

TRANSPORTATION RESEARCH BOARD

Geochemistry and Mineralogy in Chemical Soil Stabilization

April 14, 2021
1:00-3:00 PM Eastern

@NASEMTRB
#TRBwebinar

PDH Certification Information:

- 2 Professional Development Hours (PDH) – see follow-up email for instructions
- You must attend the entire webinar to be eligible to receive PDH credits
- Questions? Contact Reggie Gillum at RGillum@nas.edu

#TRBwebinar

The Transportation Research Board has met the standards and requirements of the Registered Continuing Education Providers Program. Credit earned on completion of this program will be reported to RCEP. A certificate of completion will be issued to participants that have registered and attended the entire session. As such, it does not include content that may be deemed or construed to be an approval or endorsement by RCEP.



REGISTERED CONTINUING EDUCATION PROGRAM

Learning Objectives

1. Determine the role of mineralogy in chemical soil stabilization.
2. Describe the basics of mineralogical tests such X-ray diffraction and thermogravimetric analysis.
3. Apply appropriate modeling techniques to mineralogy.

#TRBwebinar





Dallas Little
D-little@tamu.edu
Texas A&M University



Pavan Akula
pavan.akula@tamu.edu
Texas A&M University



Anand Puppala
anandp@tamu.edu
Texas A&M University



Narain Hariharan
nhariharan@graymont.com
Graymont

Erol Tutumluer
tutumlue@illinois.edu
*University of Illinois at
Urbana-Champaign*

Geology and Geotechnical Engineering (AKG00)

- AKG00(1) Geotechnical Asset Management Section Subcommittee
- AKG10 Engineering Geology
- AKG20 Soil and Rock Properties and Site Characterization
- AKG30 Geo-Environmental and Climatic Impacts on Geomaterials
- AKG40 Mechanics and Drainage of Saturated and Unsaturated Geomaterials
- AKG50 Transportation Earthworks
- AKG60 Geotechnical Instrumentation and Modeling
- AKG70 Foundations of Bridges and Other Structures
- AKG80 Geosynthetics
- **AKG90 Stabilization of Geomaterials and Recycled Materials**

Chair: Chud Lundgreen, USDA Forest Service



**Expansive
(Swelling)
Soils**



**We could have controlled the negative effects
of these expansive soils!!!**

Expansive (Swelling) Soils

- Expansive soils **shrink and swell** with change in moisture content
- Identification is a key component of geotechnical investigation
 - % passing No. 200 sieve size and % finer than 2 μm
 - Plasticity Index (PI) = LL - PL, and/or **Shrinkage Limit**
 - Swell pressure tests, expansion index, etc.



Schematic Illustration of Relative Swelling and Consolidation Volumes as a Function of Matrix Potential

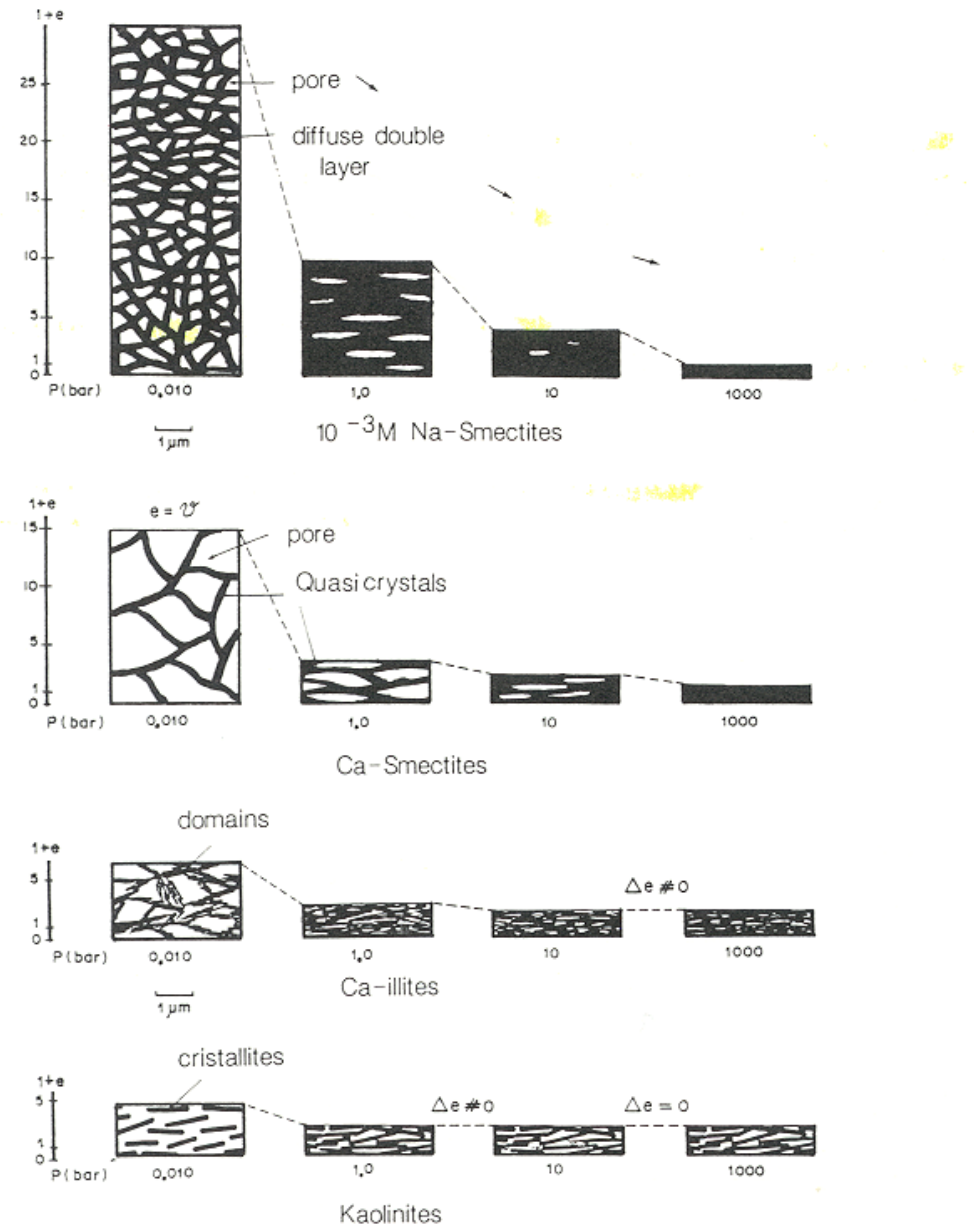


Fig. 12: Schematic illustration of relative swelling and consolidation volumes as a function of matrix potential. (e = void ratio — the volume of pore space to solid particle volume)

Skempton's (1953) Activity Index

$$\text{Activity } (A_c) = \frac{\text{Plasticity index}}{\% \text{ by weight finer than } 2 \mu\text{m}} \quad (3.1)$$

Skempton suggested three classes of clays according to activity as *inactive*, for activities less than 0.75; *normal*, for activities between 0.75 and 1.25; and *active*, for activities greater than 1.25. Active clays provide the most potential for expansion. Typical values of activities for various clay minerals are as follows:

Mineral	Activity
Kaolinite	0.33 to 0.46
Illite	0.9
Montmorillonite (Ca)	1.5
Montmorillonite (Na)	7.2

Table 1.1
Composition and Swell Properties of Natural and Artificial
Soils (After Basu and Arulanandan, 1973)

Soil Type	CLAY MINEROLOGY (%)				Non-Clay Minerals (%)	PI (%)	%<2μm	Activity (=PI/C)	Δε ₀	%Swell
	Montmorillonite	Mixed Layer	Illite	Kaolinite						
1*	0	5	0	0	95	6	23	0.26	10	3
1PB*	0	52	5	0	43	31	44	0.70	46	24
2*	0	10	0	0	90	NP	8	0.00	9	2
3*	10	5	0	0	85	1	8	0.13	10	2
3SC*	35	5	0	0	60	30	34	0.88	42	27
6*	0	13	0	0	87	23	25	0.92	27	9
7*	0	5	0	0	95	4.5	10	0.45	18	2
8*	0	20	0	0	80	2	10	0.20	22	2
9*	20	5	0	0	75	22	50	0.44	31	11
11*	0	20	0	0	80	9	19	0.45	11	--
12*	0	10	0	0	90	NP	8	0.00	4	--
15*	15	0	0	0	85	11	33	0.33	23	6
16*	Predominantly Vermiculite					122	48	2.50	16	12
Illite-Grundite	Predominantly Illite					45	50	0.90	--	23
Hydrite R	Predominantly Kaolinite					30	100	0.30	18	4
Marysville Red (MR)*	Montmorillonite-Kaolinite-Chlorite Mixture					11	20	0.55	41	30

Notes: * Natural Soils
 1. The percentage of different clay minerals present in each soil (shown above) are based on the total weight of the soil. (Clay mineralogy data supplied by California Division of Highways).
 2. Data of Marysville Red is from Arulanandan's personal file.
 3. NP = Non plastic

Soil Structure – Arulanandan (2003)

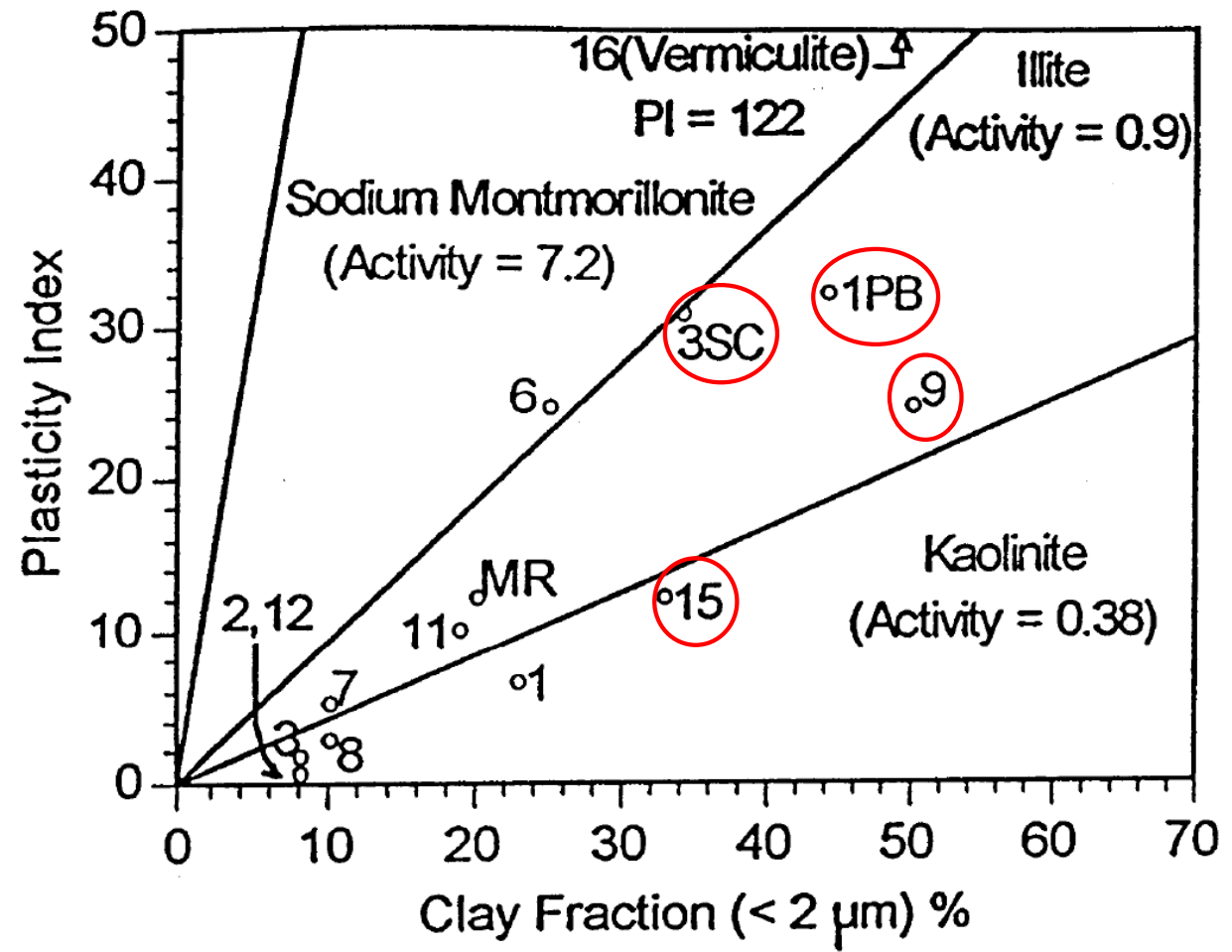


Figure 1.4
Clay Fraction and Plasticity Index of Some Natural Soils in
Relation to the Activity Chart of Skempton (1953)

Guidelines for Stabilization of Soils & Base Materials

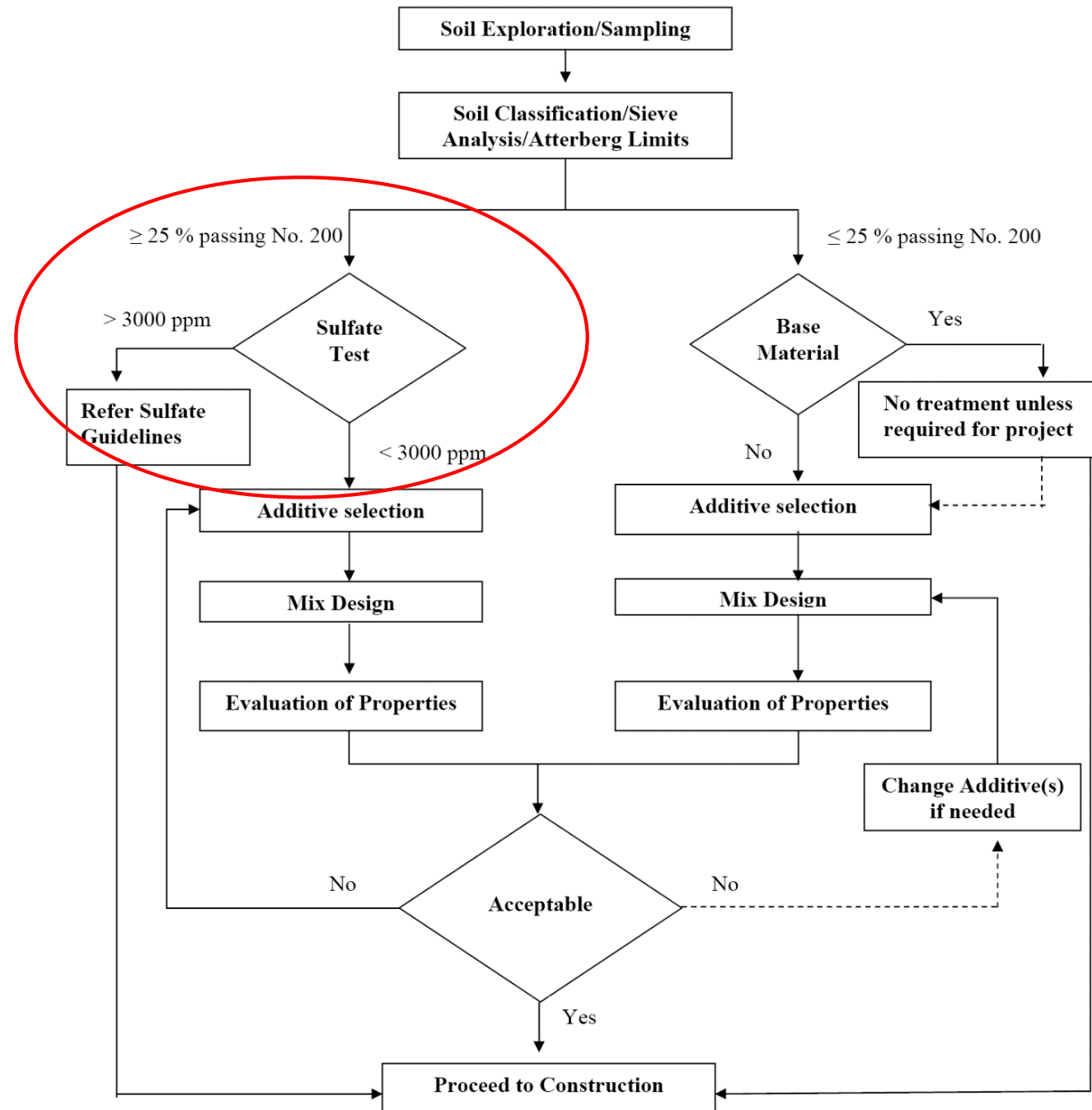
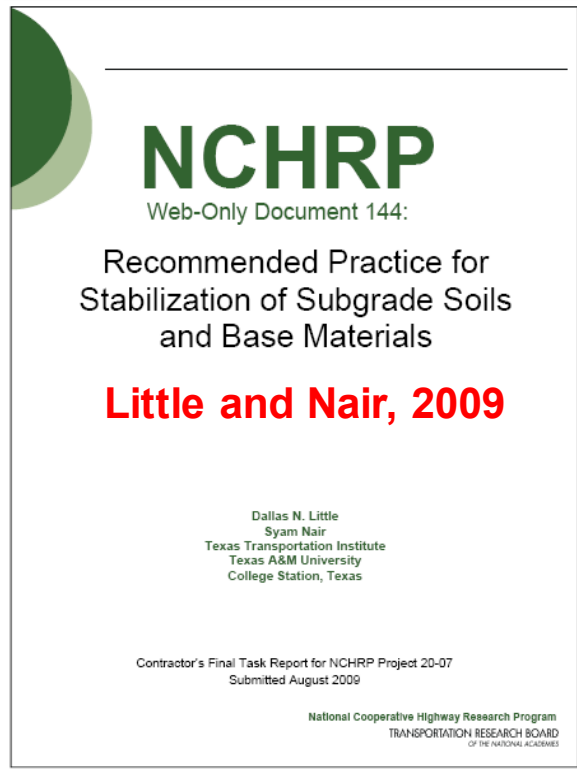
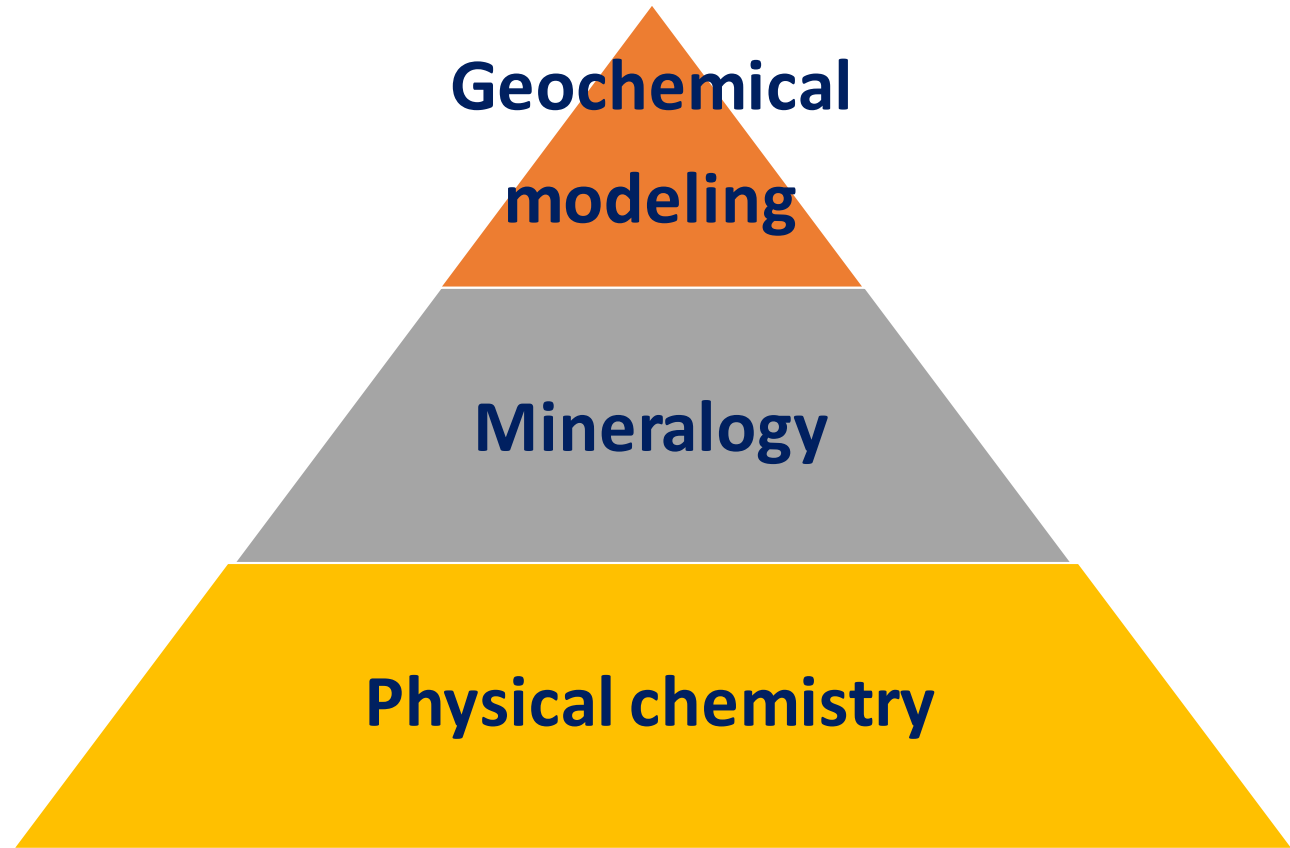


Figure 1. Guideline for stabilization of soils & base materials for use in pavements (12).

