Transportation Consortium of South-Central States

Tran-SET

Solving Emerging Transportation Resiliency, Sustainability, and Economic Challenges through the Use of Innovative Materials and Construction Methods: From Research to Implementation

Rice Husk Ash (RHA) as Stabilizing Agent for Problematic Subgrade Soils and Embankments

Project No. 21GTASU01

Lead University: Arkansas State University

Collaborative University: Oklahoma State University

Final Report

August 2022

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Acknowledgements

The authors gratefully acknowledge the funding support, which was provided by the United States Department of Transportation (USDOT) through the Transportation Consortium of the South- Central States (Tran-SET). The authors also acknowledge the members of the Project Review Committee (PRC) for their technical support and direction throughout the duration of this project. The authors are grateful to engineers and supervisors of construction projects at the Arkansas Department of Transportation (ARDOT) District 10 for assisting in getting test materials from ongoing construction projects for this study.

TECHNICAL DOCUMENTATION PAGE

1. Project No.	2. Government Accession No.	3. Recipient's Catalog No.
21GTASU01		

4. Title and Subtitle Using Rice Husk Ash (RHA) as Stabilizing Agent for Problematic Subgrade Soils and Embankments.	**5. Report Date** Aug. 2022
	6. Performing Organization Code
7. Author(s) PI: Zahid Hossain https://orcid.org/0000-0003-3395-564X Co-PI: Rifat Bulut, https://orcid.org/0000-0001-6047-1873 GRA: Fares Tarhuni https://orcid.org/0000-0001-7093-304X GRA: Hussein Al-Dakheeli, https://orcid.org/0000-0003-3240-7537	**8. Performing Organization Report No.** 21GTASU01
9. Performing Organization Name and Address Transportation Consortium of South-Central States (Tran-SET)	**10. Work Unit No. (TRAIS)**
University Transportation Center for Region 6 3319 Patrick F. Taylor Hall, Louisiana State University, Baton Rouge, LA 70803	**11. Contract or Grant No.** 69A3551747106
12. Sponsoring Agency Name and Address United States of America Department of Transportation	**13. Type of Report and Period Covered** Final Research Report August 2021 – July 2022
Research and Innovative Technology Administration	**14. Sponsoring Agency Code**

15. Supplementary Notes

Report uploaded and accessible at [Tran-SET's website (http://transet.lsu.edu/)](http://transet.lsu.edu/).

16. Abstract

Arkansas produces the most of the rice in the United States. About 20% of poddy is rice husk (RH), which is burnt under controlled conditions to produce rice rusk ash (RHA). The RHA is considered an environmental hazard and a significant challenge for rice millers. However, RHA is rich in pozzolanic material, which is mainly silica. In this study, RHA is used to stabilize poor soils. Another commonly used stabilizer, hydrated lime (HL), has also been evaluated for comparison purposes. Thus, this study aimed to determine the optimum percentages of RHA, HL, or a combination of these two agents by evaluating selective physical, mechanical, and chemical properties of four subgrade soils (two from Arkansas and two from Oklahoma). Various amounts (by mass of soil) of RHA (3, 6, and 9%), HL (1, 3, and 5%), and RHA+HL have been utilized to know their optimum dosages. Routine tests including the Atterberg limits, Modified proctor, pH, California Bearing Ratio (CBR), unconfined compressive strength (UCS), free swell, and one-direction shrinkage were conducted for untreated and treated soils. Further, scanning electron microscopy (SEM) with X-ray diffractometer tests were performed to evaluate the changes in microstructure due to stabilization. Treated soils show a significant improvement in UCS and CBR data. Additionally, the free swell test also indicates a reduced swelling of treated soils. The optimum dosages of RHA and HL were found to be 6% and 3%, respectively. When these two agents were used together, a blend of 4%RHA and 1%HL was found to be the most effective in improving engineering properties The findings of this research can significantly benefit the construction industry in Arkansas by reducing costs associated with traditional soil stabilization methods and finding a sustainable and environmentally way of using RHA.

17. Key Words	18. Distribution Statement
Soil stabilization, Rice Huck Ash, Hydrated Lime, Unconfined compressive strength, California Bearing Ratio, Scanning Electron Microscopy	No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	65	

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized.**

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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ACRONYMS, ABBREVIATIONS, AND SYMBOLS

AASHTO	American Association of State Highway and Transportation Officials
AHTD	Arkansas Highway Department of Transportation
AR-1	Arkansas Soil 1
AR-2	Arkansas Soil 2
ARDOT	Arkansas Department of Transportation
A-STAE	Arkansas State University
ASTM	American Society for Testing and Materials
CBR	California Bearing Ratio
FAA	Federal Aviation Administration
FSL	Free Swell Index
HL	Hydrated Lime
LL	Liquid Limit
MDD	Maximum Dry Density
NLA	National Lime Association
OK-1	Oklahoma Soil 1
OK-2	Oklahoma Soil 2
OMC	Optimum Moisture Content
OSU	Oklahoma State University
PI	Plasticity Index
PL	Plastic Limit
RH	Rice Hull
RHA	Rice Husk Ash
SEM	Scanning Electron Microscopy
UCS	Unconfined Compressive Strength
XRD	X-Ray Diffraction

EXECUTIVE SUMMARY

Traditional soil stabilizers such as lime, fly ash, and cement are commonly used to improve the engineering properties of poor soils. However, there is a high demand for another stabilizer that can be found easily and is relatively low in cost. In recent years, researchers have been conducting experiments on the potential of using Rice Husk Ash (RHA) as an alternative to another subgrade stabilizer. More importantly, RHA has received much attention as it is an agricultural by-product and eco-friendly.

