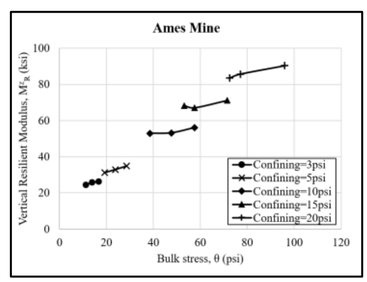
Resilient modulus of Ames Mine varying with bulk stress



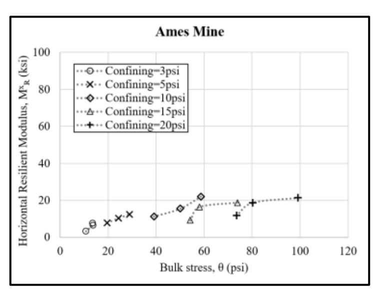
Resilient modulus of Plymouth County varying with bulk stress



Resilient modulus of Ames Mine with fitted bulk stress model

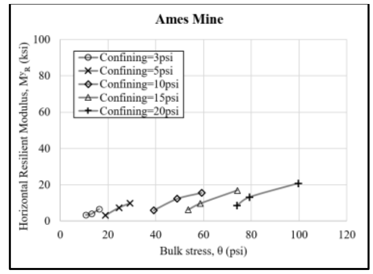


Vertical z-axis resilient modulus of Ames Mine varying with bulk stress



Horizontal x-axis resilient modulus of Ames Mine varying with bulk stress

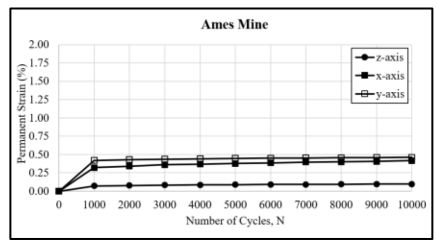
- Shambaugh Quarry, similar to the base material, exhibited nonlinear stress-dependent characteristics in all directions: z-axis, x-axis, and y-axis. In line with other results, the highest stiffness values were observed vertically, ranging between 18-56 ksi, while x-axis values were between 4-17 ksi and y-axis values ranged from 2-12 ksi.
- Both base and subbase materials displayed stress-hardening behavior, meaning that stiffness increased with higher confining stress.
- Plymouth County showed distinct characteristics compared to the base and subbase materials. Notably, the z-axis exhibited stress-softening behavior, contrary to the stress-hardening behavior seen in the base/subbase materials. Moreover, both horizontal directions (x- and y-axes) exhibited stress-hardening behavior, with varying levels of stiffness characteristics. Vertical stiffness was measured between 11-21 ksi for the subgrade material. The x-axis had stiffness values ranging between 8-17 ksi, while y-axis values ranged from 2-6 ksi. The discrepancy between the two horizontal is believed to be the result of the applied stress history.
- Anisotropy ratios were determined for each direction of the tested materials. The results indicated that, for base materials, vertical stiffness was 3 to 11 times higher than horizontal stiffness. For subbase material, vertical stiffness was recorded as 4 to 10 times higher than the horizontal stiffness. For subgrade material, vertical stiffness was 2 to 11 times higher than the y-axis while it was 0.7 to 3 times higher than the x-axis.
- For Ames Mine, the z-axis displayed a permanent strain of 0.10%, while the x-axis and y-axis had higher values of 0.42% and 0.46%, respectively. In Crocker Pit, the z-axis exhibited a permanent strain of 0.11%, while the x-axis and y-axis underwent plastic deformations at rates of 0.47% and 0.38%, respectively. The subbase material showed a very similar permanent strain on the z-axis compared to the base materials, measuring at 0.09%. The x-axis and y-axis displayed plastic deformations of 1.60% and 1.49%, respectively. In the subgrade material, the z-axis showed slightly lower permanent strains at 0.06%, while the x-axis and y-axis recorded values of 0.09% to 0.10%, respectively.



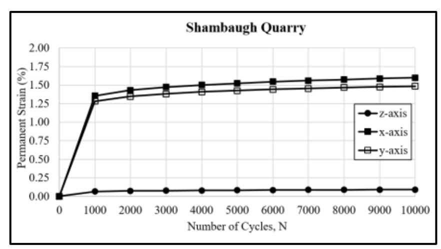
Horizontal y-axis resilient modulus of Ames Mine varying with bulk stress

Material	Direction	k_1	k_2	R^2
Ames Mine	Vertical z-axis	4.24	0.67	0.96
	Horizontal x-axis	1.22	0.62	0.72
	Horizontal y-axis	0.68	0.68	0.68
Crocker Pit	Vertical z-axis	3.05	0.65	0.94
	Horizontal x-axis	0.53	0.71	0.83
	Horizontal y-axis	0.67	0.66	0.83
Shambaugh Quarry	Vertical z-axis	3.82	0.60	0.91
	Horizontal x-axis	0.69	0.67	0.91
	Horizontal y-axis	0.81	0.53	0.68