Application of Geochemistry and Mineralogy in Chemical Soil Stabilization

Dallas N. Little, Ph.D., Distinguished Professor, Texas A&M University-College Station
Pavan Akula, Ph.D., Postdoctoral researcher, Texas A&M University-College Station

Durable Stabilized Soils



Durable Stabilized Soils

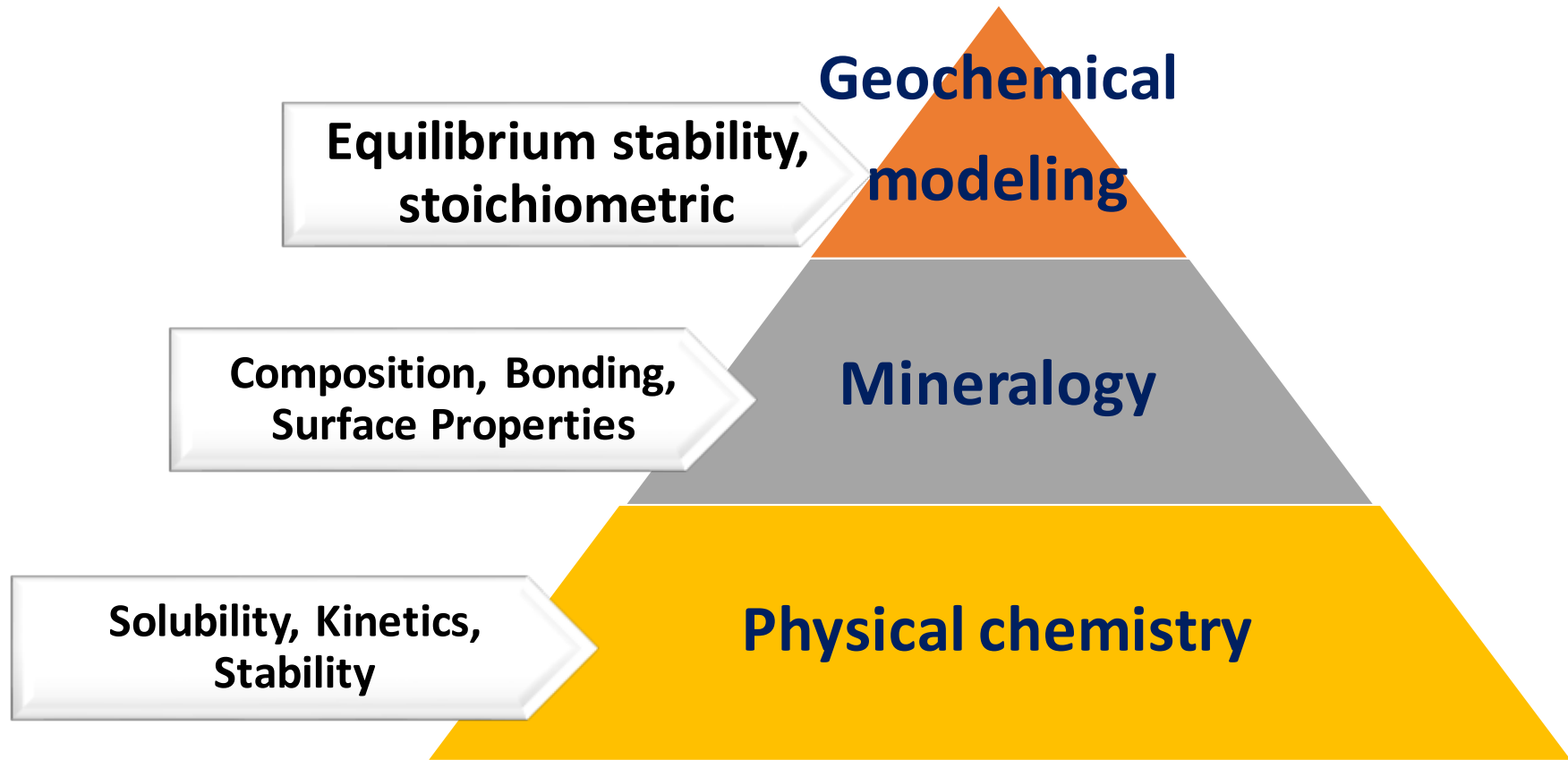
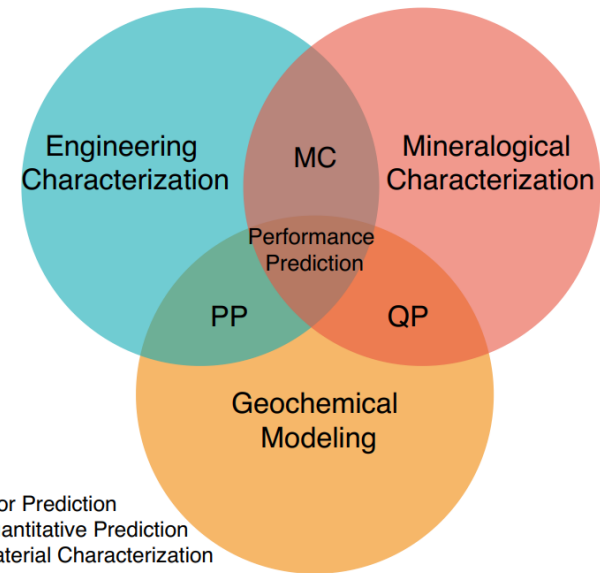
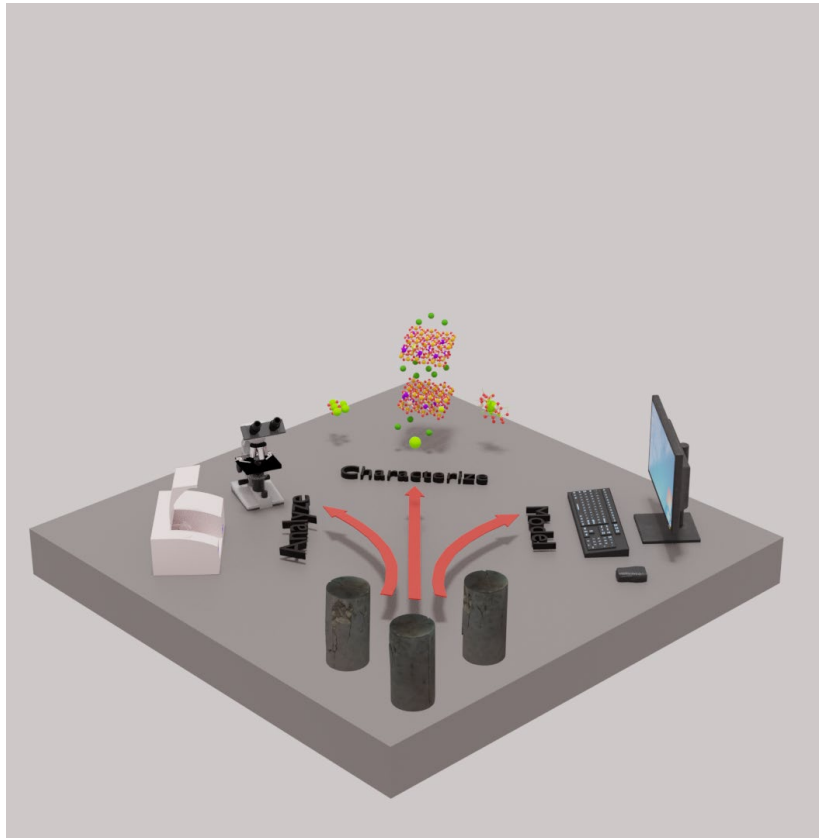


Table of Contents

- Introduction: Durable Stabilized Soils
- Approach
- Thermodynamic modeling
- Background
 - Soil Mineralogy
 - Geochemistry of ettringite formation
- Application(s)
 - P1: Predicting Ettringite Formation (sulfate attack)
 - P2: Evaluating durability of a 47-year-old embankment

Approach



PP - Poor Prediction
QP - Quantitative Prediction
MC - Material Characterization

- Characterization methods
 - Mineralogical
 - Engineering
 - Geochemical methods
- Use characterization data to develop geochemical model
- Predict the formation of pozzolanic products

Geochemical Modeling

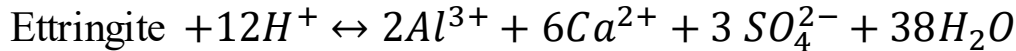
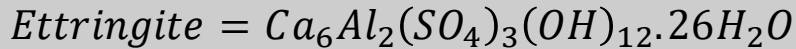
- Thermodynamics is a system of consistent chemical equations used to describe the state of a system.
- It describes the energy differences between different states:
 - Thermodynamics gives information of what reactions may occur (thermodynamically feasible)
 - A simple method to understand internal consistency of thermodynamic data in a specific system

Geochemical Modeling

- Thermodynamic models can predict the concentrations (activities) of species present in a system
- There are two distinct methods that can be used to delineate these processes:
 - **Law of Mass Action (LMA)** uses equilibrium constants to solve numerically for the equilibrium state of multicomponent system
 - **Gibbs Energy Minimization (GEM)** uses optimization theory to solve the equilibrium problem by minimizing the free energy directly

Law of Mass Action (LMA)

Solubility Product



$$\text{Log}K_{sp}(25^\circ\text{C}) = 57.00$$

$$Q = \frac{(\text{Al}^{3+})^2 (\text{Ca}^{2+})^6 (\text{SO}_4^{2-})^3 (\text{H}_2\text{O})^{38}}{(\text{H}^+)^{12} (\text{Ettringite})}$$

K_{sp} - constant at equilibrium

Q - reaction quotient at non-equilibrium conditions

(Products) = Activity of products

(Reactants) = Activity of reactants

$Q < K_{sp} \Rightarrow$ Dissolution is favored

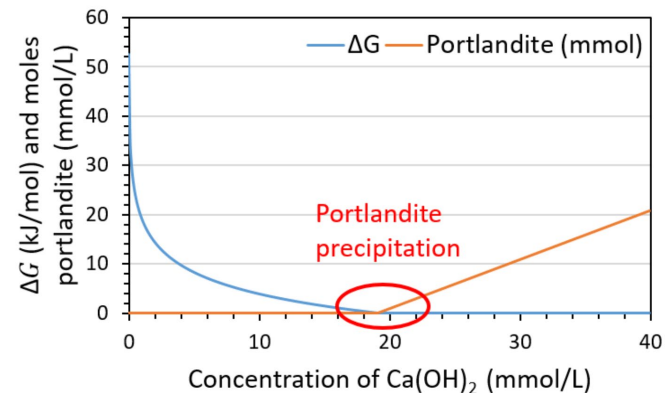
$Q > K_{sp} \Rightarrow$ Precipitation is favored

Gibbs Energy Minimization (GEM)

The goal of GEM is to find a vector of the (Dependent) DC mole amounts, $\mathbf{n} = \{x_j, j \in L\}$, such that:

$$\min G = \mathbf{n}^T \boldsymbol{\mu} = \sum_{i=1}^N n_i \mu_i \text{ subject to } \begin{cases} A\mathbf{n} = \mathbf{b} \\ n \geq 0 \end{cases}$$

$$\mu_i = \left[\frac{\delta G}{\delta n_i} \right]_{T,P,n_{i \neq i}}$$



Credits: Prentice Dale

$\mathbf{A} = \{a_{ij}, i \in N, j \in L\}$ is a matrix of formula stoichiometry coefficients of the i -th (independent) IC in the j -th DC

$\mathbf{b} = \{b_i, i \in N\}$ is the input vector of total mole amounts of IC

G is the total Gibbs energy function of the whole system

Geochemical Modeling

Thermodynamic Model

Reaction solver algorithm

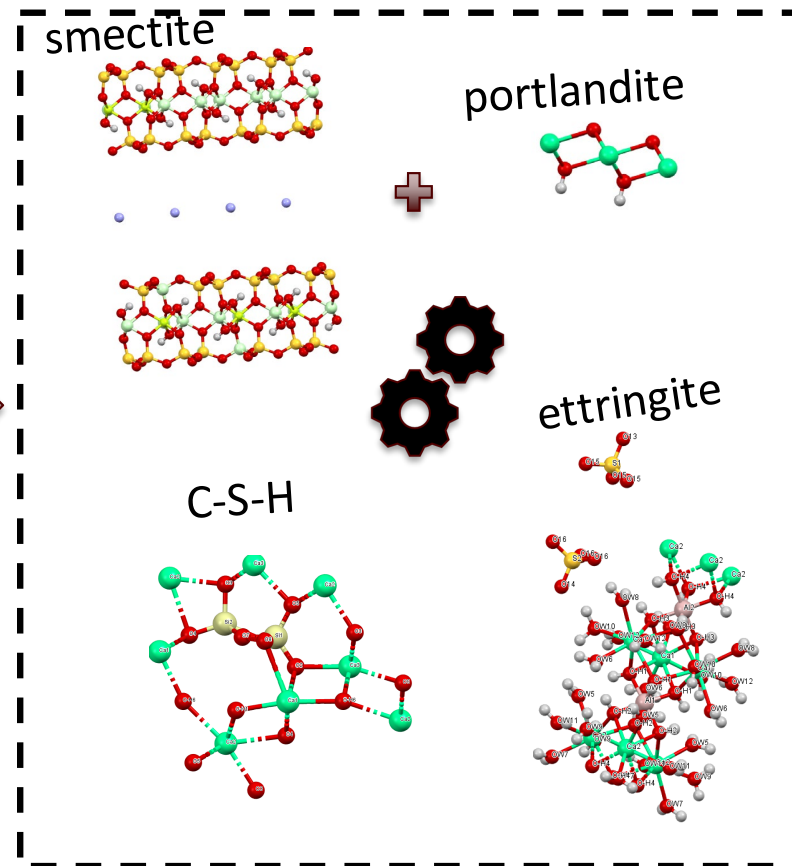
Determines which minerals/
phases are stable



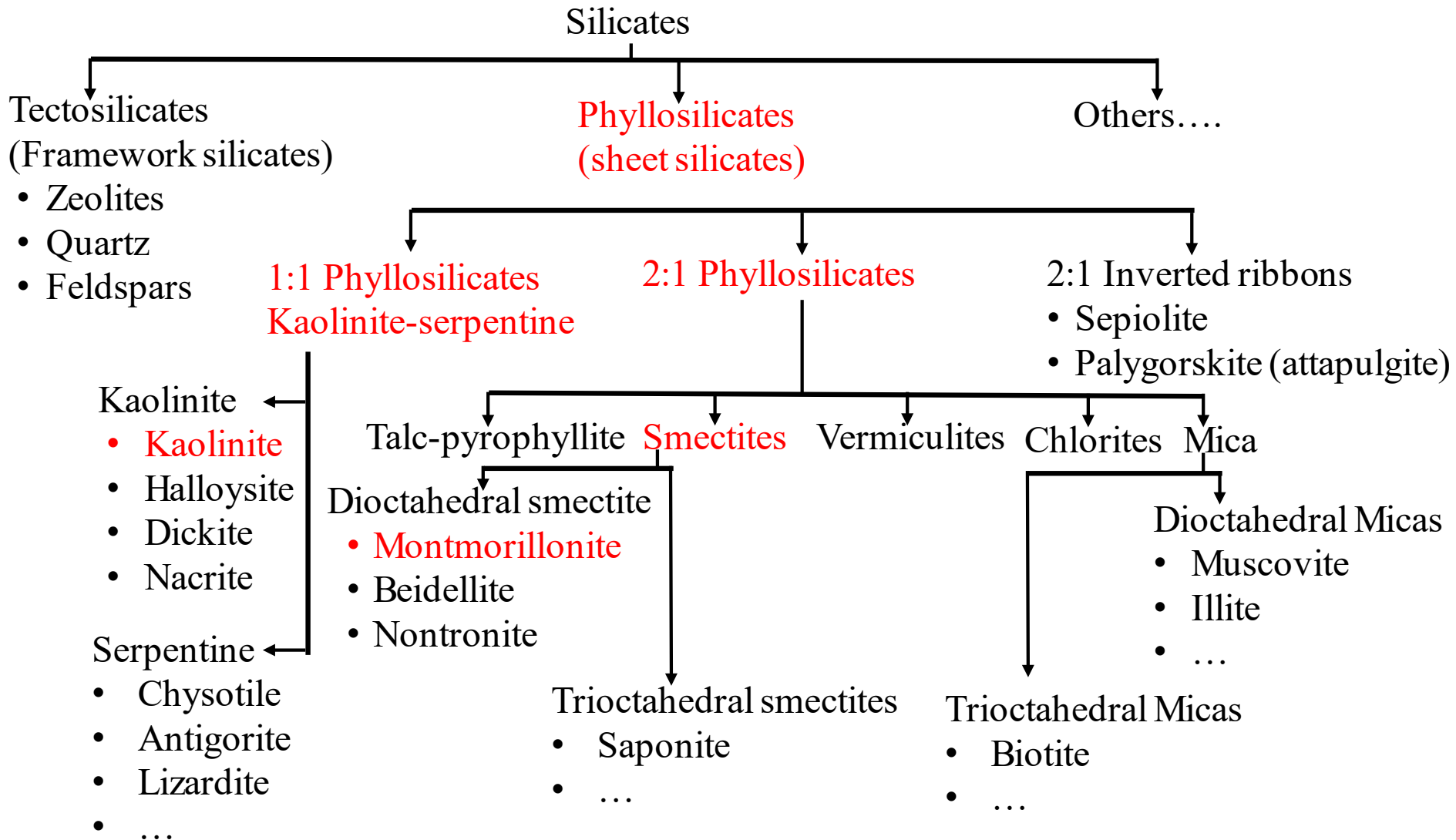
Database

Solubility product, Gibbs free
energy, enthalpy, and entropy
used by solver

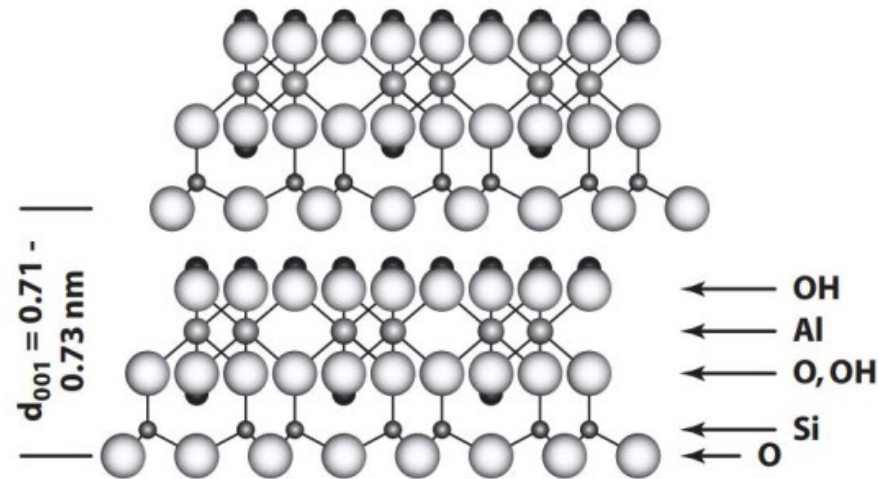
Precipitation



Background: Soil Mineralogy



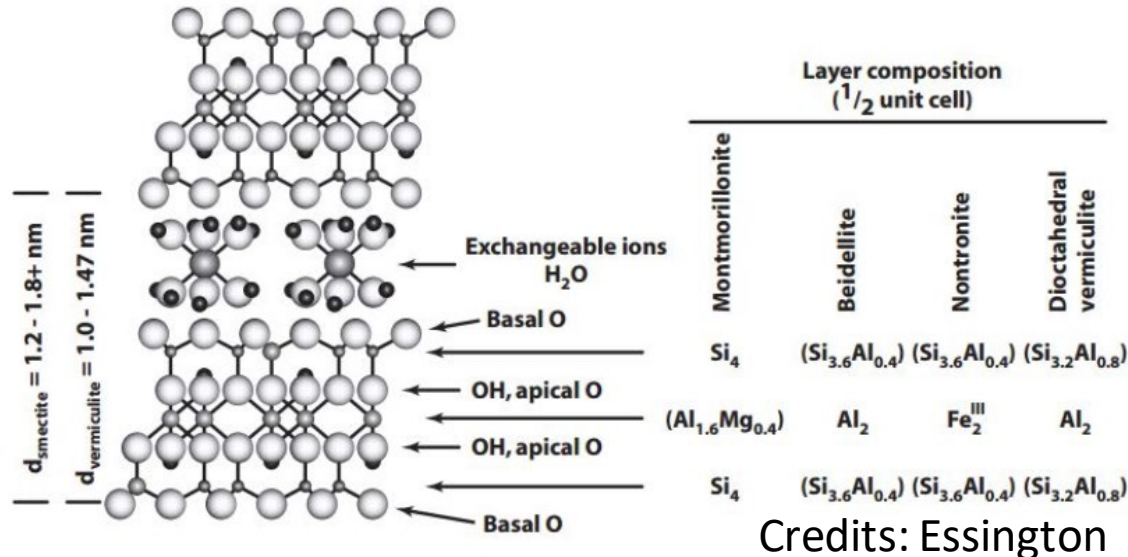
Kaolinite



Credits: Essington

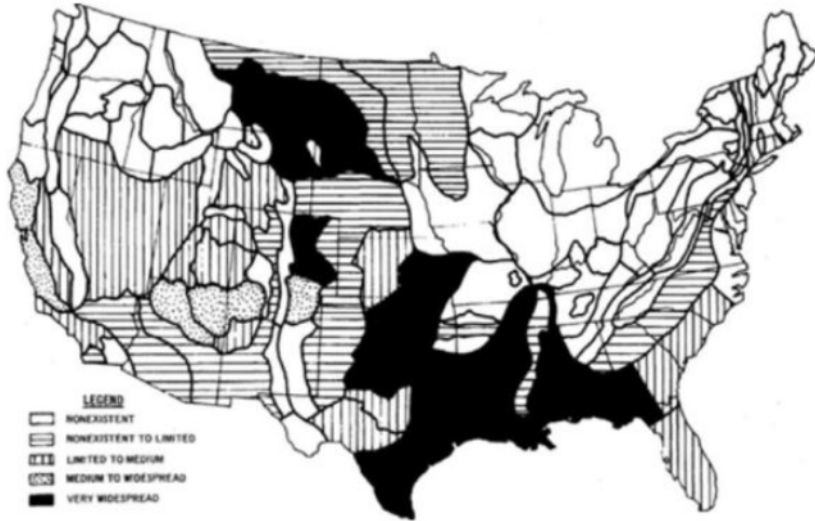
- Non-expansive clay mineral
- 1:1 Phyllosilicate mineral
- Common in Texas
- Good source of Al and Si for pozzolanic reactions

Montmorillonite



- Expansive clay mineral (shrink-swell clays)
 - Isomorphic substitution: A layer charge of 0.4 arises from the substitution of 0.4 Mg²⁺ atoms for Al³⁺ atoms in the octahedral layer
- 2:1 Phyllosilicate mineral
- Common in Texas
- Good source of Al and Si for pozzolanic reactions

Expansive Clays



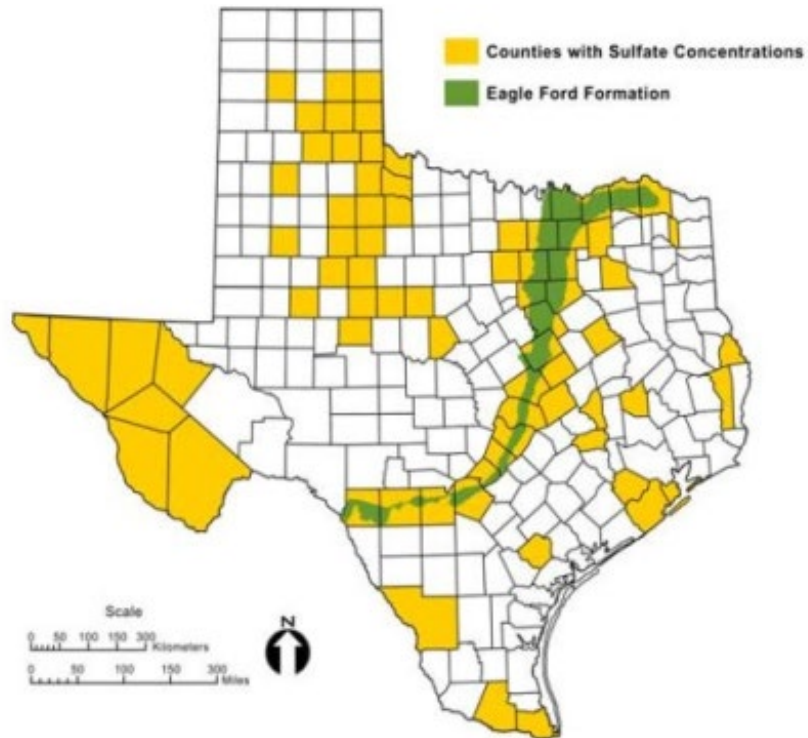
Credits: TxDOT



Credits: TxDOT

- Expansive clays are found in various states of the USA
- Lime is a popular chemical stabilized used to modify and stabilize expansive clays.

Sulfate attack



Credits: TxDOT



Credits: Petri



Predicting Ettringite Formation

Introduction:

- Investigate the applicability of geochemical models for case studies
- A multistoried shopping complex in Mississippi with recorded distress in the base was chosen for the study
- Ash with excessive sulfate content (40-70%) was used to stabilize the clay in the base layer
- The ash contained 40-70% sulfates
- Two years after hydration, several cracks and signs of distress to the structure were recorded

Case History

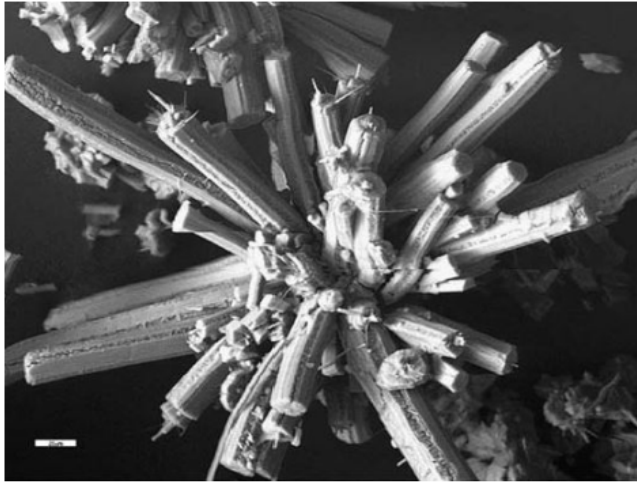
Objectives:

- Evaluate the applicability of geochemical models to predict ettringite formation
- Qualitative and quantitative comparison of the predicted ettringite content with the experimental results
- Determine the limitations of the model

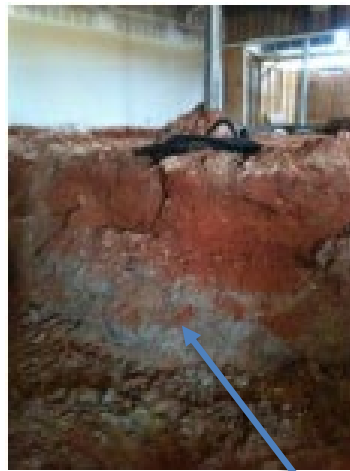
Available Data and Assumptions:

- Mineralogical data about the in-situ soil is not available
- Ash's mineralogical data indicated significant variability in gypsum content (40 – 70%)
- Material was assumed to be homogeneously mixed

Ettringite Formation



Mineral structure of Ettringite
Credits: Dr. Michael Schwarz



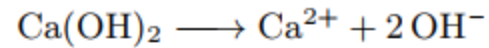
Ash



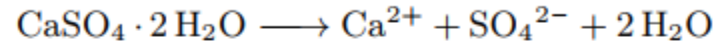
- Ettringite is a calcium-alumino-sulfate mineral ($\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12}\cdot 26\text{H}_2\text{O}$)
- Formation of ettringite requires the presence of Ca^{2+} , Al^{3+} , SO_4^{2-} and H_2O
- Formation of excessive ettringite can cause distress in pavements and concrete structures
- Typical Ash composition includes CaO (source of Ca^{2+}), Al_2O_3 (source of Al^{3+}), CaSO_4 (source of SO_4^{2-})
- Presence of excessive sulfate in ash can form ettringite

Geochemical Reactions

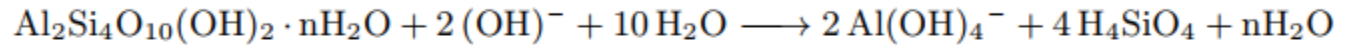
Portlandite



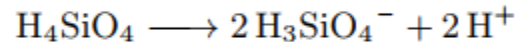
Gypsum



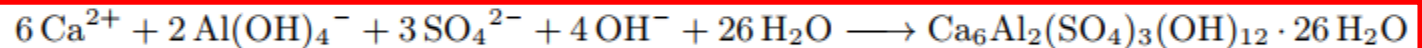
Phyllosilicate



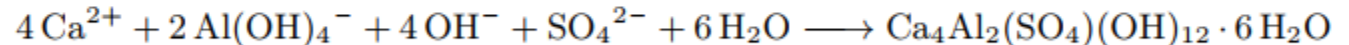
Silicic acid



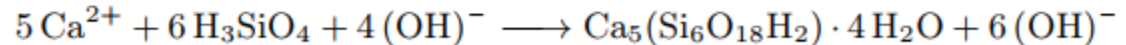
Ettringite



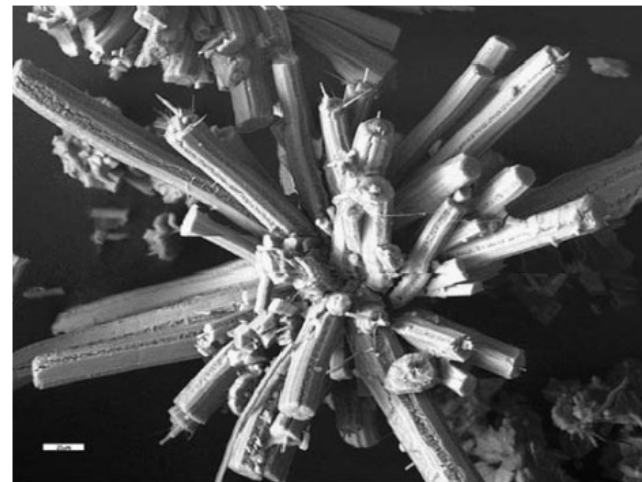
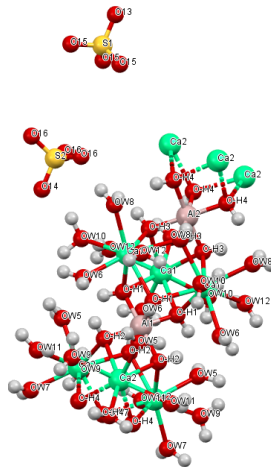
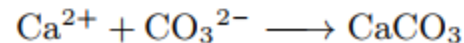
Monosulfoaluminate



C-S-H



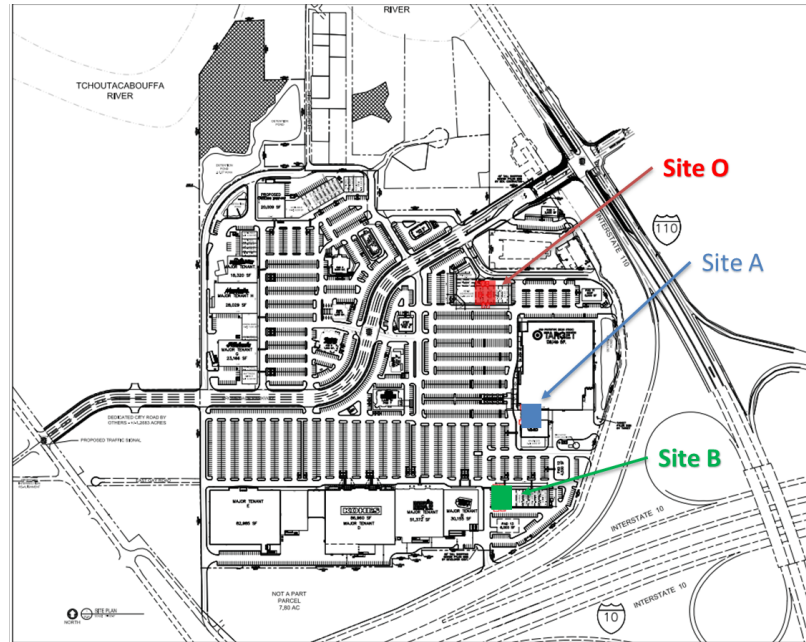
Calcite (pH \geq 10)



Sample Collection and Composition

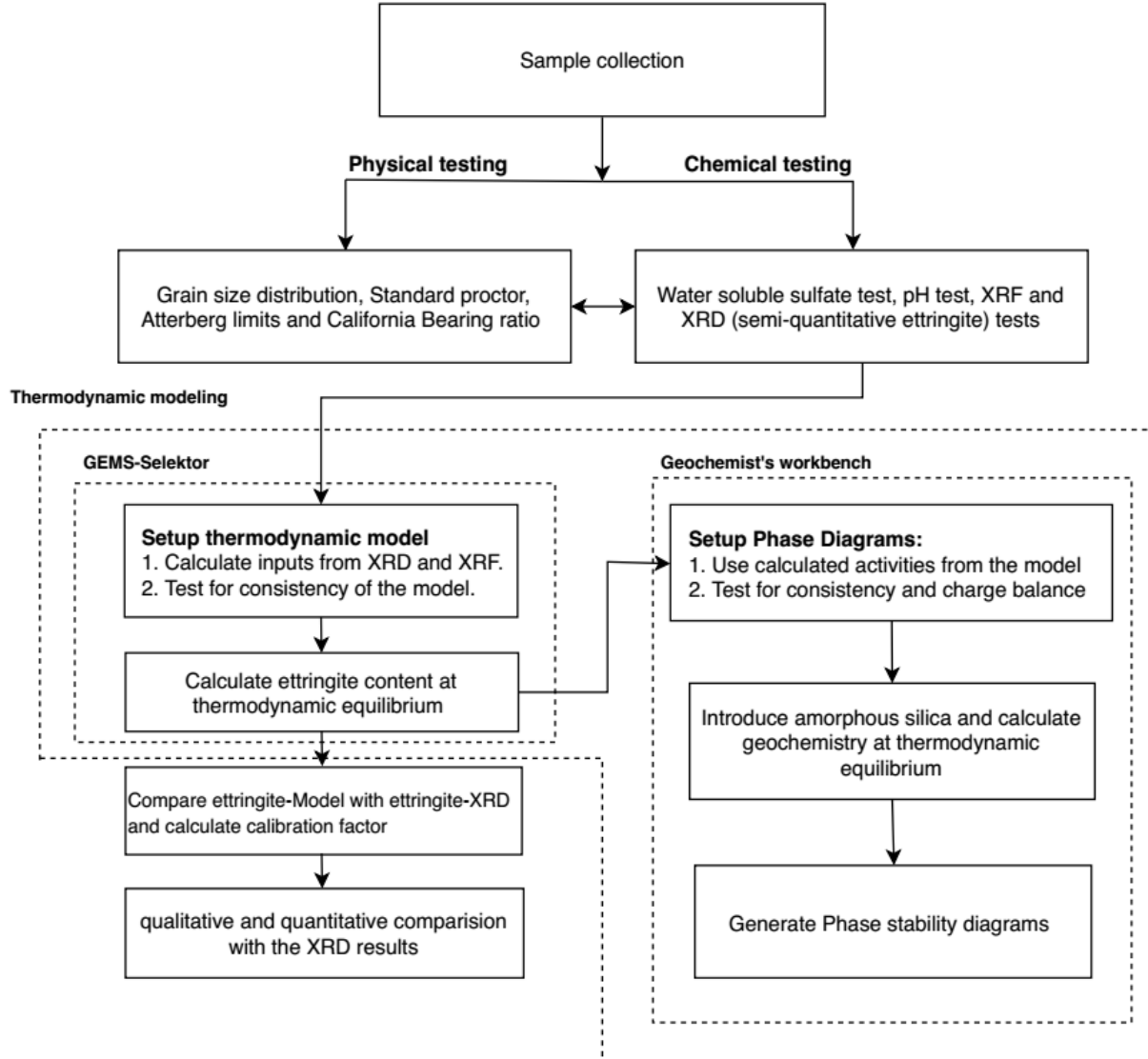
Table 1: Fluidized bed ash mineralogy analysis

Common name	Chemical formula	Percent composition (%)
Gypsum	$CaSO_4 \cdot 2H_2O$	43 – 70
Hydrated lime	$Ca(OH)_2$	20 – 30
Calcite	$CaCO_3$	4 – 22
Magnesium Hydroxide	$Mg(OH)_2$	1.7 – 2.5
Quartz	SiO_2	< 2.5
Magnesium Oxide	MgO	< 1
Lime	CaO	< 1
Free moisture	H_2O	5 – 10



- Soils samples collected from three locations in the shopping complex.
 - Sampling depths from 0 ft to 10 ft
 - A total of 50 samples
- High amount of gypsum (source of sulfate) in the stabilizer.
- Hydrated lime and magnesium hydroxide can increase the pH of the soil favoring pozzolanic reaction and ettringite formation.

Project Flowchart



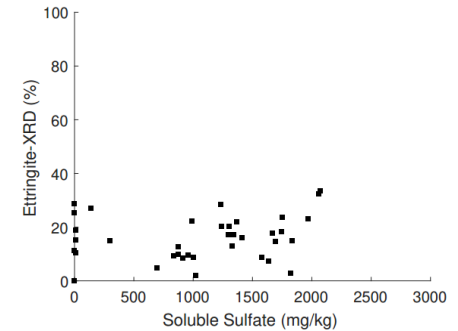
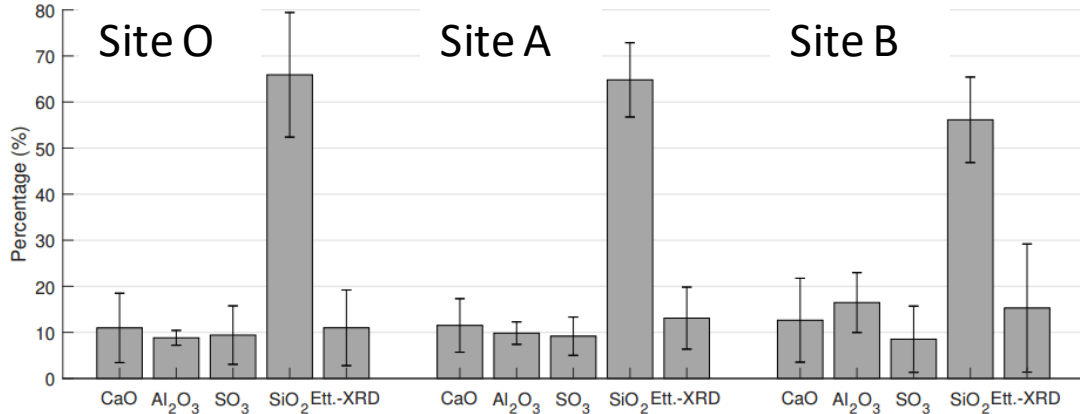
Soil Characterization

Shop Id.	Sample No.	USCS ¹ Symbol	Liquid Limit, LL (%)	Plastic Limit, PL (%)	Plasticity Index, PI (%)	Grain Size			CBR Value ² (Unit)	Compaction ³	
						Gravel (%)	Sand (%)	Fines (%)		Max. Dry Density (pcf)	Optimum Moisture Content (%)
A	CBR-1	SM	30	25	5	11.6	58.5	29.9	45	104.1	19.0
B	CBR-2	SC-SM	26	21	5	9.3	75.4	15.3	30	116.2	13.0
O	CBR-3	SC	29	20	9	11.3	52.9	35.8	31.6	110.4	16.5

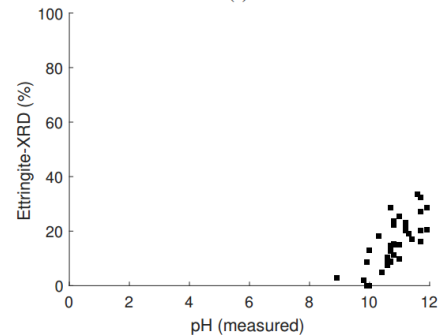
Notes:

1. Unified Soil Classification System.
2. The CBR value was measured on samples remolded at four different moisture contents and using standard Proctor compactive effort (ASTM D 698). The shown CBR value is the maximum value at 0.100" deflection.
3. In accordance with ASTM D 698, Standard Proctor Method.

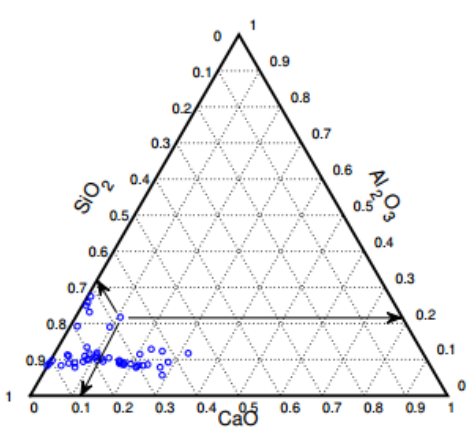
Chemical Composition (Stabilized material)



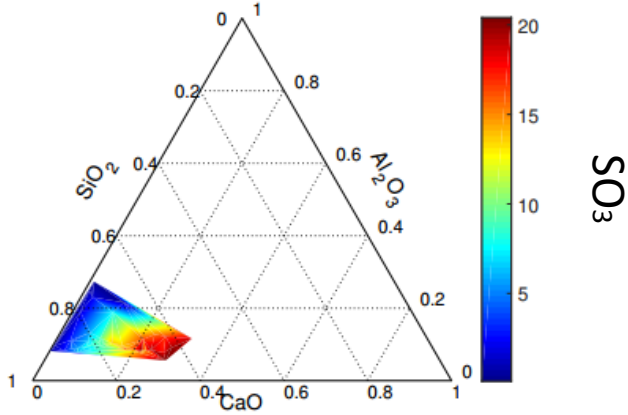
- pH measurements indicate favorable conditions for ettringite formation.
- The total SO₃ content ranged from 0 – 170,000 ppm
- Soluble sulfate levels (post stabilization) less than 3000 ppm



Composition Analysis

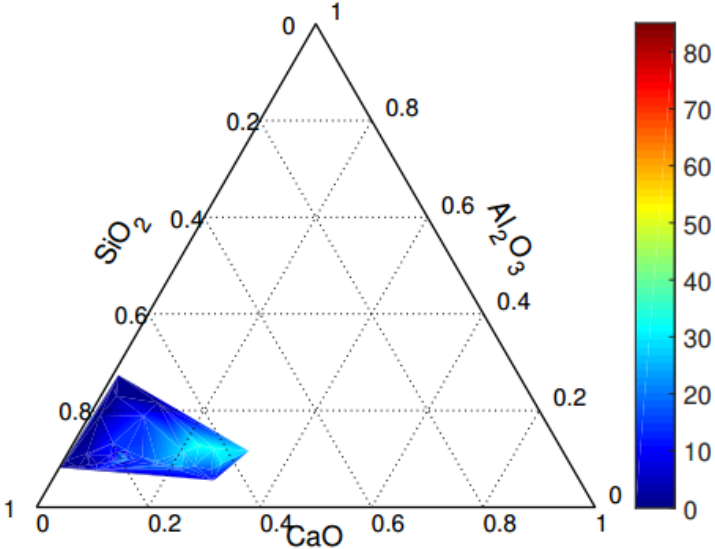


(a)

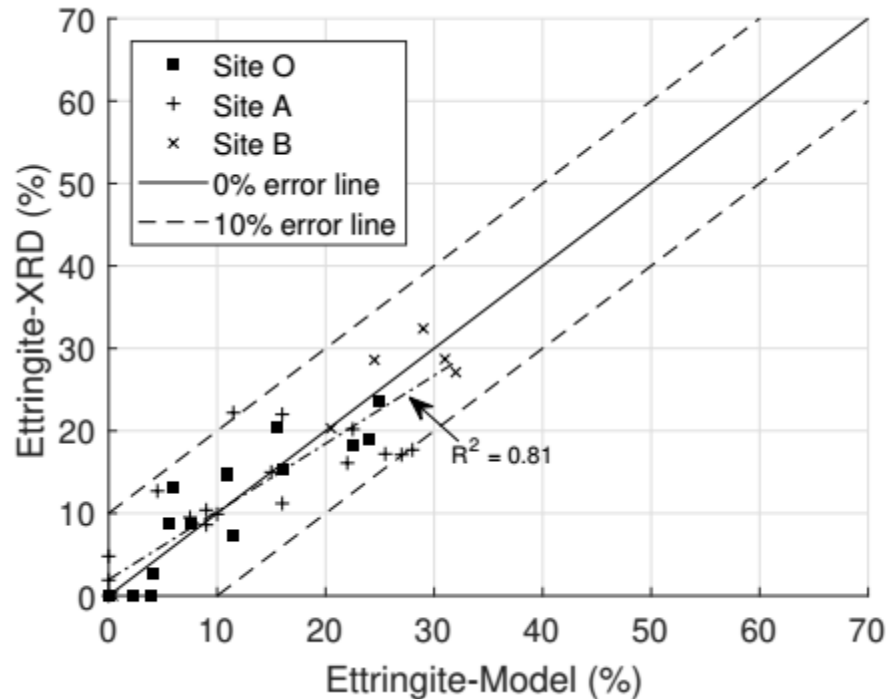


(b)

Ettringite

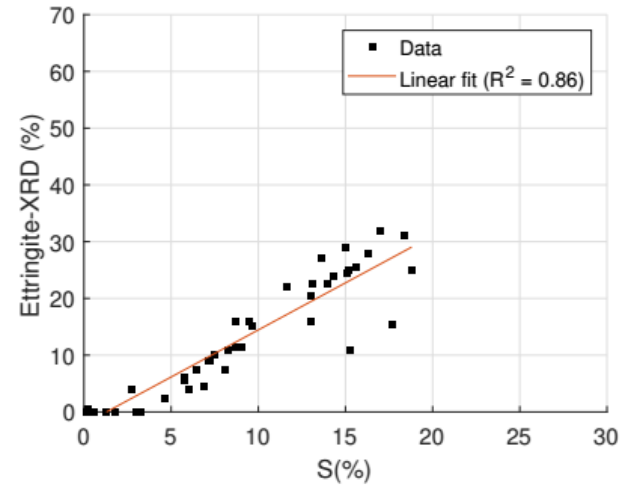
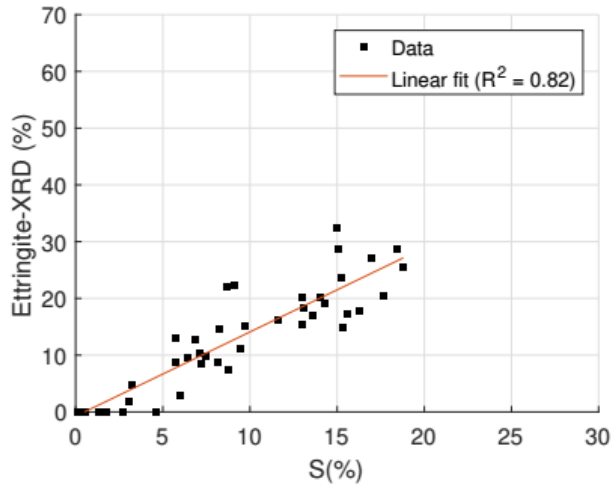
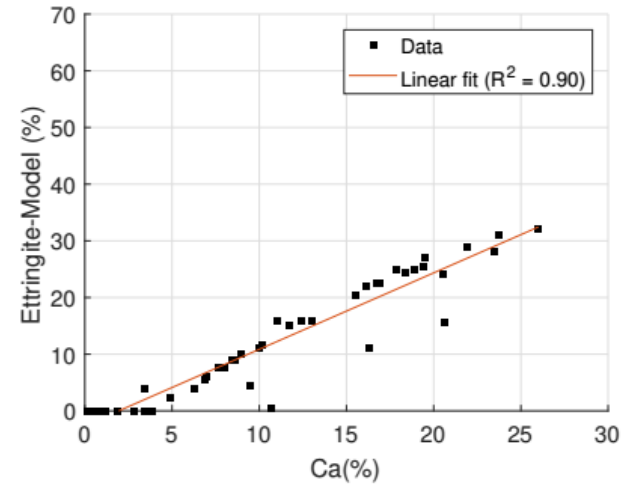
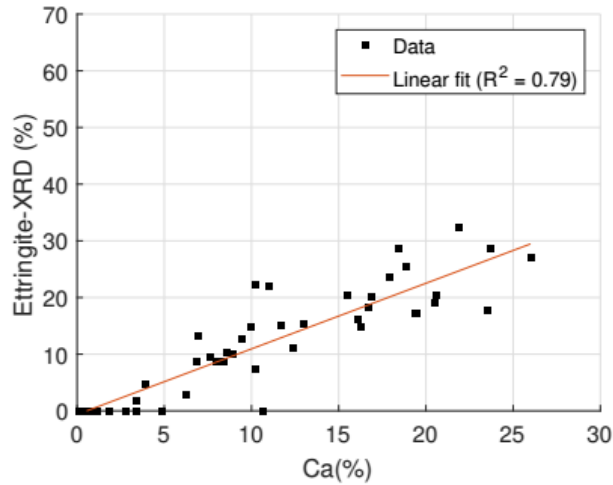


Model Results

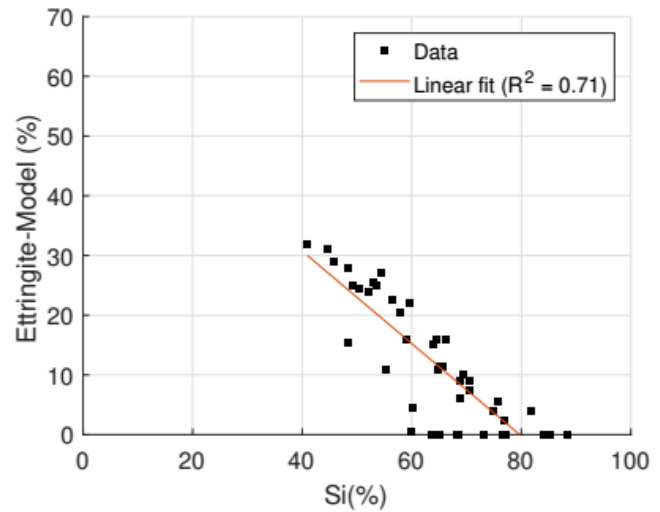
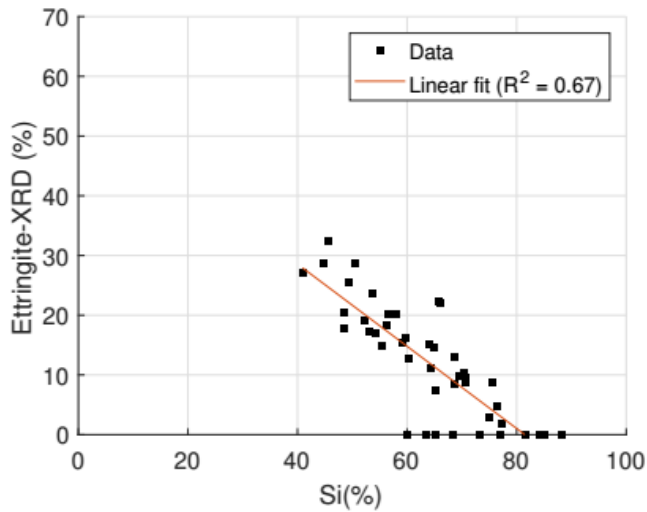
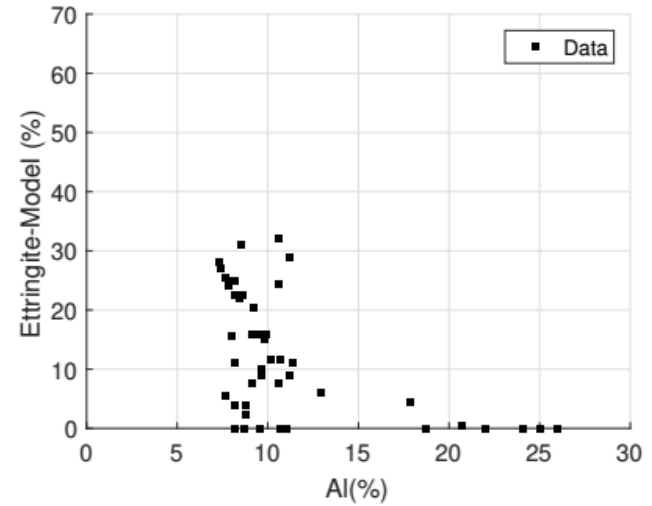
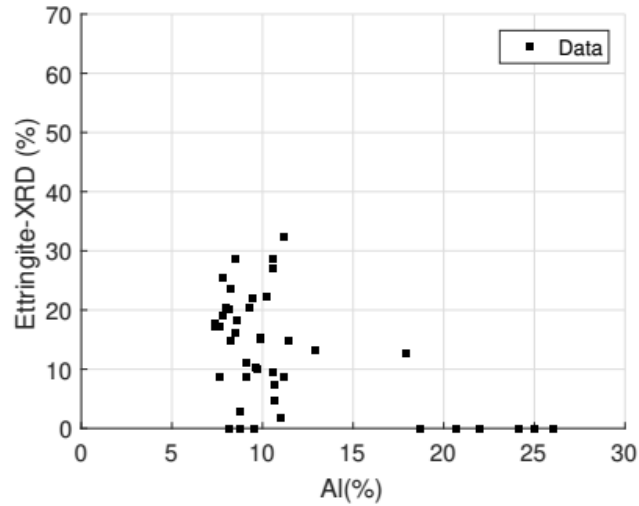