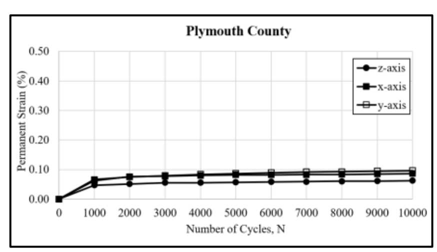
Model parameters and coefficient of determination for bulk stress model of base and subbase materials



Permanent strains in the z-axis, x-axis, and y-axis of Ames Mine



Permanent strains in the z-axis, x-axis, and y-axis of Shambaugh Quarry



Permanent strains in the z-axis, x-axis, and y-axis of Plymouth County

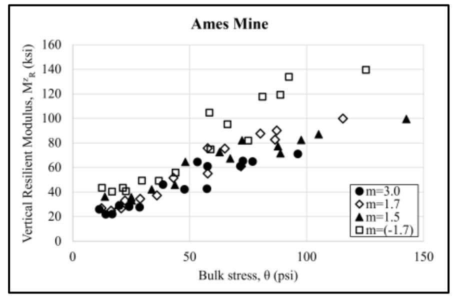
- For the base materials (Ames Mine, Bethany Falls Limestone, Crocker Pit, Oneota Formation Dolomite, Plano Quarry, Weber Quarry), the greatest vertical stiffness value was noted at a stress path slope (m) of -1.7, particularly when subjected to higher levels of confining stress. Conversely, the smallest vertical stiffness value occurred with an m of 3.0. As for horizontal stiffness, the minimum values were observed with an m of 1.7. The subsequent application of stress paths did not appear to elevate the stiffness in the horizontal direction, likely due to the optimal packing of the structurally weak composition during the m=1.7 testing phase. Similar to the trend in the base materials, the highest vertical stiffness among subgrade materials was seen at m=(-1.7). m=3.0 resulted in slightly diminished values in comparison to other m values [1.7, 1.5, (-1.7)]. In terms of horizontal stiffness, the highest values occurred with m=(-3.0), while the lowest values were obtained for m=1.7.

According to the evaluation of actual freeze-thaw performance of geomaterials test results:

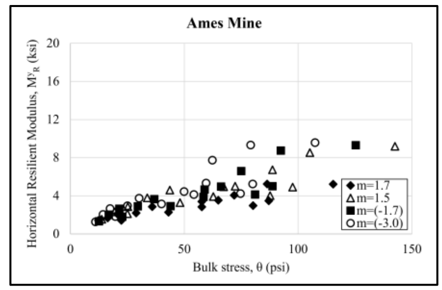
- The results revealed a consistent trend where an increase in fine content led to a decrease in the stiffness of the base materials at their optimum moisture content.
- After 8 freeze-thaw cycles, the stiffness values decreased by 19%, 27%, and 25% for fines contents of 5%, 10%, and 15%, respectively. It was observed that an increase in the fine content of the materials led to higher permanent deformations.
- The results suggest that fine content 5% displayed higher heave and settlement compared to 10% and 15%, which exhibited lower heave and settlement.

Recommendations

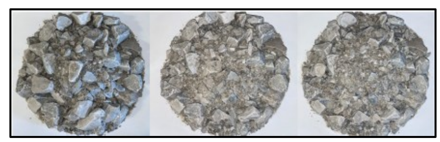
- Conducting comprehensive laboratory testing to increase the fundamental knowledge of cross-anisotropy of various materials such as recycled materials, chemically stabilized soils, and geomaterials with geosynthetics.
- Performing pavement response analysis using nonlinear cross-anisotropic material properties to obtain reliable analysis results.
- Integrating field observations and measurements to laboratory material characterization process.



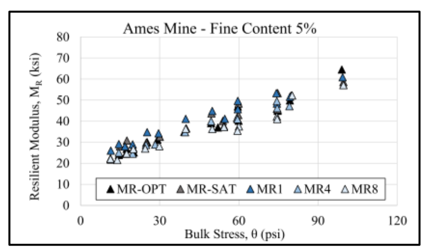
Vertical z-axis resilient modulus change with bulk stress of Ames Mine at different stress path slopes



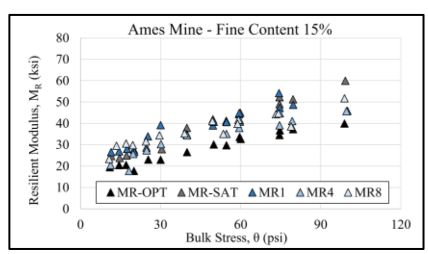
Horizontal y-axis resilient modulus change with bulk stress of Ames Mine at different stress path slopes



Ames Mine with increasing fines contents: 5% 10% and, 15%



Effect of freeze-thaw on the resilient modulus of Ames Mine with fine content of 5%



Effect of freeze-thaw on the resilient modulus of Ames Mine with fine content of 15%