- The modeling results are consistent across Site's O, A, and B.
- Model predicted the formation of ettringite (qualitative) with a 92% reliability
- A maximum error of 10% was recorded
 - Prediction accuracy reduced for samples with less than 1% ettringite
 - AI assisted model (under development) improves the accuracy in this region

Effect of Ca and S

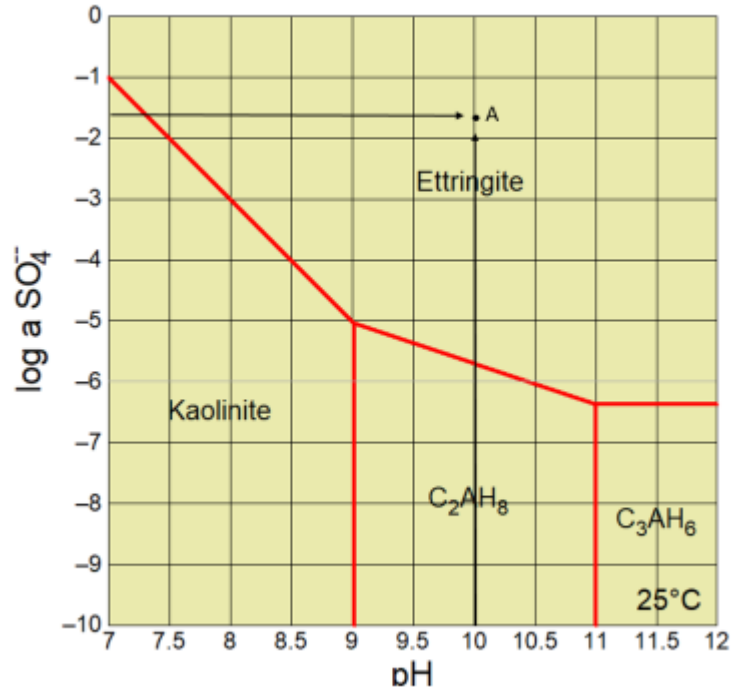


Effect of Al and Si

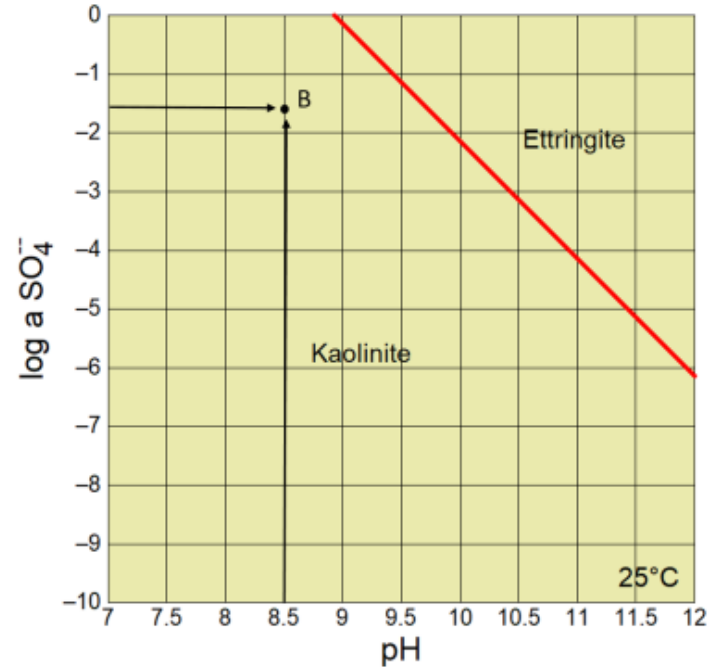


Modeling the Effect of Amorphous Silica

0% Amorphous silica



10% amorphous silica



- Phase stability diagrams are useful in determining ettringite formation
- Effect of ettringite inhibiting chemicals can be modeled
 - Addition of amorphous silica reduces the favorability to form ettringite
 - Several experimental studies have recorded similar effects

Summary

- XRF data was used in the geochemical model to study ettringite formation
- Model predicted the formation of ettringite (qualitative) with 92% reliability
- Results from geochemical model were calibrated to account for the assumptions that reduced the mean error to 0.12 % (SD 4.3%)
- Characterization of the hydrated phases can help improve the accuracy of the model

Useful references

- **Pavan Akula**, Dallas N. Little. “*Thermodynamic approach to evaluate ettringite formation in a fluidized bed ash by-product stabilized soil: A case study*”. Transportation Geotechnics. 2021
- **Pavan Akula**, Dallas N. Little. “*Mineralogical characterization and thermodynamic modeling of synthesized ettringite from Ca-Al-SO₄ suspensions*”. Journal of Construction and Building Materials. 2021.
- **Pavan Akula**, Narain Hariharan, Dallas N. Little. “*Evaluating the Long-Term Durability of Lime Treatment in the Friant-Kern Canal: A Case Study*”. Transportation Research Record: Journal of the Transportation Research Board. 2020.
- **Pavan Akula**, Dallas N. Little. “*Methods to detect calcium silicate hydrates in lime stabilized soils*”. MethodsX. 2020.
- **Pavan Akula**, Dallas N. Little, Paul Schwab. “*Thermodynamic evaluation of smectite treated with Hydrogen Ion Stabilizer*”. ASCE: Journal of Materials in Civil Engineering. 2020.

Thank You!

Engineering and Mineralogical Characterization to Evaluate Durability of a Lime Treated Embankment : Case Study

**TRB Webinar : Geochemistry and Mineralogy in Chemical Soil Stabilization
April 14, 2021**

Narain Hariharan, Ph.D., Graymont

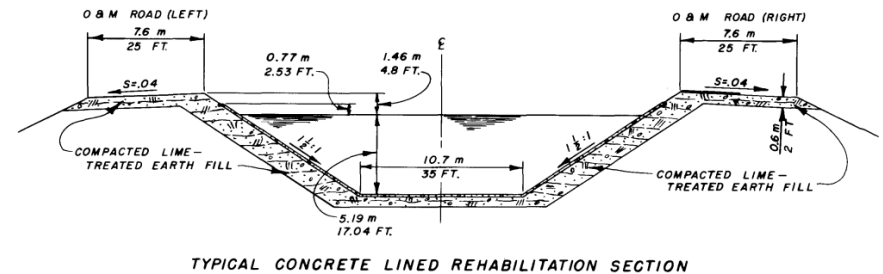
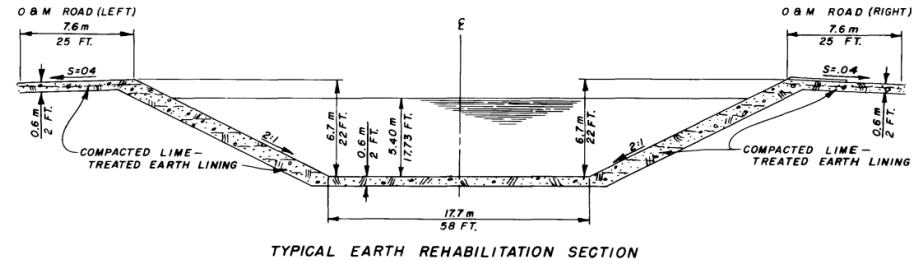
Pavan Akula, Ph.D., Texas Engineering Experiment Station

Presentation Outline

- Background – Friant Kern Canal (FKC)
- Case study objectives
- Sample collection at FKC
- Engineering characterization of FKC soils
- Mineralogical characterization of FKC soils
- Thermodynamic Modeling
- Conclusions

Background – Friant Kern Canal (FKC)

- Location: FKC is an irrigation canal located at the foothills of Sierra Nevada
- Length : 240 km (~150 mile)
- Year: 1940's.
- Details about lime treatment
 - Year: 1970's
 - Dosage: 4.0% hydrated lime
 - Length: 54 miles
 - Reason: Failure of slopes due to expansive clays



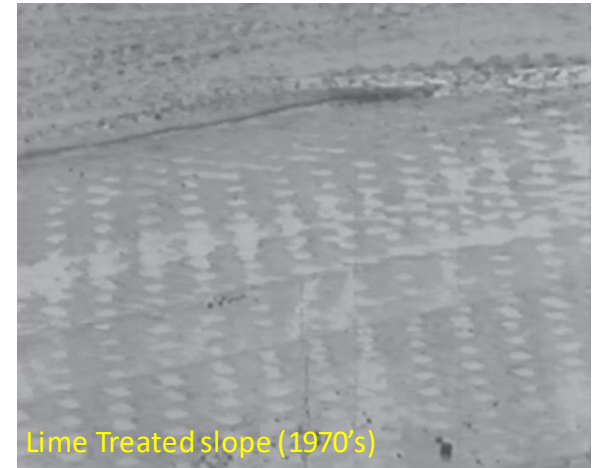
Background – Friant Kern Canal (FKC)



Failed slope



1970's



Lime Treated slope (1970's)



1970's



Lime Treated slope (2019)

(Source: Herrier et. al. 2012)

Case Study Objectives

Goal: To substantiate the long-term durability of lime treatment in hydraulic structures using principles of geochemistry and mineralogy

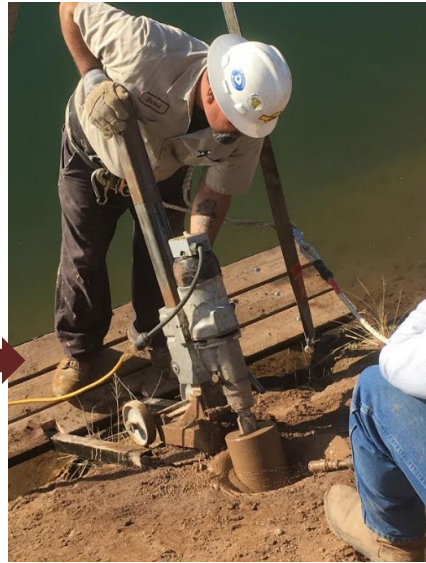
Tasks involved:

- Procure native and nearly 50-year-old lime treated samples from the FKC embankment slopes
- Compare basic engineering properties of the native and lime treated FKC soils collected
- Evaluate mineralogical transformations over time
- Model the long-term chemical reactions in the soil-lime system

Sample Collection at FKC

Rotatory drilling

Lime Treated section



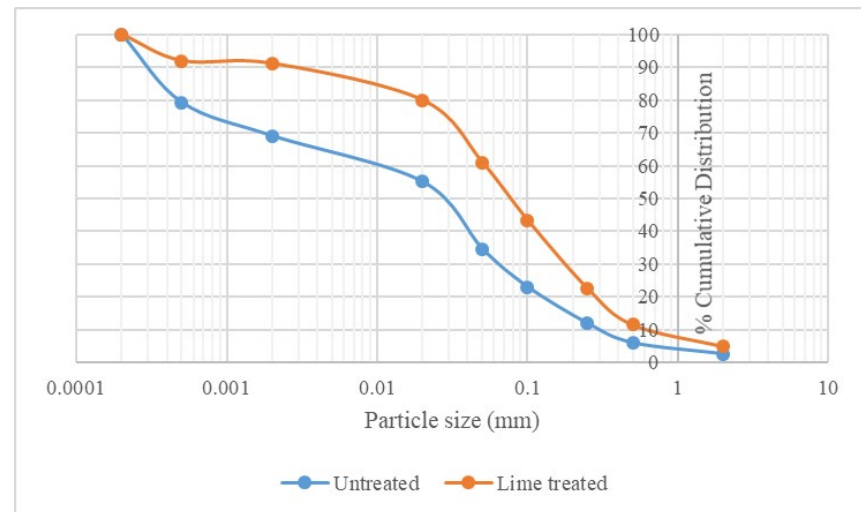
Percussion drilling

Engineering Characterization of FKC Soils

Sample	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (PI) (%)	% passing 75 μm	USCS classification	OMC (%)
Native Soils	41	18	23	69.6	CL	18.1
Lime Treated Soils	34	28	6	48.5	ML	21.4

- Lime treated samples

- Show a decrease in PI
- Silt fraction dropped from 37% to 30% and clay fraction dropped from 30% to 9%.
- Sand fraction increases to 60% from 33%



Engineering Characterization of FKC Soils

Sample	Compressive Strength (psi)		Expansion Potential – ASTM D4829			Relative Erosion Resistance	
	Remolded Strength (psi)	Standard Deviation	Expansion Index (EI)	Standard Deviation	Classification	Absorbance Intensity	Classification
Native soils	12	5	54.9	2.68	Moderate	0.23	High
Lime treated soils	140	15	12.5	0.28	Very low	0.14	Low

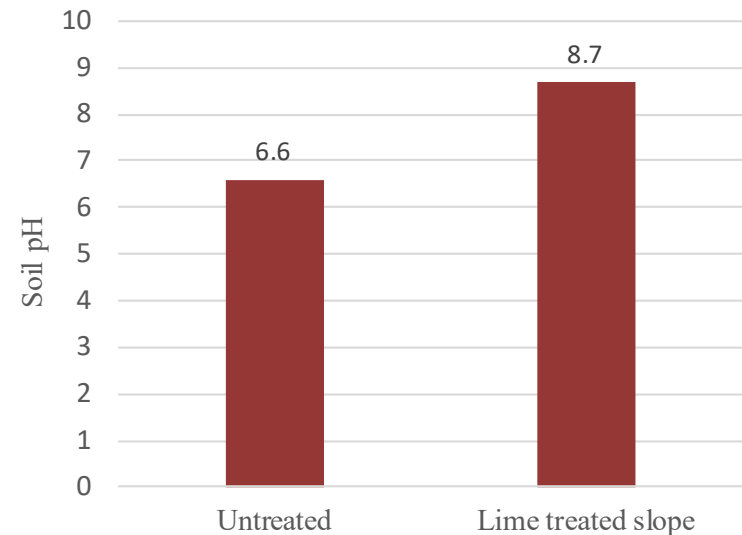
- Lime treated samples
 - Increase in compressive strength.
 - EI reduces from moderate to very low
 - Reduction in erodibility (from absorbance test)

Mineralogical Characterization - XRF and pH

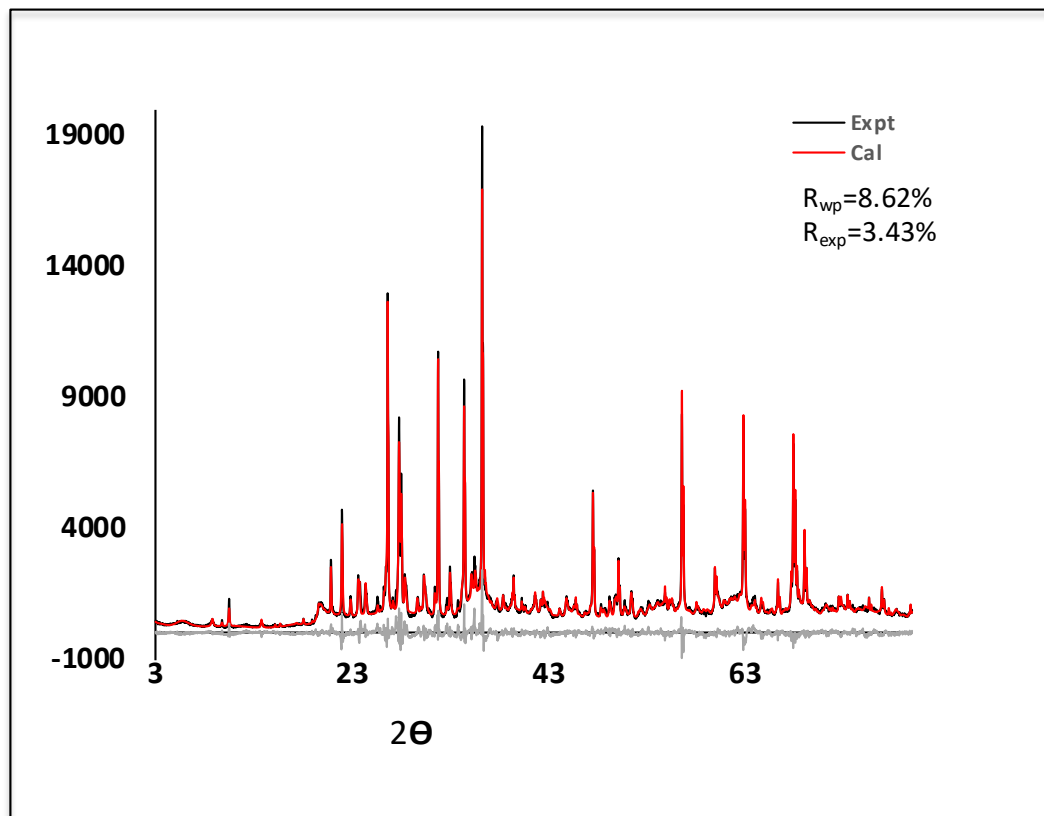
Element/ Composition	Untreated soils (%)	Lime treated soils (%)
CaO	4.7	8.6
SiO ₂	57.2	54.8
Al ₂ O ₃	21.2	20.4
Fe ₂ O ₃	12.4	11.4
SO ₃	0.0	0.0
MgO	3.0	3.0
K ₂ O	1.9	1.1
Na ₂ O	0.6	0.6
Organic Carbon	1.8	1.7

- After ~50 years

- Lime treated samples have 3.9% more CaO indicating negligible leaching.
- As expected, no significant change in Si, Al concentration.
- An increase in pH indicates pozzolanic reaction.



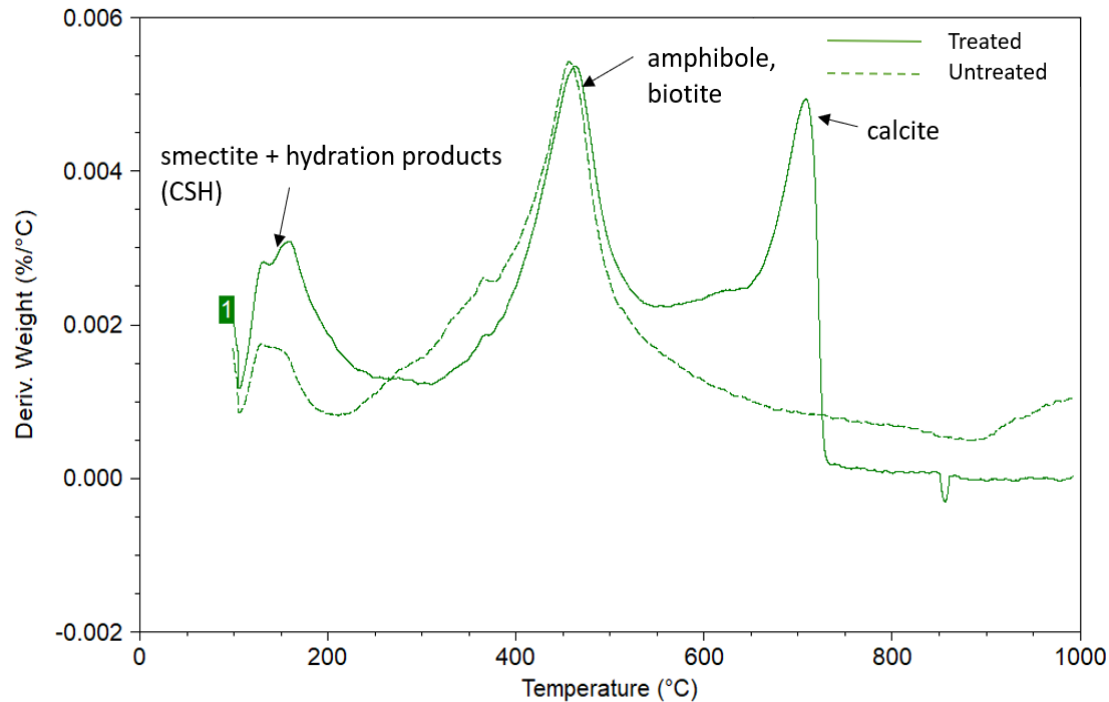
Mineralogical Characterization - XRD



Mineral	Wt. proportion (%)
Augite	1.8
Quartz	11.3
Albite	26.1
Biotite	5.2
Amphibole	8.3
Di-Smectite	39.7
Amorphous phases	7.7

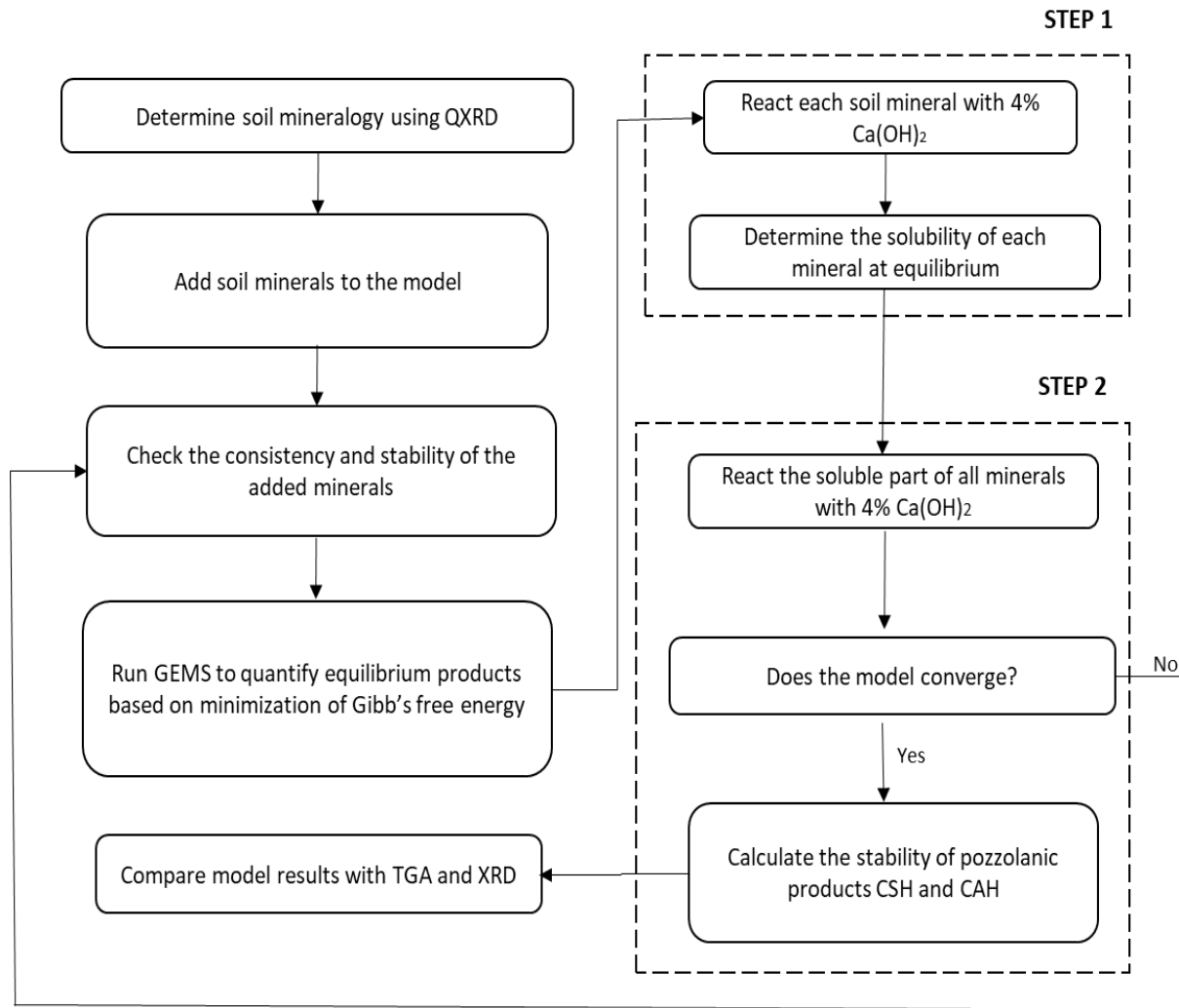
- $R_{wp} < 10\%$ indicates reliable quantitative prediction.
- Insignificant difference between the calculated and the experimental XRD profile
- The untreated samples contains
 - Smectite, an expansive clay mineral is detected. This agrees with the expansion index test.
 - Significant Quartz (SiO_2) content.

Mineralogical Characterization -TGA



- Both native and lime treated samples show dihydroxylation (removal of OH) at 400°C
- In lime treated samples,
 - Weight loss between 100-220°C shows presence of CSH in treated samples
 - Calcite formation due to carbonation of CaO is seen in the treated samples

Thermodynamic Modeling - Steps



Thermodynamic Modeling - Results

STEP 1				STEP 2				
Input			Output	Input		Output		
	Phase	Content (%)	Dissolved content (%)	Phase	Content (%)	Phase	Content (%)	
Sub-model 1	Quartz	11.31	0.00	Primary Model	Quartz	0.00	CSH	8.31
	Atm. air (g)	1.00	-		Albite	1.00	Calcite	2.43
	Ca(OH) ₂	4.00	-		Biotite	0.31		
Sub-model 2	Albite	26.06	1.00		Amphibole	4.00		
	Atm. air (g)	1.00	-		Smectite	7.01		
	Ca(OH) ₂	4.00	-		SiO ₂ (am)	4.00		
Sub-model 3	Biotite	5.18	0.31		Atm. air	1.00		
	Atm. air (g)	1.00	-		Ca(OH) ₂	4.00		
	Ca(OH) ₂	4.00	-		CO ₂ (g)	1		
Sub-model 4	Amphibole	8.26	4.00					
	Atm. air (g)	1.00	-					
	Ca(OH) ₂	4.00	-					
Sub-model 5	Smectite	39.70	7.01					
	Atm. air (g)	1.00	-					
	Ca(OH) ₂	4.00	-					

A two-step approach was adopted

- **Step 1:** Determine the reactivity (dissolution) of soil mineral when 4% of Ca(OH)₂ is added.
 - As expected, smectite is highly reactive (High pH favors smectite dissolution)
 - Amphiboles and biotite are lesser reactive minerals.
- **Step 2:** React dissolved minerals to determine the stability of when Ca(OH)₂ is added.
 - As indicated by the TGA analysis, CSH is calculated to be thermodynamically stable.
 - In addition, calcite formed due to carbonation is also stable in equilibrium.

Conclusions

- FKC stands out as example of the efficacy of using lime treatment in hydraulic structure.
- The long-term durability of lime treatment in hydraulic structures was established by demonstrating
 - Permanent textural modification of the clays
 - High long-term compressive strength and low expansion potential and erodibility
 - Presence of significant amounts of 'CaO' in solid phases indicating minimal leaching
 - Presence of CSH and calcite contributing to long-term durability
- Mineralogical evaluation and thermodynamic modeling applying concepts of geochemistry can be used to predict pozzolanic products and supplement engineering tests.

Questions?



TEXAS A&M UNIVERSITY

Zachry Department of
Civil & Environmental Engineering

Advanced Engineering and Mineralogical Characterization Methods for Soil Stabilization Studies

Anand J. Puppala, PhD, PE

Professor and A.P. & Florence Wiley Chair

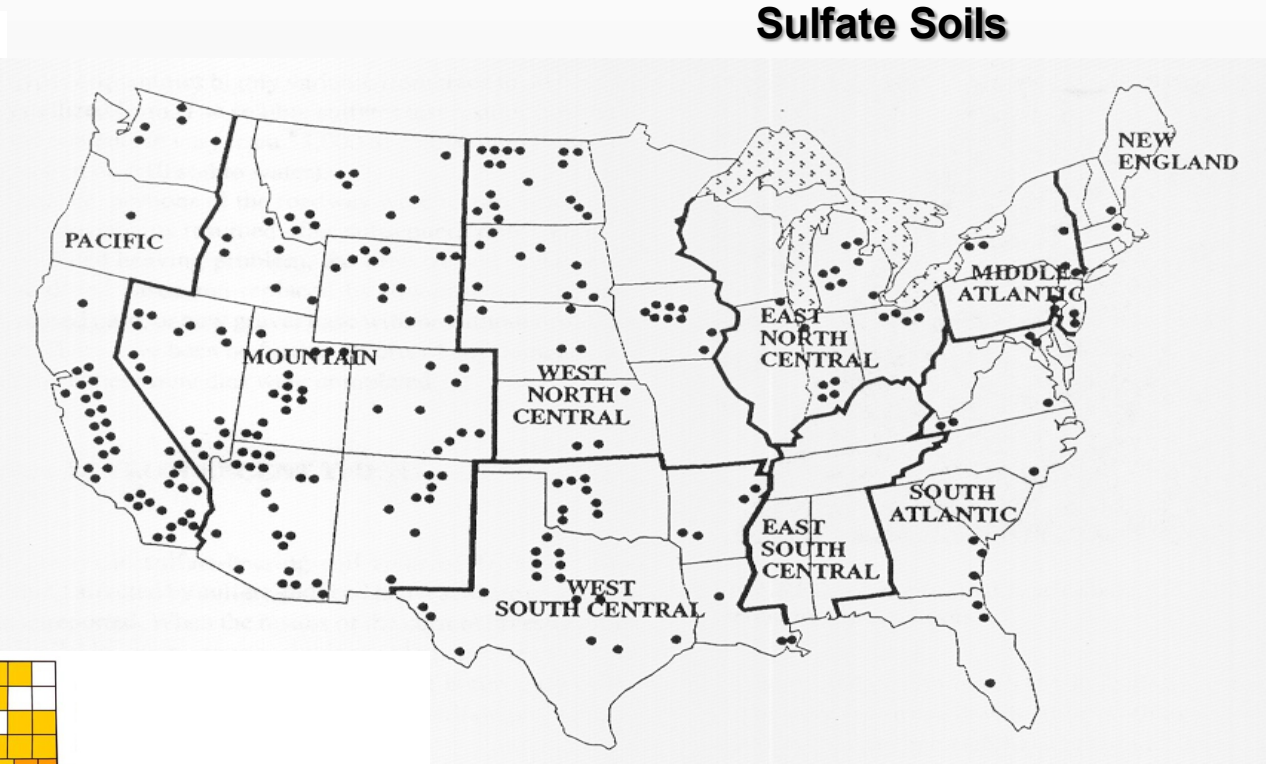
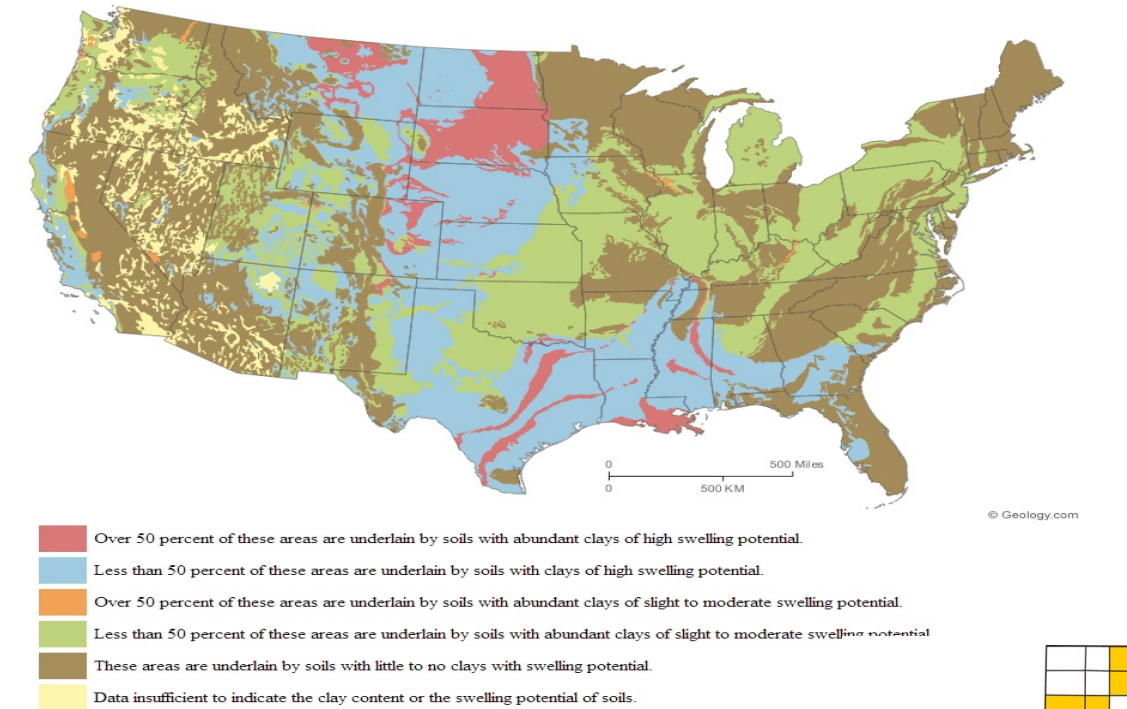
**TRB AKG 90 Webinar: Application of Geochemistry and Mineralogy
in Chemical Soil Stabilization**

April 2021

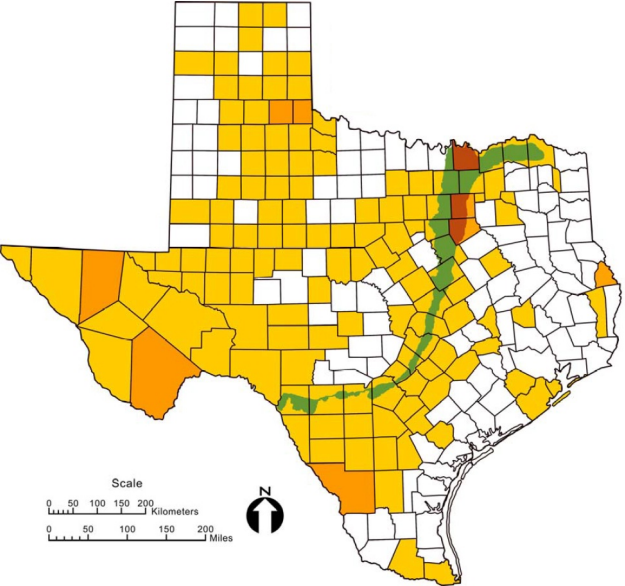
Presentation Outline

- 1. Introduction and Background**
- 2. Stabilization of Soils: Low-Sulfate & High-Sulfate**
- 3. Engineering Characterization**
- 4. Mineralogical Characterization**
- 5. Three Experimental Studies:**
 - I. Geopolymer (GP) Treatment of Sulfate Soils**
 - II. Treating Gypseous Soil Using Carbide Slag (CS)-Ground Granulated Blast Furnace Slag (GGBS)**
 - III. Crystalline Silica Fines Treatment of Sulfate Soils**
- 6. Summary Comments**

Introduction and Background



Source: USGS Surveys
Expansive and Sulfate Soils in USA



Focus of my presentation is on sulfate soil; however same is applicable to problematic soils we encounter in the field!

Introduction and Background

➤ Traditional Ca-based stabilizers → Treat problematic soils

➤ Treated soils

- ❖ Workability ↑; Strength ↑; Stiffness ↑; Durability ↑
- ❖ Water affinity ↓; Swell-Shrink ↓

➤ Not suitable for sulfate-laden soils

- ❖ Ettringite
- ❖ Thaumasite



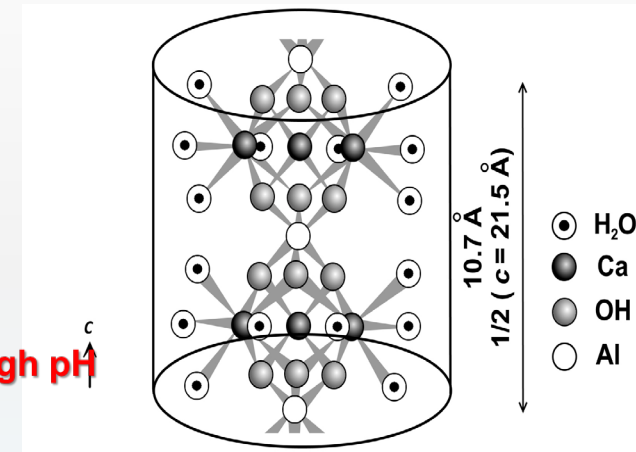
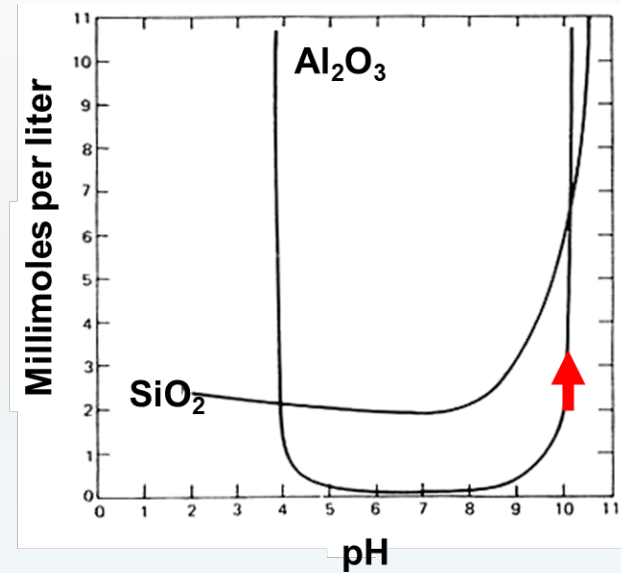
Gypsum
Crystals in Soil
Formation



Introduction and Background

➤ Sources of sulfates in soil

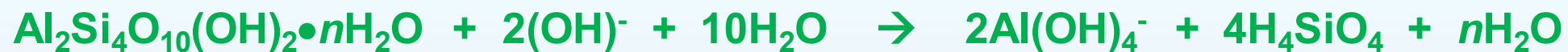
- ❖ Gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$)
- ❖ Sodium Sulfate (Na_2SO_4)
- ❖ Magnesium Sulfate (MgSO_4)



Ettringite Mineral Structure



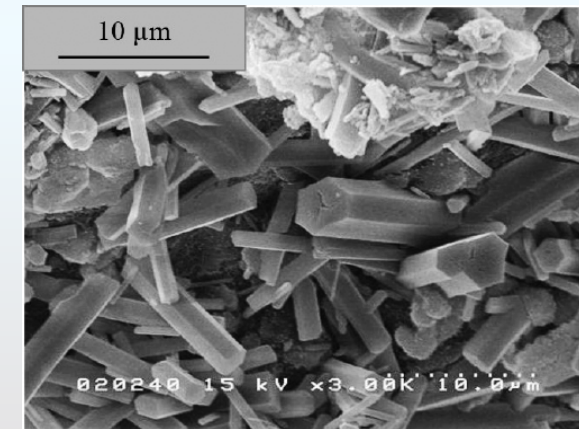
(Dissolution of Lime in Water)



(Dissolution of clay mineral at $\text{pH} > 10.5$, Free Alumina)



(Formation of Ettringite, expansive mineral)

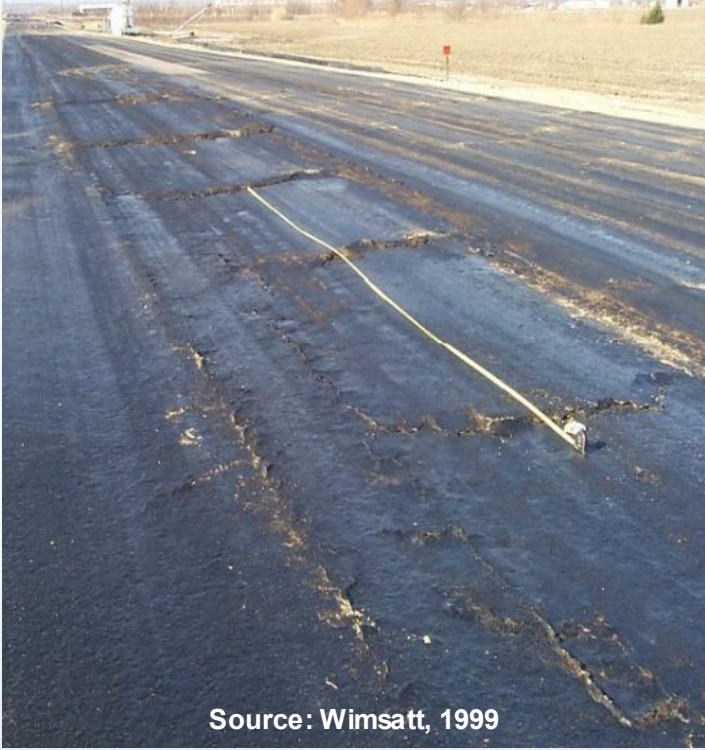


Introduction and Background

Heaving on Joe Pool Lake Road, Grand Prairie, Texas



Heaving on US 67, Midlothian, Texas



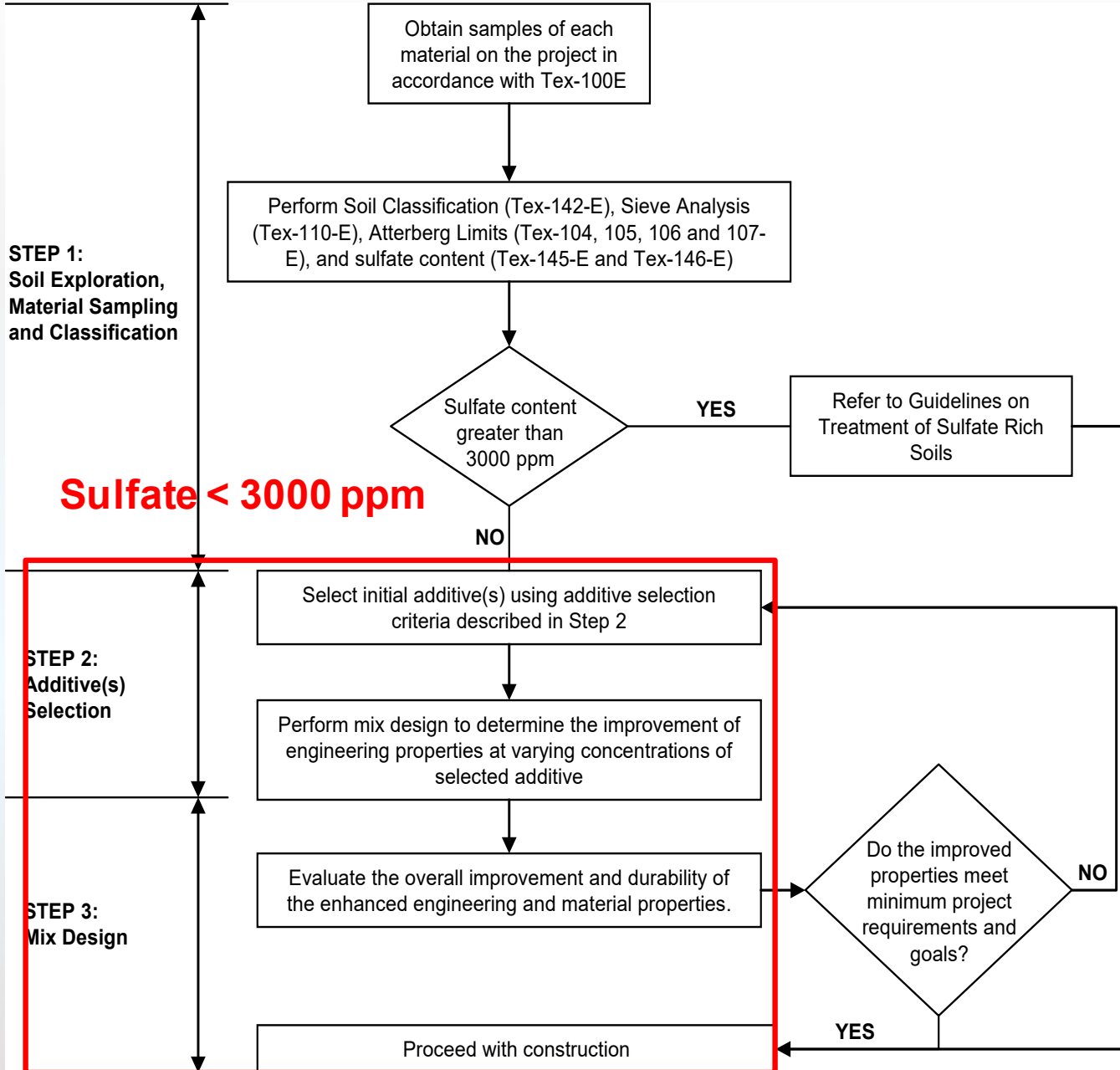
Subsoils Near DFW Airport



Introduction and Background

Location	Soil Type	Reaction products	Lime(L)/ Cement(C) %	Sulfate Content (mg/kg)	Heave Appearance after Construction
Parking Lots, Kansas, Southern California	N/A	Ettringite	NA	NA	NA
Stewart Avenue, Las Vegas, Nevada	Silty clay	Ettringite and Thaumasite	4.5% (L)	43,500	6 months
Lloyd Park, Joe Pool Lake, Dallas, Texas	OC Clays	Ettringite	5% (L)	2,000 – 9,000	Immediately
Auxiliary Runway, Laughlin AFB, Spofford, Texas	Clays	Ettringite	6-9% (L)	14,000 – 25,000	2 months
Cedar Hill State Park, Joe Pool Lake, Dallas, Texas	Highly plastic residual clays	Ettringite	6% (L)	21,200	2 months
Denver International Airport, Denver, Colorado	Expansive Clays	Ettringite	NA (L)	2,775	NA
SH-118, Alpine & SH-161, Dallas	Clayey Subgrades	Ettringite	4% (C) 6-7%(L)	>12,000	6 to 18 months
Dallas – Fort Worth International Airport, Irving, Texas	Clay	Ettringite	5% (L)	320 – 13,000	3 months
Near Shreveport, Louisiana	Aggregates	Ettringite	NA	NA	NA
Holloman Air Force Base, NM	Crushed Concrete	Ettringite	NA	NA	Several years
U.S.82,TX	N/A	Ettringite	6%(L)	100-27800	Immediately
Baylor Creek Bridge, Childress, TX	All soils	Ettringite	5%(L); 3%(C)	6800-35000	Several years
Western Oklahoma	Clays	Ettringite	0-5%(L)	194-84000	NA

Stabilization of Soils: Low Sulfate Soils – Mature Practice!



TxDOT Practice

Primarily based on PI

Moderate to High Sulfate Soils – Research and Practice

➤ Sulfate Levels < 8000 ppm

- ✓ Low Risk: < 3000
- ✓ Medium Risk: 3000 to 5000ppm
- ✓ Moderate to High Risk: 5000 to 8000ppm

➤ Sulfate Levels > 8000ppm

- ✓ High Sulfate Soil: Severe Concern
- ✓ Lime/Cement Stabilization to be Avoided
- ✓ Remove and Replace Sulfate Soils or Blend in Non-Plastic Soils

Treatments for Sulfate Soils

- ❖ Ground Granulated Blast Furnace Slag (GGBFS)
 - ✓ Shown to be effective
- ❖ Class F Fly Ash
- ❖ Sulfate Resistant Cements
 - ✓ Results show successful stabilization
- ❖ Mellowing / Double Lime Treatment
 - ✓ Mixed results
 - ✓ Reappearance of heave

Stabilization of Moderate to High Sulfate Soils

➤ **Sulfate Resistant Cements: Type II and Type V**

- ❖ **Laboratory Results Show Successful Stabilization**

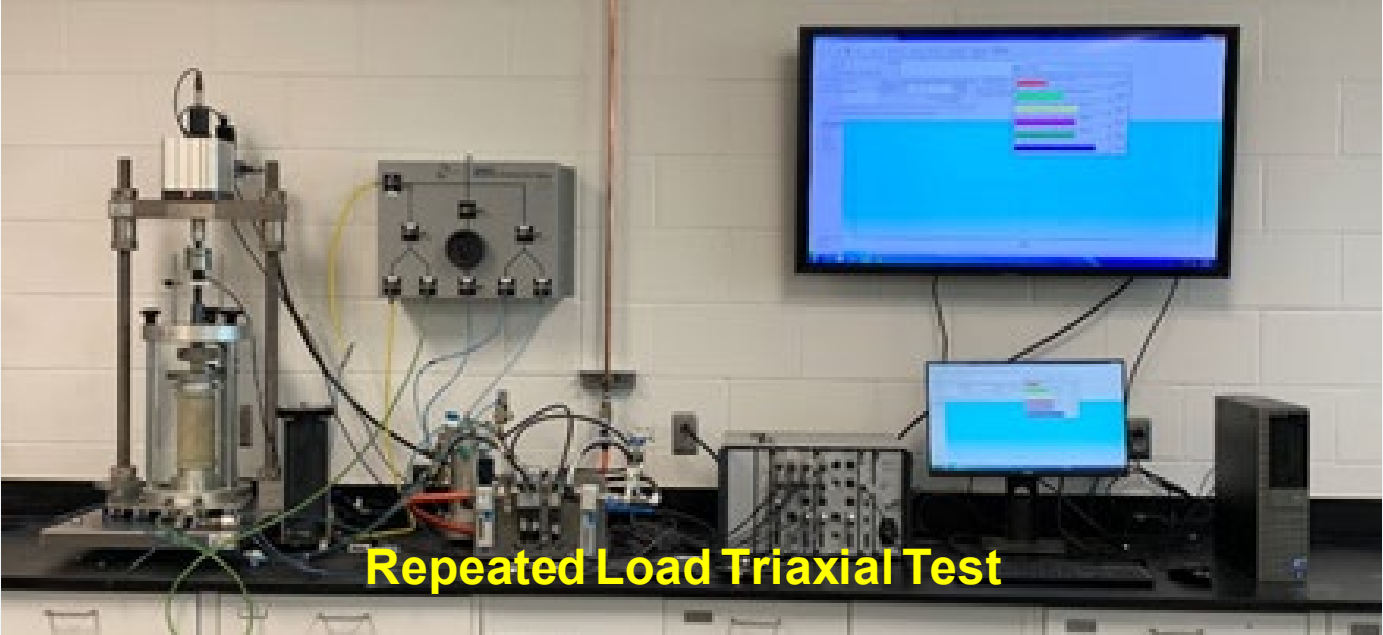
➤ **Lime Treatment**

- ❖ **Extended Mellowing**
- ❖ **With Class F Fly Ash**

➤ **Ground Granulated Blast Furnace Slag (GGBS)**

- ❖ **Shown to be Successful in US and UK**
- ❖ **On-Going Study in Singapore**

Engineering Characterization: Performance Tests



Repeated Load Triaxial Test



1-D Free Swell Tests

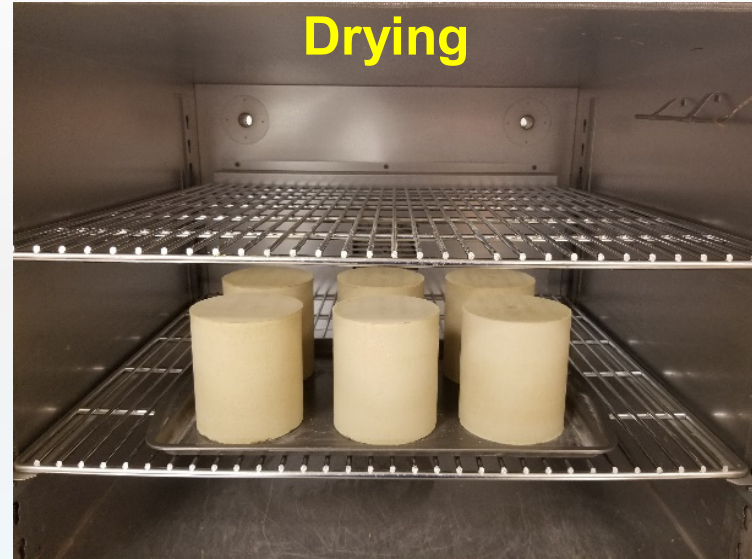
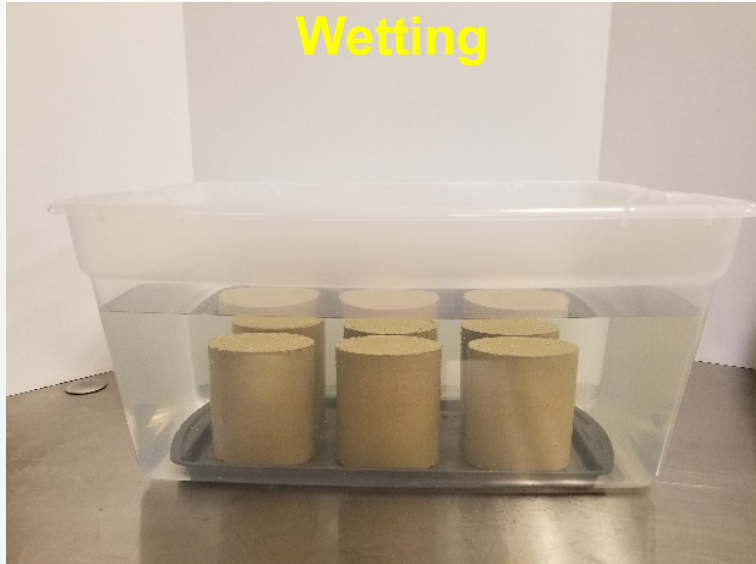


Linear Shrinkage Tests



Unconfined Compression Test

Engineering Characterization: Durability Tests



ASTM D 559

5 hrs wetting

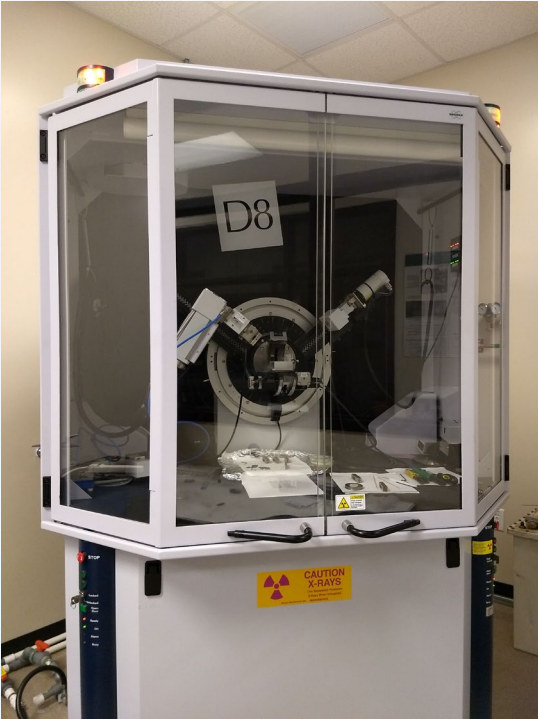
+

42 hrs drying at 70 °C



**Effect of
wetting and
drying cycles
- Durability**

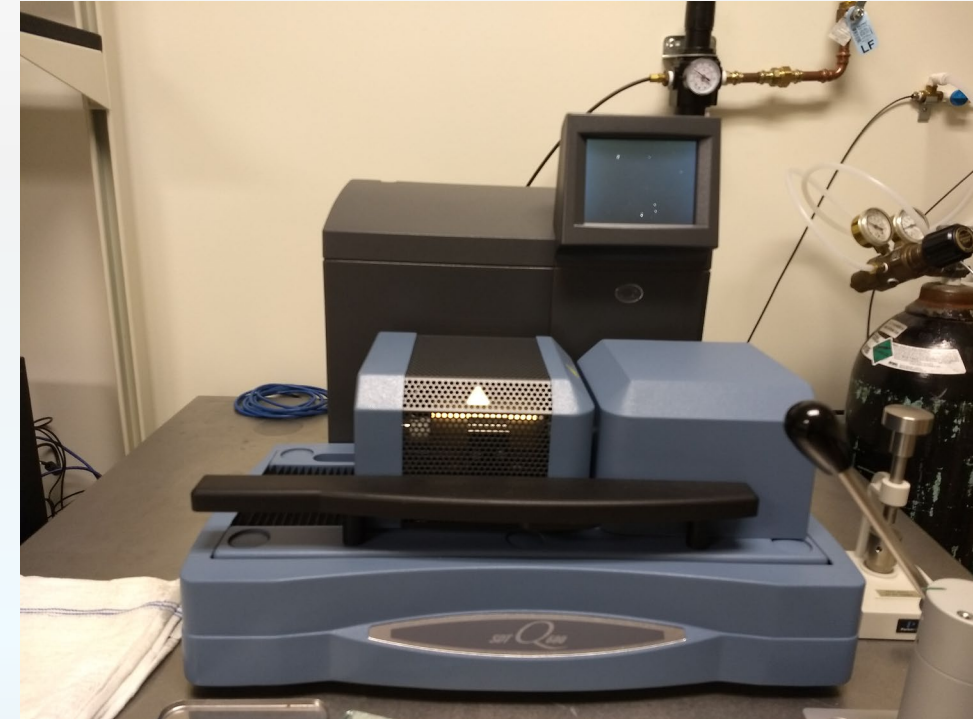
Mineralogical Characterization : Chemical & Mineralogical Tests



**X-Ray Diffraction
(XRD)**



**Scanning Electron Microscope
(SEM) Imaging and Energy
Dispersive X-Ray
Spectroscopy (EDXS)**



**Differential Scanning
Calorimetry (DSC)**

Three Experimental Studies:

I. GeoPolymers

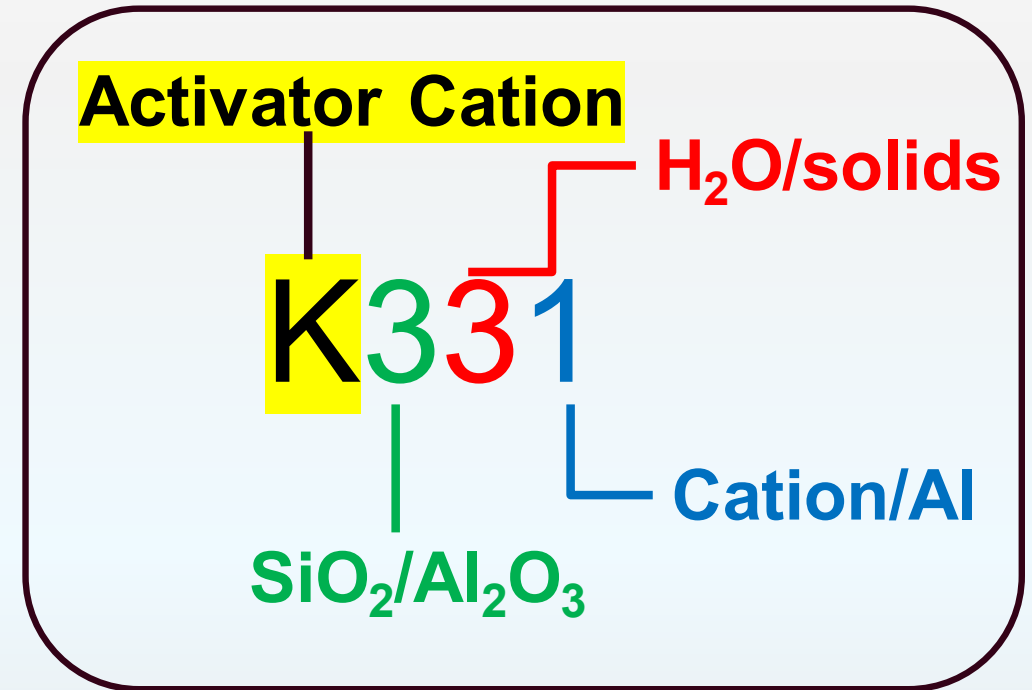
II. Slags

III. Crystalline Silica Admixture

I. Geopolymer (GP) Treatment of Sulfate Soils

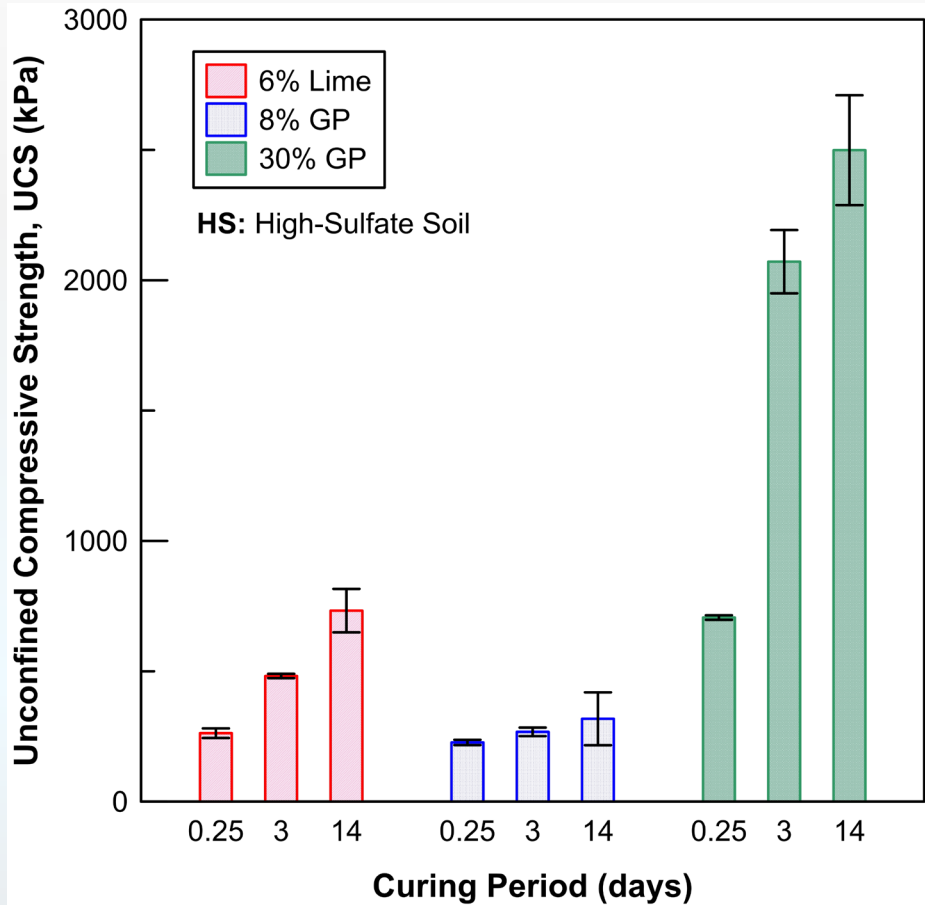
Geopolymer Development and Characterization

- $M_n(-(\text{SiO}_2)_z-\text{AlO}_2) \cdot w\text{H}_2\text{O}$
 - **M** is a monovalent cation (K, Na, etc.)
 - **z** is the molar ratio $\text{SiO}_2/\text{Al}_2\text{O}_3$
 - **n** is a molar ratio M/Al
 - **w** is water molar amount ($\text{H}_2\text{O}/(\text{SiO}_2+\text{Al}_2\text{O}_3)$)
- Utilization of **metakaolin** as a pure source of aluminosilicate for better control of different parameters
 - Instead of fly ash which is inconsistent and becoming more expensive

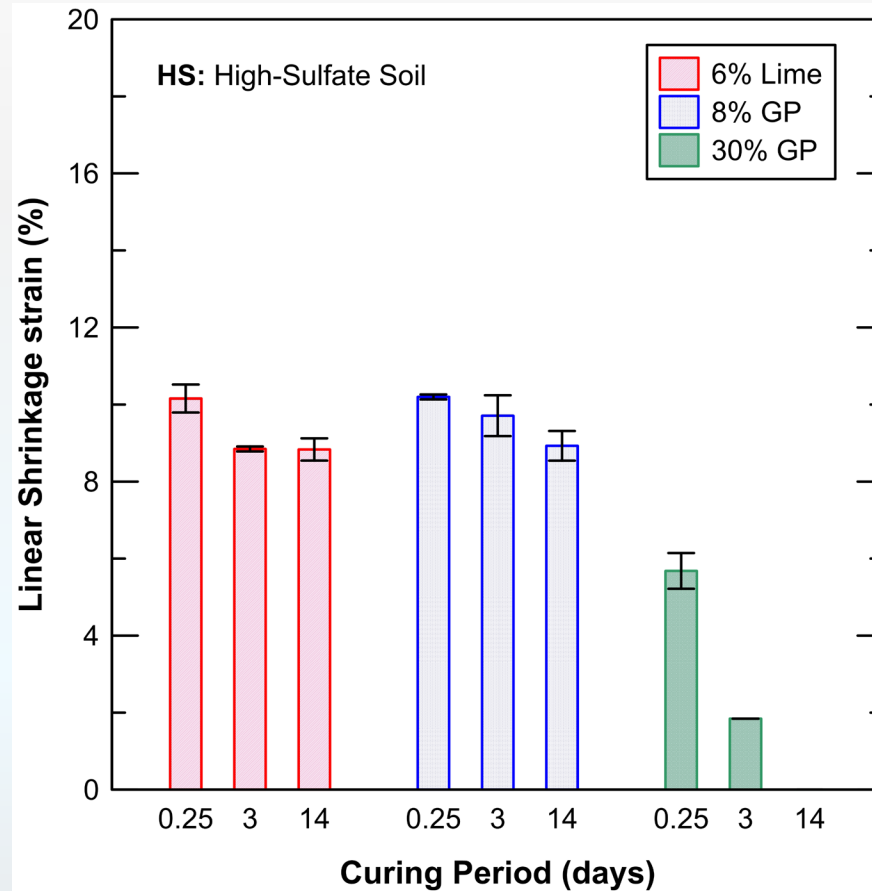


I. Geopolymer (GP) Treatment of Sulfate Soils

GP Test Results – UCS and Linear Shrinkage Test



Unconfined Compressive Strength (UCS) of Natural Soil = 145 kPa



Linear Shrinkage Strain of Natural Soil = 15.1%

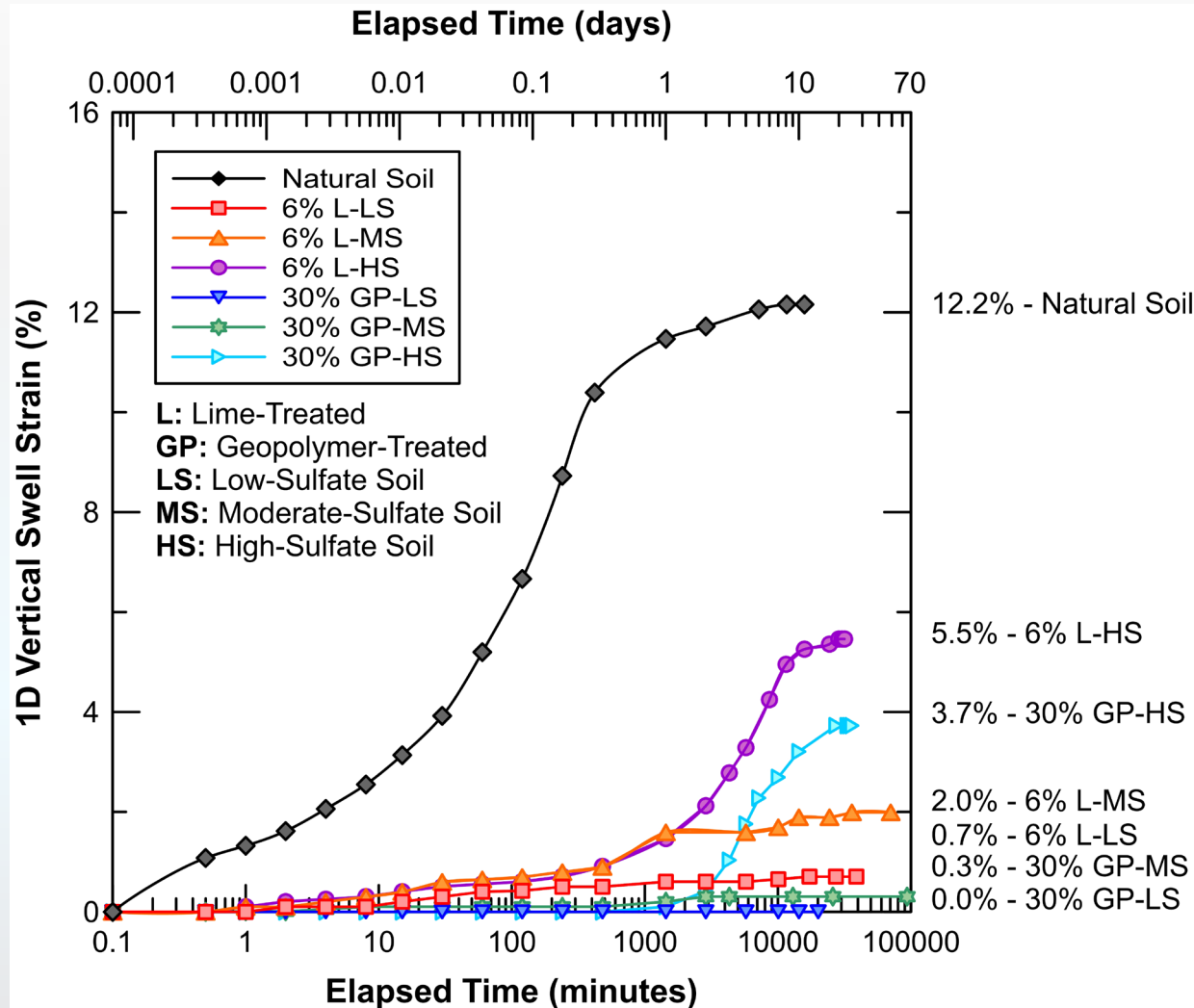
Shrinkage strain decreases with:

- ❖ Increase in GP dosage
- ❖ Longer curing period

Strength improvement with curing time: 8% Geopolymer \leq 6% Lime < 30% Geopolymer

I. Geopolymer (GP) Treatment of Sulfate Soils

GP Test Results – 1D Free Swell Tests



* Treated soil samples cured for 3 days

- **Immediate swelling**
 - ❖ Natural soil → Clay mineral swelling
 - ❖ Lime and GP treatment reduced clay mineral swelling
- **Swelling after 1 day of soaking**
 - ❖ Ettringite-induced swelling in lime-treated high-sulfate soil
 - ❖ Swelling after GP-treatment < lime treatment



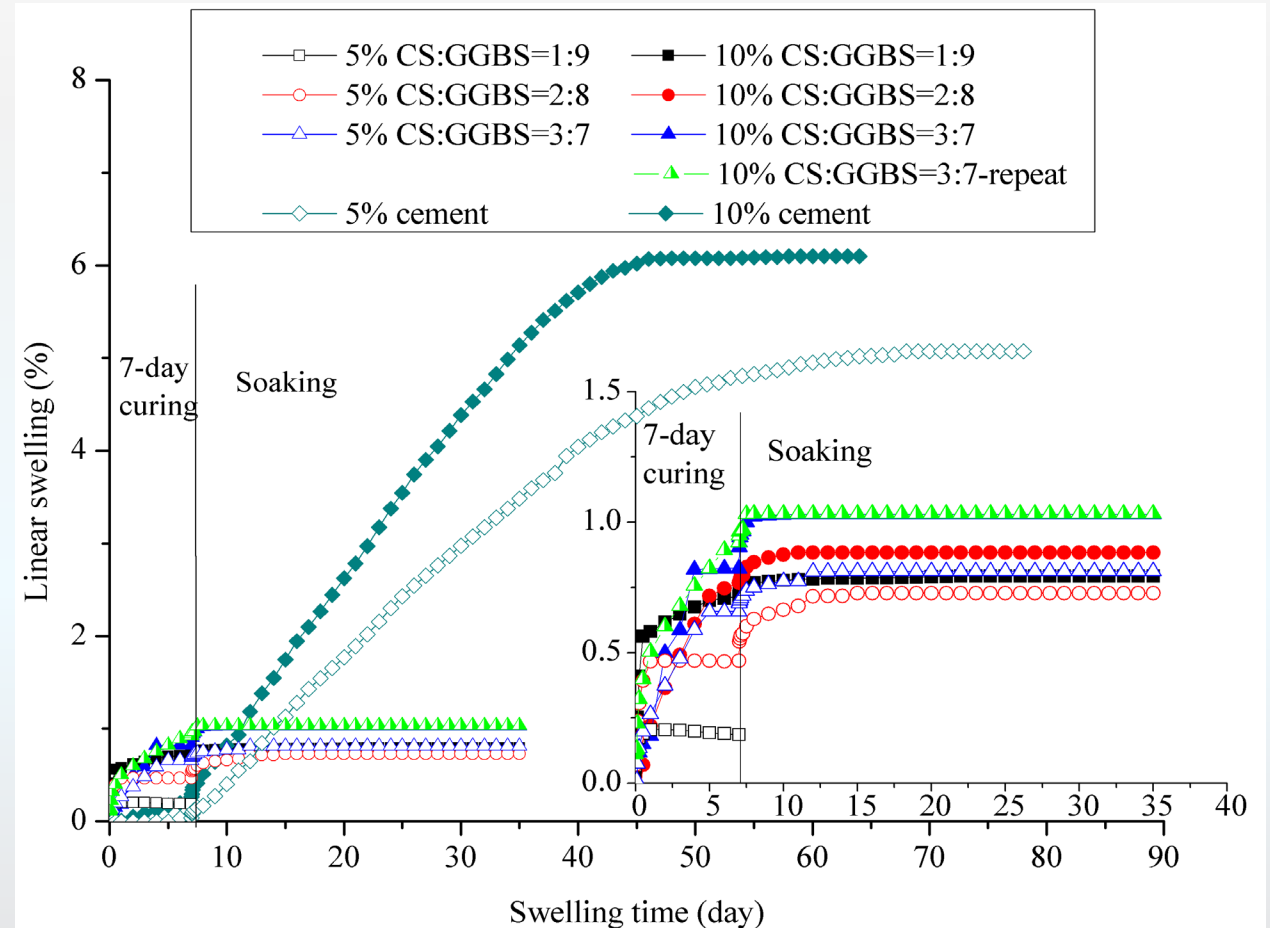
Metakaolin-based Geopolymer is effective in reducing sulfate heaving

II. Treating Gypseous Soil Using Carbide Slag (CS)-Ground Granulated Blast furnace Slag (GGBS)

- CS is by-product from acetylene gas production, GGBS is by-product from steel making
- Swell significantly less
- Cease swell earlier

**Collaborator: Dr. Yaolin Yi,
Nanyang Technological
University (NTU), Singapore**

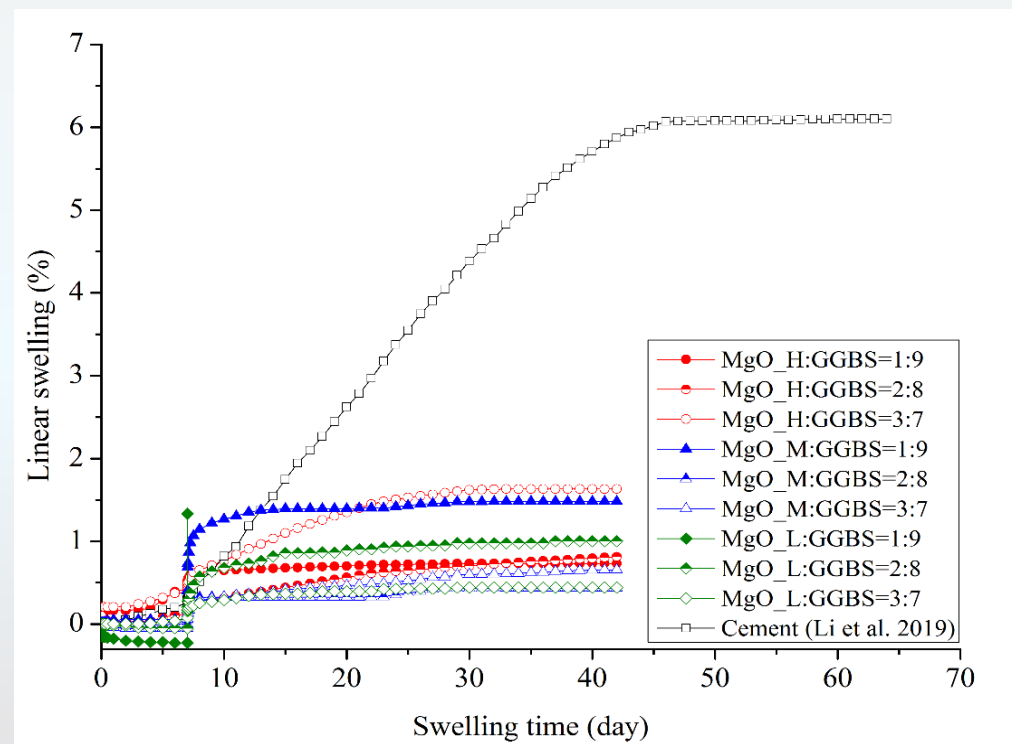
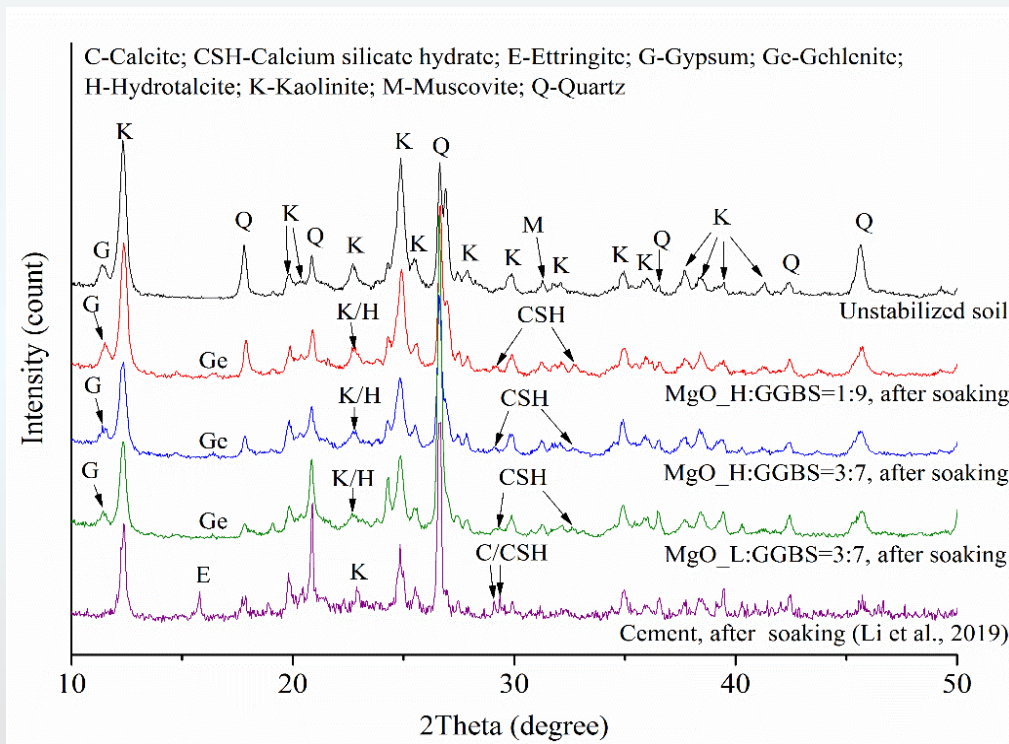
yiyaolin@ntu.edu.sg



Li, W., Yi, Y. & Puppala, A.J. (2019). Utilization of carbide slag-activated ground granulated blastfurnace slag to treat gypseous soil. *Soils & Foundations*, 10.1016/j.sandf.2019.06.002.

II. Treating Gypseous Soil Using Carbide Slag (CS)-Ground Granulated Blast furnace Slag (GGBS)

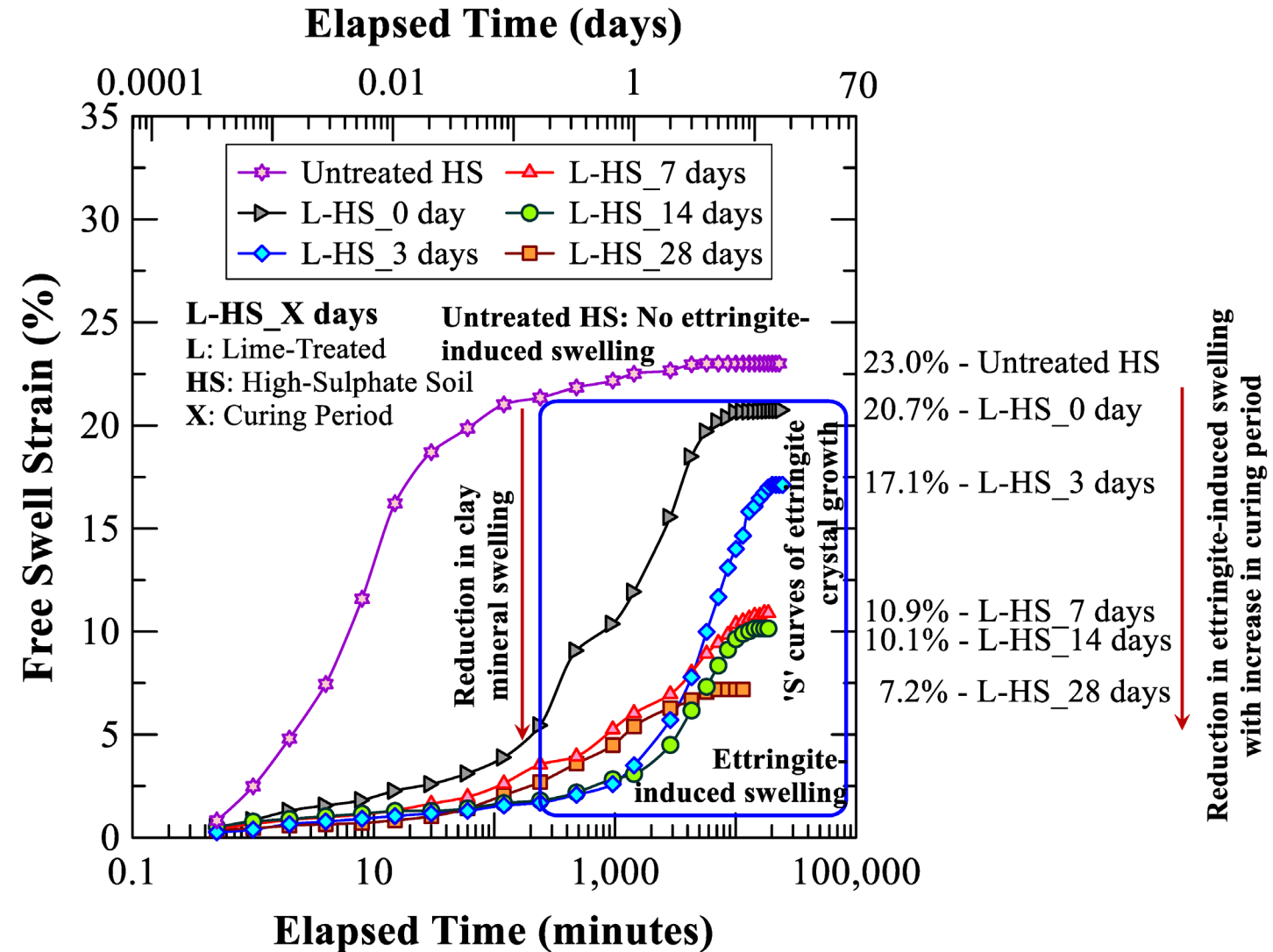
- Reactive MgO is calcinated at low temperatures of 700–800° C
- Gypsum remain unreacted, NO ettringite produced
- Swell less, cease swell earlier



III. Crystalline Silica Admixture Treatment of Sulfate Soils

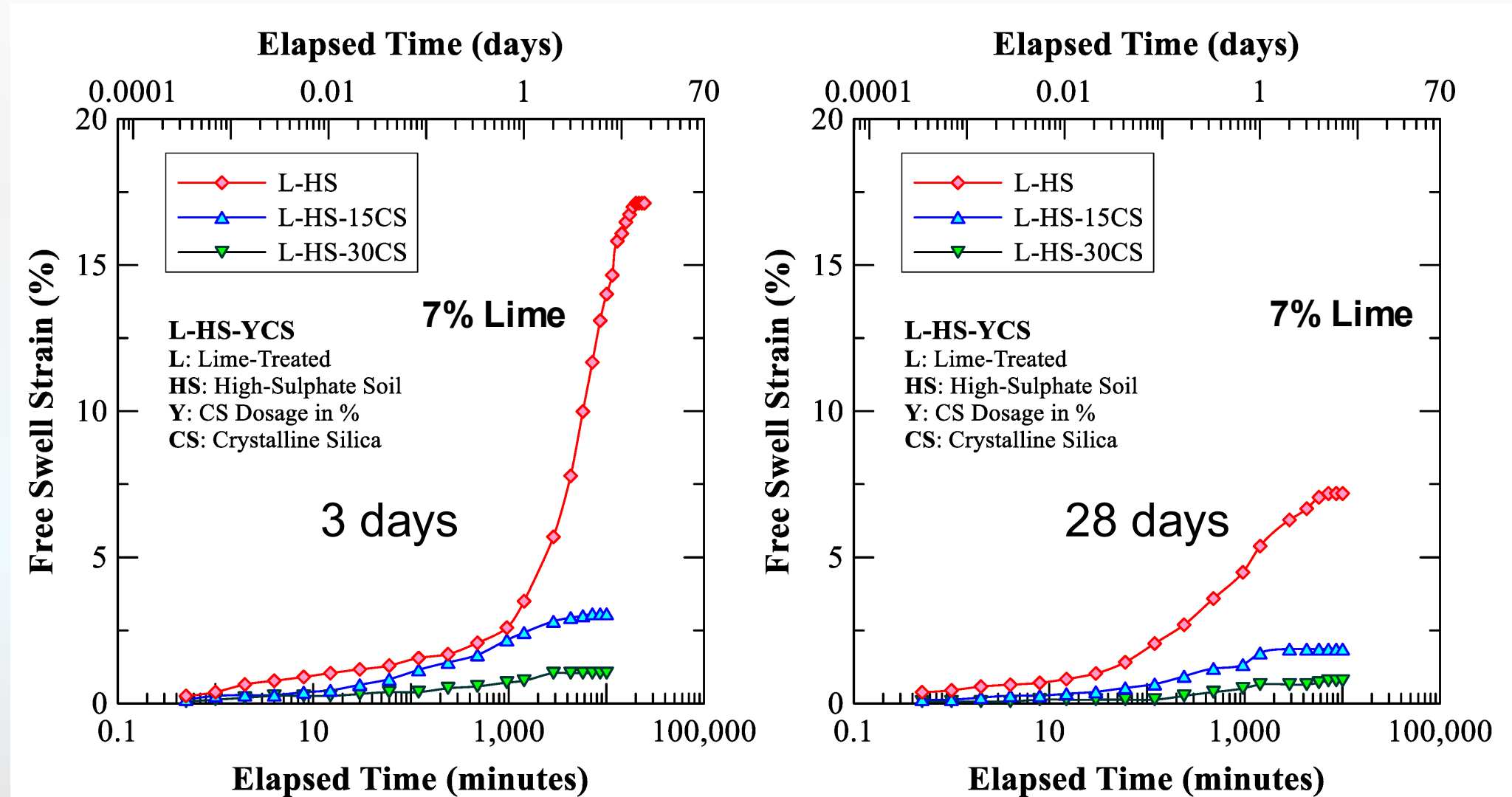
1D Free Swell Tests

- Lime treatment (7%) → Clay mineral-induced swelling ↓
- Ettringite-induced swelling observed in lime-treated specimens
- High swelling characteristics even after 28 days of curing



III. Crystalline Silica Admixture Treatment of Sulfate Soils

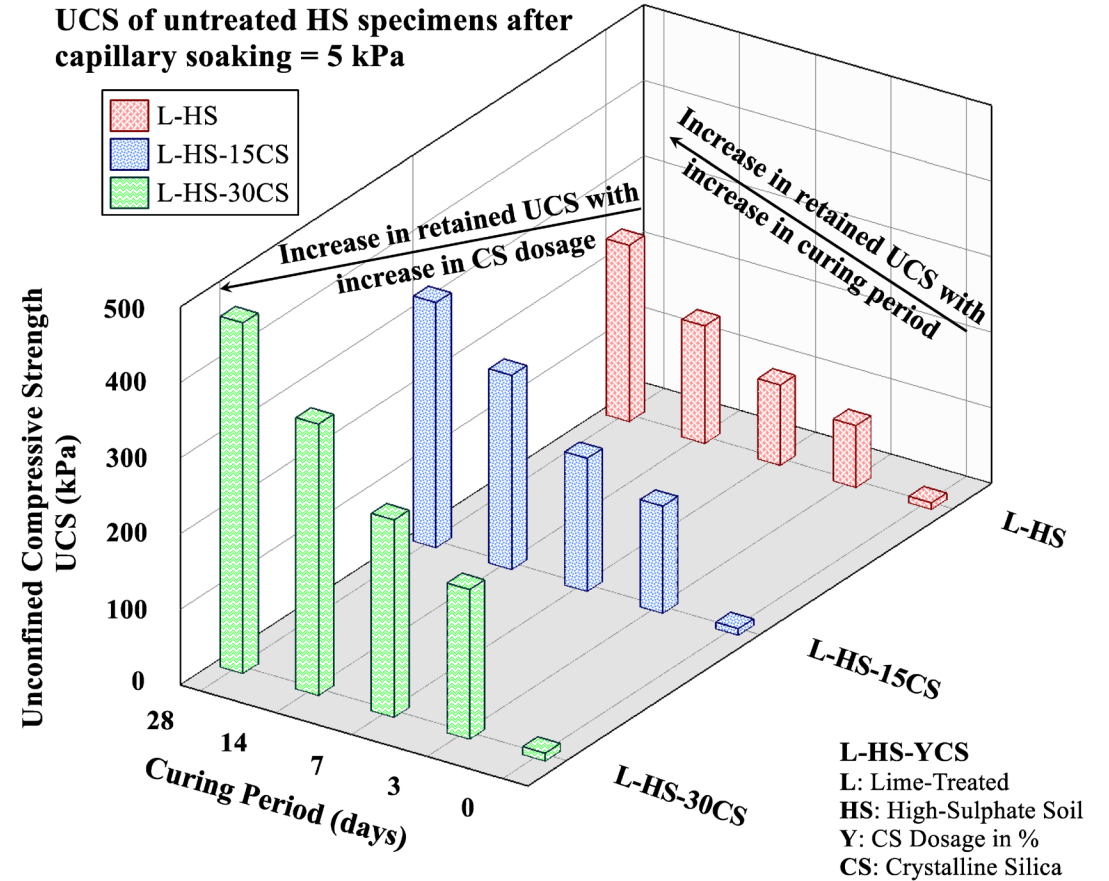
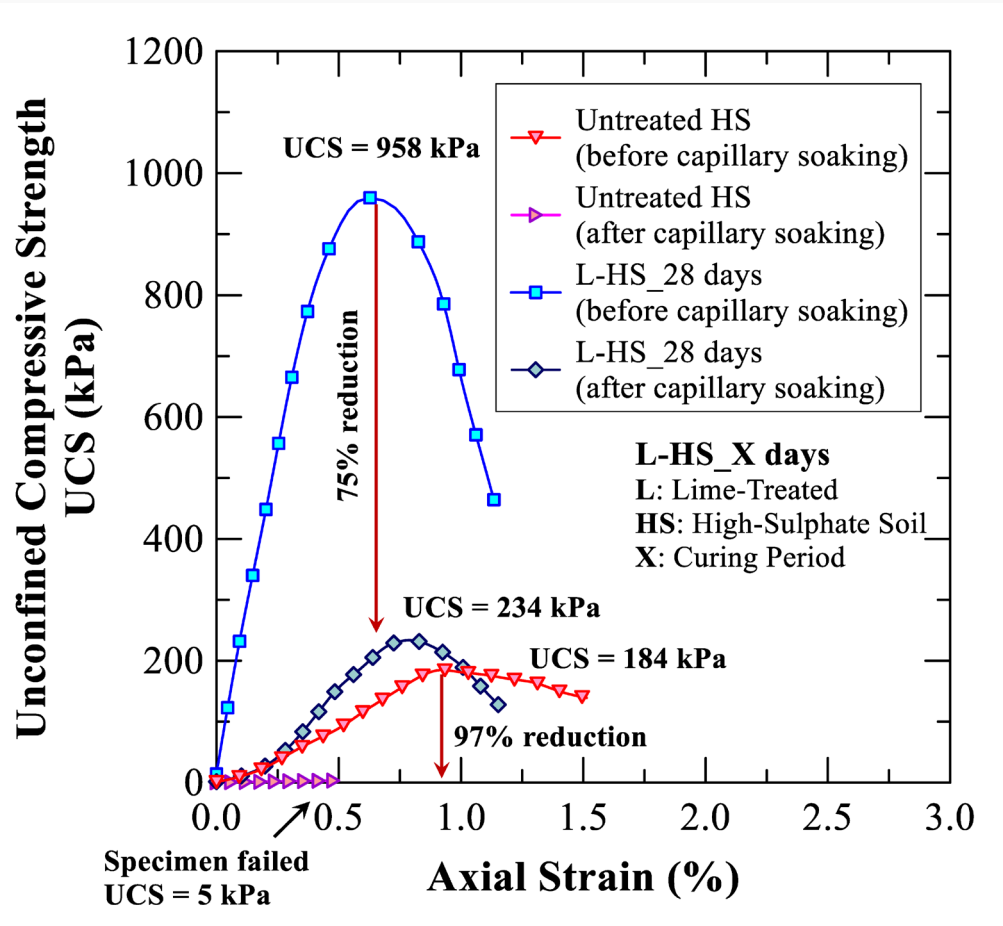
1D Free Swell Tests



Chakraborty, S., Puppala, A.J. and Biswas, N., 2021. Role of crystalline silica admixture in mitigating ettringite-induced heave in lime-treated sulfate-rich soils. *Géotechnique*, pp.1-17.

III. Crystalline Silica Admixture Treatment of Sulfate Soils

UCS Test and Durability



Crystalline Silica helps to improve the retained strength → Durable ↑

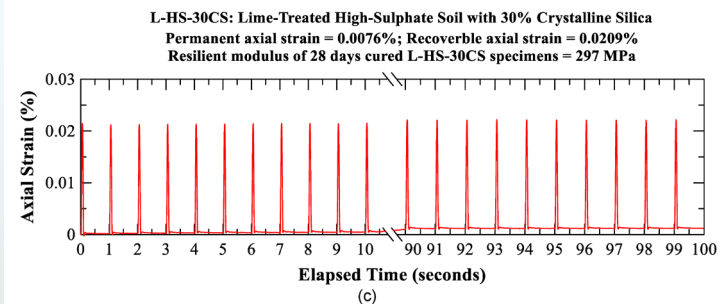
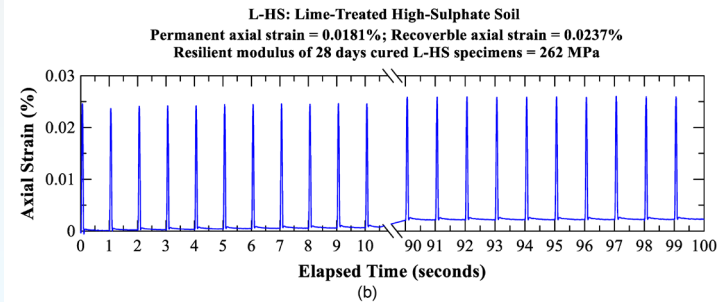
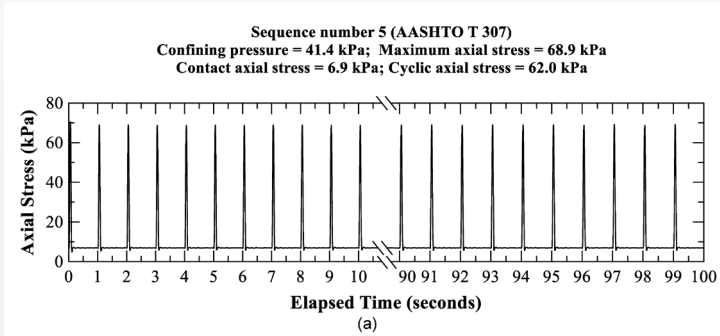
Chakraborty, S., Puppala, A.J. and Biswas, N., 2021. Role of crystalline silica admixture in mitigating ettringite-induced heave in lime-treated sulfate-rich soils. *Géotechnique*, pp.1-17.

III. Crystalline Silica Admixture Treatment of Sulfate Soils

Resilient Modulus (M_r)

$$M_r = k_1 P_a \left(\frac{\theta}{P_a} \right)^{k_2} \left[\left(\frac{\tau_{oct}}{P_a} \right) + 1 \right]^{k_3}$$

where M_r is the resilient modulus; k_1 , k_2 and k_3 are model constants; θ is the bulk stress; P_a is the atmospheric pressure; and τ_{oct} is the octahedral shear stress.

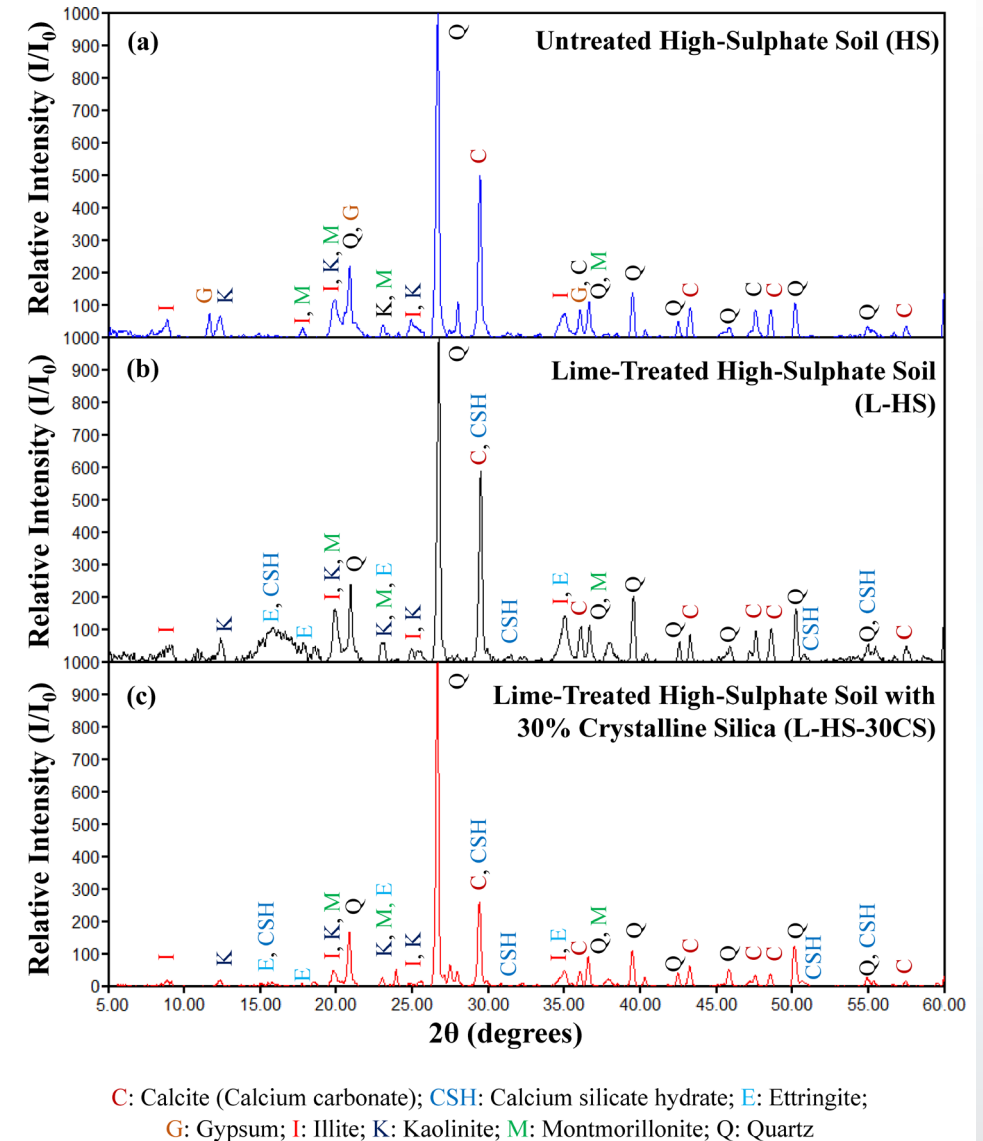
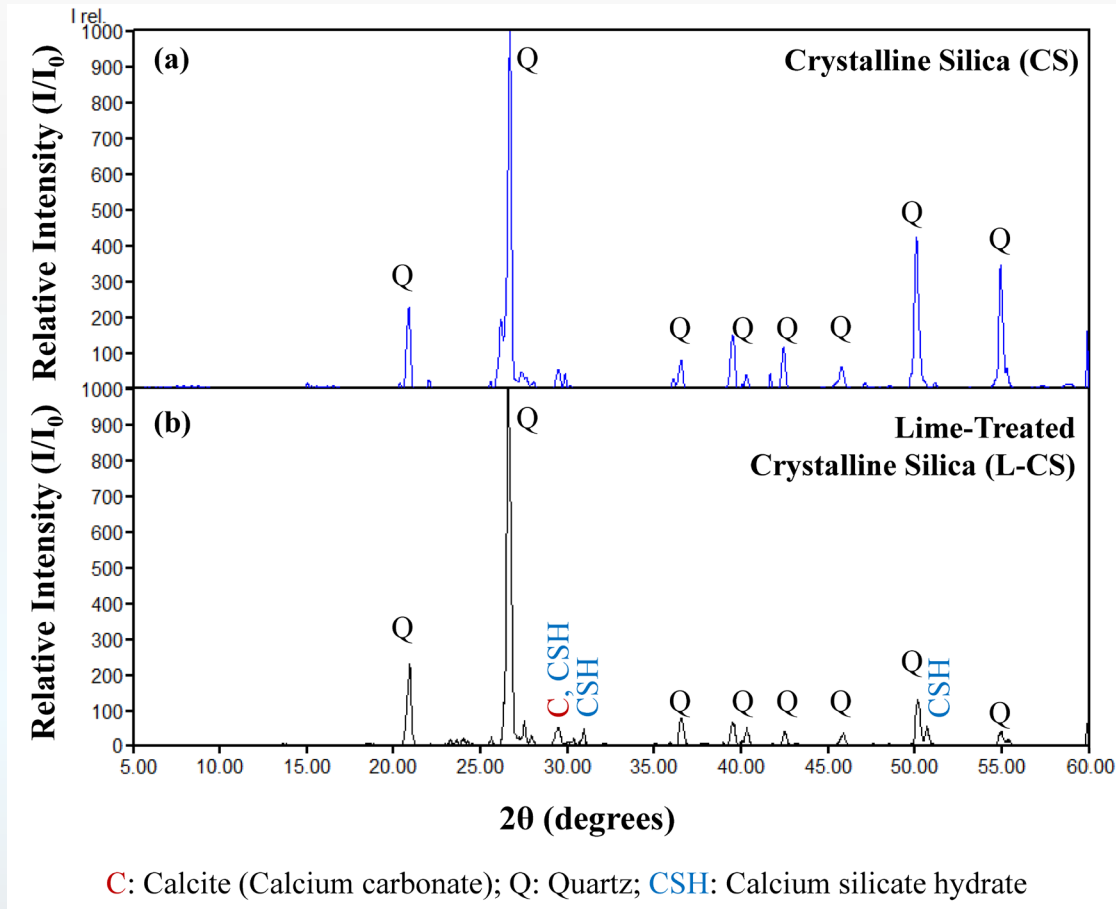


Curing period (days)	k_1		k_2		k_3		R^2	
	L-HS	L-HS-30CS	L-HS	L-HS-30CS	L-HS	L-HS-30CS	L-HS	L-HS-30CS
0	1473	1449	0.128	0.175	0.161	0.358	0.90	0.94
3	1676	1684	0.131	0.171	0.233	0.383	0.97	0.96
7	1877	1920	0.169	0.138	0.310	0.413	0.94	0.93
14	2002	2136	0.127	0.169	0.499	0.505	0.91	0.91
28	2049	2147	0.151	0.152	0.562	0.797	0.90	0.93

Crystalline silica (CS) admixture $\rightarrow M_r$ values \uparrow

III. Crystalline Silica Admixture Treatment of Sulfate Soils

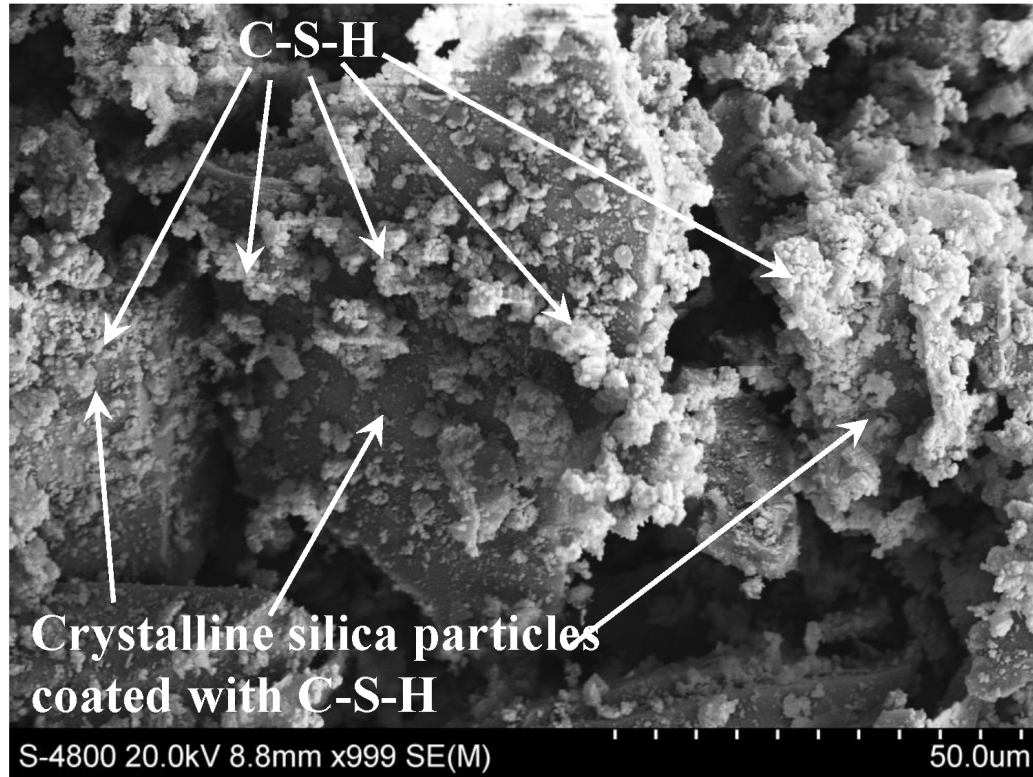
X-ray Diffraction Studies



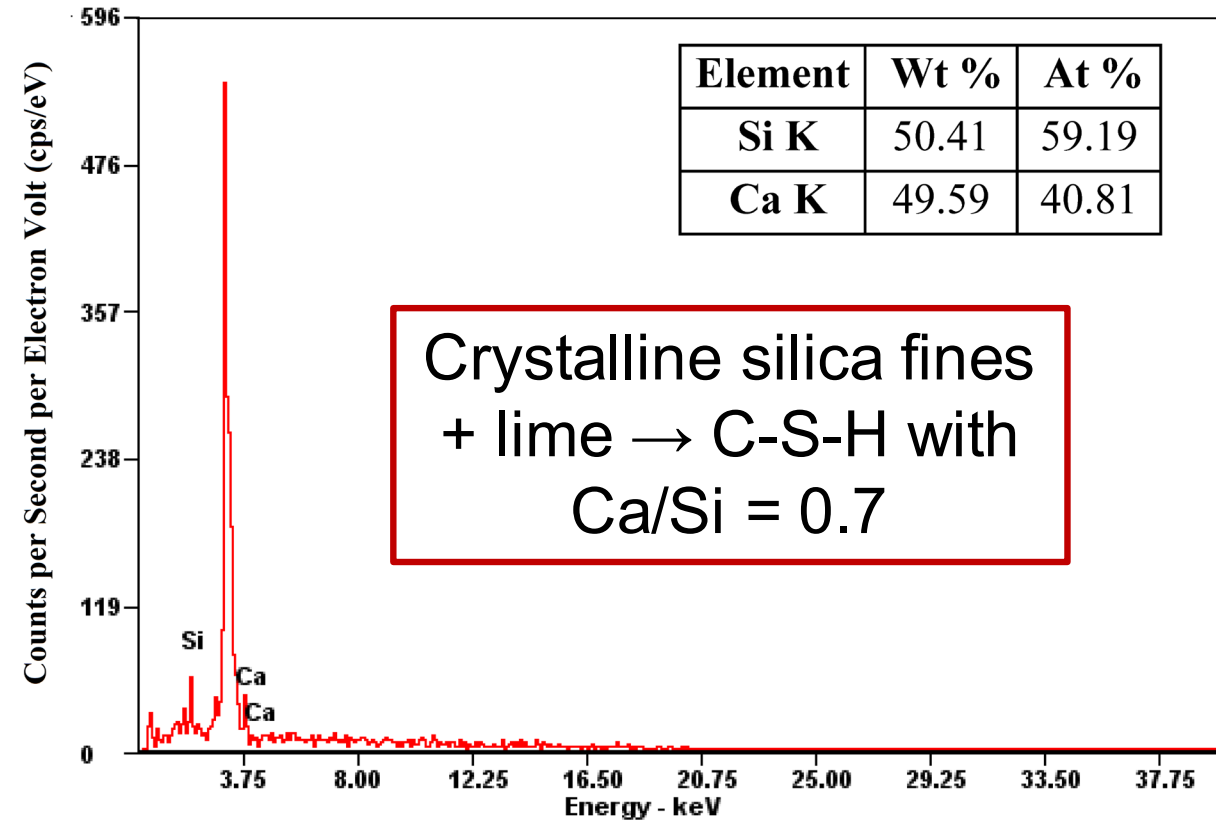
Crystalline silica fines participated in chemical reaction

III. Crystalline Silica Admixture Treatment of Sulfate Soils

SEM & EDXS



**Lime-Treated Crystalline Silica (L-CS)
Particles at 1,000x**



Note: The strongest peak corresponds to silver (Ag) since the specimens were sputter coated with Ag

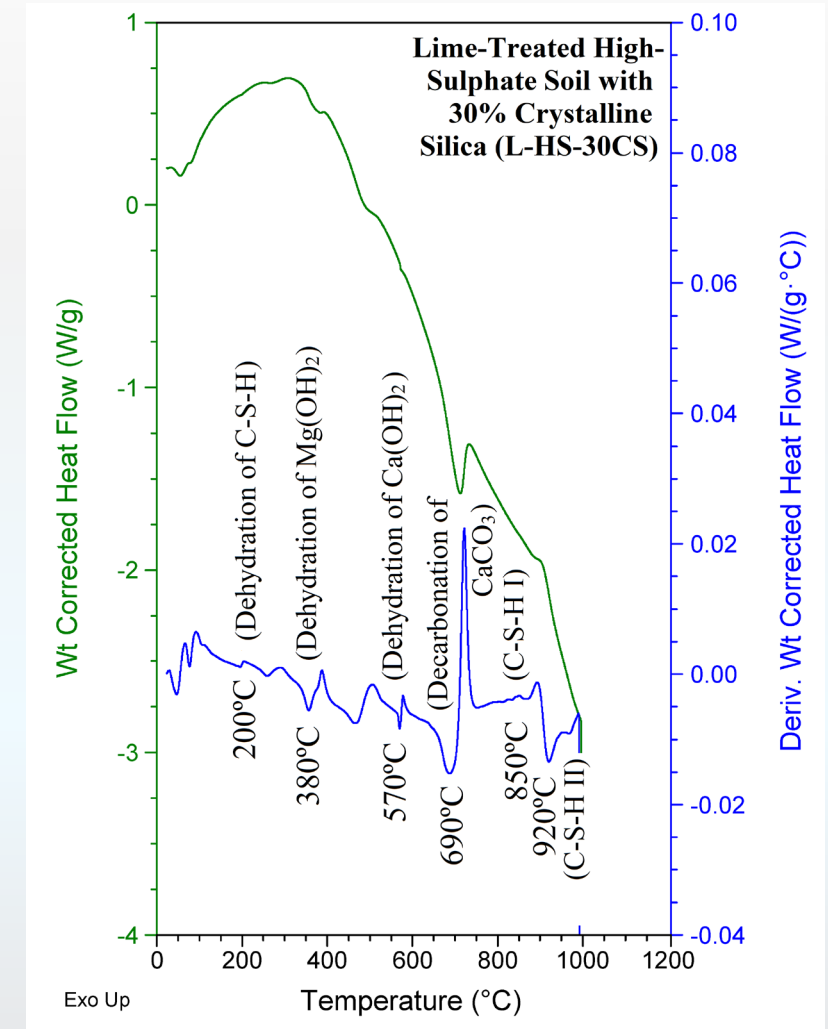
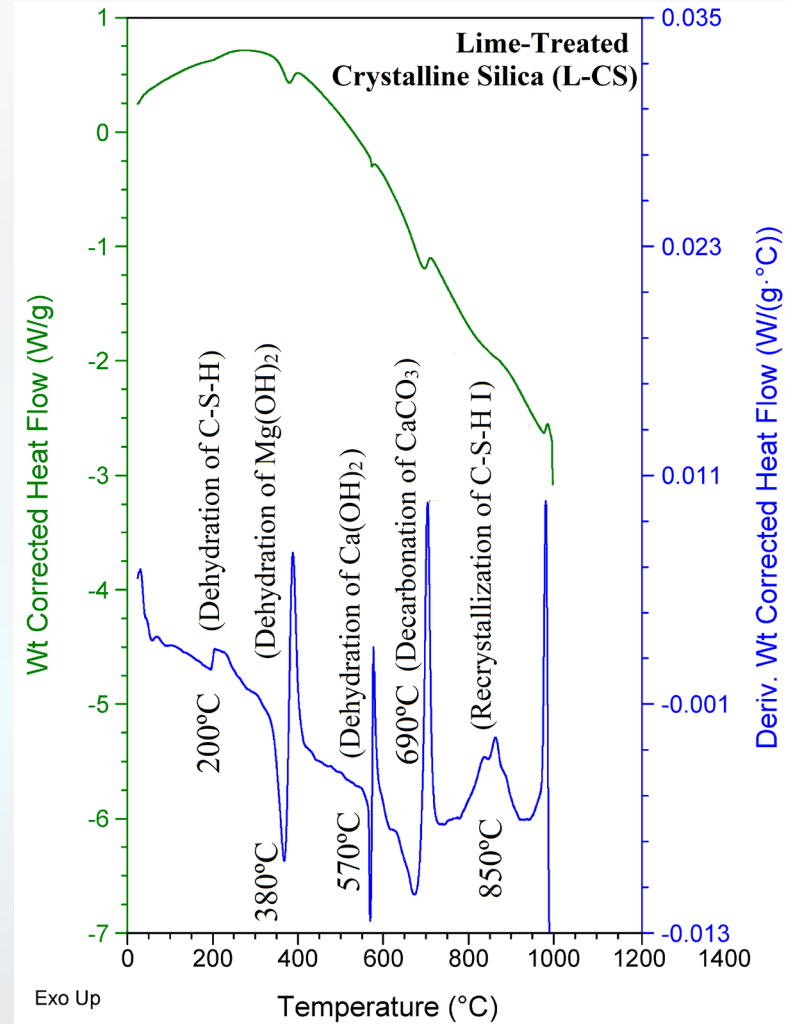
Crystalline silica fines participated in chemical reaction

Chakraborty, S., Puppala, A.J. and Biswas, N., 2021. Role of crystalline silica admixture in mitigating ettringite-induced heave in lime-treated sulfate-rich soils. *Géotechnique*, pp.1-17.

III. Crystalline Silica Admixture Treatment of Sulfate Soils

Differential Scanning Calorimetry

Recrystallization exothermic peak at 850°C typical of CSH-I formed when crystalline silica fines react with lime



Mitigation of High Sulfate Soils in Texas

Anand J. Puppala, Ahmed Gaily, Aravind Pedarla, Aritra Banerjee
 Department of Civil Engineering, The University of Texas at Arlington, Arlington, Texas, 76019



AASHTO RAC Showcase Poster

Transportation Research Board Annual Meeting, Washington, DC, 2018

Recent Paper in ASCE JGGE 2020: Talluri et al. 2020 – High Sulfate Soils

Concept

- Pavement distress in chemically stabilized sulfate bearing soils is a growing concern for highway agencies

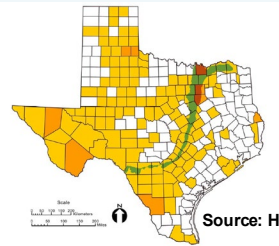


Source: Les Perrin, USACE

- Researchers have conducted studies on heave mechanisms in chemically treated soils containing sulfate levels below 10,000 ppm
- In most of the heave cases the sulfate contents were reported to be as high as 50,000 ppm
- The main intent of the research is to understand heave mechanisms in soils with sulfate contents above 10,000 ppm

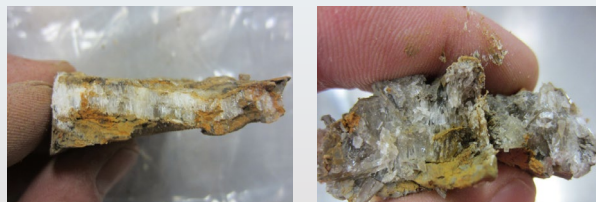
Background & Innovation

- Sulfate Bearing Expansive Soils



Source: Harris et al. (2004)

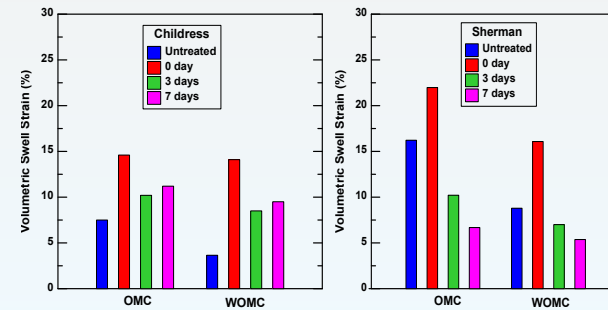
- Lime/Cement treated bases are used to support the pavement infrastructure
- Some of these expansive soils contain sulfate minerals such as Gypsum (CaSO₄·2H₂O) in their natural formation
- $6Ca^{2+} + 2Al(OH)^{-4} + 4OH^{-} + 3(SO_4)^{2-} + 26H_2O \rightarrow Ca_6[Al(OH)_6]_2(SO_4)_3 \cdot 26H_2O$
 (Formation of Ettringite)



Gypsum Crystals in Natural Soil

Laboratory Testing Program

- Experimental Variables: Soils (Childress, MH & Sherman, CH); Moisture Contents (OMC & WOMC); Sulfate Contents (24,000 & 44,000 ppm); Stabilizer (Lime); Dosage (6%)
- Chemical and Mineralogical Tests Performed: Cation Exchange Capacity (CEC); Specific Surface Area(SSA); Total Potassium(TP) and Reactive Alumina & Silica
- 'Mellowing Technique' is used in stabilizing the soils with lime; Mellowing Periods Considered: 0, 3 and 7 days (swell tests only)
- To compensate moisture loss and early dissolution of Gypsum during mellowing additional 3% moisture is provided
- After the mellowing period, the soils are remixed and compacted
- Engineering tests were performed on the treated mellowed high sulfate soils
- Engineering tests data from treated soils is compared with the untreated data



Construction - US 82 Bells



Performance Evaluation Studies



FWD and Surface Profiler Studies

Conclusion

- Mellowing technique reduces volumetric swell increase
- Childress soil shows less swelling compared to Sherman soil
- Low initial reactive alkalinity reduces the ineffectiveness of mellowing

Acknowledgements

- Joe Adams, Wade Odell, Wade Blackmon & Richard Williammee, Texas Department of Transportation
- Pat Harris, Sam Houston State University

Summary Comments

- **Performance based engineering testing with mineralogical studies**
- **Ettringite-induced heaving in moderate to high sulfate soils → swelling characteristics and associated strength loss**
- **Treatment Methods: Low to Moderate Sulfate Soils (< 8000 ppm)**
 - **Lime with Mellowing & Blast Furnace Slag Showed Promise**
 - **Sulfate Resistant Cements & Class F Fly Ash (Co-additive with lime)**
- **Treatments: Moderate to High Sulfate Soils (> 8000 ppm)**
 - **Lime and Fly Ash Additives with Mellowing**
 - **Geopolymers, Slags, Crystalline Silica Fines**

Research Team and Colleagues

➤ My Research Group

❖ Former Students - Drs. Inthrasombat, Wattanasanticharoen, Chittoori, Talluri, Chakraborty, Congress

❖ Current PhD Students – Nripojyoti Biswas, Jungyeon Jang, Ahmed Gailey

➤ Prof. Dallas Little, Dr. Rajan Vempati, Dr. Pat Harris, Dr. Yaolin Yi

➤ Richard Williammee, Jimmy Si, and Others

➤ Dr. Akula, Lundgreen (Chair – AKG 90) & Dr. Tutumluer (Chair – AKG00)

Related Papers

- Talluri, N., Puppala, A. J., Congress, S. S., & Banerjee, A. (2020). Experimental Studies and Modeling of High-Sulfate Soil Stabilization. *Journal of Geotechnical and Geoenvironmental Engineering*, 146(5), 04020019.
- Puppala, A. J., Congress, S. S.C., Talluri, N., & Wattanasanthicharoen, E. (2019). Sulfate-Heaving Studies on Chemically Treated Sulfate-Rich Geomaterials. *ASCE Journal of Materials in Civil Engineering*, 31(6), 04019076.
- Puppala, A. J., Talluri, N., Congress, S. S. C., & Gaily, A. (2018). Ettringite induced heaving in stabilized high sulfate soils. *Innovative Infrastructure Solutions*, Springer, 3(1), 72.
- Puppala, A. J., Pedarla, A., & Gaily, A. (2016). Implementation: Mitigation of High Sulfate Soils in Texas: Development of Design and Construction Guidelines (Video Report 5-6618). Texas. Dept. of Transportation.
- Harris, P., Harvey, O., Jackson, L., DePugh, M., & Puppala, A. J. (2014). Killing the Ettringite Reaction in Sulfate-Bearing Soils. *Journal of Transportation Research Record*, 2462(1), 109-116.
- Puppala, A. J., Talluri, N., Gaily, A., & Chittoori, B. (2013). Heaving mechanisms in high sulfate soils. In *Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering*, Paris, France.
- Talluri, N., Puppala, A. J., Chittoori, B. C., Gaily, A. H., & Harris, P. (2013). Stabilization of high-sulfate soils by extended mellowing. *Journal of Transportation Research Record*, 2363(1), 96-104.

Related Papers

- Puppala, A. J., Viyanant, C., Kruzic, A. P., and Perrin, L., (2002). “Evaluation of a Modified Soluble Sulfate Determination Method for Fine-Grained Cohesive Soils.” *Geotechnical Testing Journal*, Vol. 25, No. 1, pp. 85–94.
- Puppala, A. J., Intharasombat, N., Vempati, R. (2005). *Experimental Studies on Ettringite Induced Heaving in Soils*. ASCE *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 31, No. 3, pp. 325-337.
- Puppala, A. J., Kadam, R., Madhyannapu, R., and Hoyos, L. R. (2006). “Small-Strain Shear Moduli of Chemically Stabilized Sulfate-Bearing Cohesive Soils.” *ASCE Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, pp.322-336.
- Puppala, A. J., Talluri, N. S., Gaily, A., and Chittoori, B. S. (2013). “Heaving Mechanisms in High Sulfate Soils.” *Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering, Paris 2013*.
- Puppala, A. J., Wattanasanticharoen, E. and Punthutaecha, K. (2003). “Experimental Evaluations of Stabilization Methods for Sulphate-rich Expansive Soils.” *Ground Improvement* Vol. 7, No. 1, pp. 25-35.
- Bheemasetti, T. V., Chittoori, B., Zou, H., Puppala, A. J., & Thomey, J. (2016). Spatial mapping of soluble sulfate concentrations present in natural soils using geostatistics. *ASCE Journal of Geotechnical and Geoenvironmental Engineering*, 143(2), 04016090.

Thank You!

anandp@tamu.edu



Dallas Little
D-little@tamu.edu



ZACHRY DEPARTMENT OF
CIVIL ENGINEERING
TEXAS A&M UNIVERSITY



Pavan Akula
pavan.akula@tamu.edu



ZACHRY DEPARTMENT OF
CIVIL ENGINEERING
TEXAS A&M UNIVERSITY



Anand Puppala
anandp@tamu.edu



ZACHRY DEPARTMENT OF
CIVIL ENGINEERING
TEXAS A&M UNIVERSITY



Narain Hariharan
nhariharan@graymont.com



Erol Tutumluer
tutumlue@illinois.edu
University of Illinois at
Urbana-Champaign

Get Involved with TRB

Find upcoming conferences

<http://www.trb.org/Calendar>



Get Involved with TRB

#TRBwebinar

 @NASEMTRB

 @NASEMTRB

 Transportation
Research Board

Getting involved is free!

Be a Friend of a Committee bit.ly/TRBcommittees

- Networking opportunities
- May provide a path to Standing Committee membership

Join a Standing Committee bit.ly/TRBstandingcommittee

Work with CRP <https://bit.ly/TRB-crp>

Update your information www.mytrb.org

Other TRB events for you

- *May 12*: TRB Webinar: Increasing Return on Investment through Geotechnology
- *May 24*: TRB Webinar: Geotechnical Responses to Extreme Events
- *Aug 1-4*: Geospatial Data Acquisition Technologies in Design and Construction

<https://www.nationalacademies.org/trb/events>