Arkansas is the largest rice-producing state in the nation. However, the rice husk (RH) or RHA generated by local rice millers is not being used sustainably as it is being burnt to generate energy. RHA is a significant amount of amorphous silica, which is pozzolanic and can be a good alternative to commonly used stabilizing agents. Thus, the use of RHA as a construction material will create an alternative market for local rice millers.

Teams from Arkansas State University (A-STATE) and Oklahoma State University (OSU) collaborated in this research to determine the optimum percentages of RHA, HL, or a combination of these two agents by evaluating four subgrade soils. Two subgrade soils (AR-1 and AR-2) from Arkansas were subjected to a series of laboratory tests such as Atterberg limit, Modified proctor, pH, California Bearing Ratio (CBR), unconfined compressive strength (UCS), and Free swell. It was found that HL has a significant effect on soil p^H. The soil p^H reaches up to 10.5 and 13.0 when the soils are mixed with 1% and 5% HL, respectively. On the other hand, RHA has a moderate effect on soil p^H; the soil p^H has increased to reach the highest p^H of 7.75 with 9% RHA. Both RHA and HL show a reduction in the maximum dry density (MDD) and the plasticity of the soil, while an increase in the UCS and CBR values is observed.

The other two Oklahoma subgrade soils (OK-1 and OK-2) were also treated using the same stabilizing agents, and the treated and untreated soils were characterized using scanning electron microscopy (SEM) and x-ray diffraction (XRD). Additionally, the Oklahoma soils were subjected to free swell and one-directional shrinkage tests. It was found that the RHA did not provide significant mitigation to the swelling behavior as compared with HL. One percent HL was enough to introduce a high reduction (85%) of swell. In the case of RHA, the highest reduction of swell was observed when 3% RHA was used. The 3% RHA reduced the swell by 69% and 33.6% for OK-1 and OK-2 soils, respectively. The SEM tests indicated that the RHA particles worked as a filler material within the structure of the soil. However, for the treatment with lime, both XRD and SEM indicated the formation of cementitious materials such as calcium silicate hydrate in both stabilized soils from Oklahoma. Based on the findings of the limited laboratory tests of this study, it is recommended for future studies to first investigate the chemical reactions between RHA and HL before the treatment with the candidate soil.

Based on improvements in strength and physical properties, the optimum dosages of RHA and HL were found to be 6% and 3%, respectively. But 6% RHA alone was not effective in reducing swelling potential. Thus, a combination of 4% RHA and 1% HL was expected to provide a significant reduction in the soil swell potential as well as an increase in UCS and CBR values. Economically, the combination of RHA and HL would also provide a lower cost with a higher strength property (e.g., CBR value) than 6% RHA or 3% HL alone. Therefore, considering all test results and economical perspectives, 4% RHA+1% HL is recommended as the optimum combination to stabilize poor subgrade soils.

1. INTRODUCTION

1.1. Background

It is common in civil engineering projects to encounter poor soils on construction sites. From a geotechnical point of view, soils with high plasticity are more likely to change in volume when moisture is present, and thereby possess a reduced load-carrying capacity. Excessive changes in volume can lead to major structural defects such as cracking and permanent deformation of roadways. Moisture content in the soil relies on the environment condition, temperature, ground surface drainage, and groundwater table. These factors make it difficult to control the soil moisture content. Hence, poor subgrade soil needs to strengthen by one or more ground improvement methods that can enhance the soil engineering properties to meet the different project requirements. Chemical modification by using admixture is one of the widely used methods of ground improvement techniques *(1).* The primary applications of using chemical admixtures are to treat the subgrade soil for different types of projects such as pavement, runways, and railway projects *(2).* Besides that, using the stabilization agents can minimize the cost of the construction to meet the design requirements. Poor soils can be treated by mixing them with different types of chemical stabilization mixtures such as cement, lime, or fly ash. These agents can improve the soil stiffness and strength, and enhance volume stability, which is less moisture susceptibility. Rice husk ash and hydrated lime are the main two agents used in this study. In these techniques, the soil is expected to be stabilized by chemical reactions between the soil particles and the stabilizer agent.

Rice Husk Ash (RHA) is the ash generated from the combustion of the rice husk (RH), the protective coatings of rice grains. RHA is a pozzolan that has been investigated as supplementary material in the concrete mixture to substitute a large portion of Portland cement. Similarly, for soil stabilization, RHA can be beneficial when mixed with calcium hydroxide. Since it is rich in silica, the addition of RHA to lime-treated soils leads to more pozzolanic reactions that produce additional calcium silicate hydrate. RHA is available in many rice-producing countries. RHA is a result of burning the Rice Husk at a specific temperature and condition.

RHA is considered a waste material. Recycling waste is beneficial to the global environment and economy *(3).* RHA can be used to stabilize the soil because of the high amount of silica which is a cementitious material *(4, 5).* However, the use of RHA as a soil stabilizer is still limited in the U.S. Some researchers indicated the potential of RHA to increase the soil strength (e.g., California Bearing Ratio) and reduce the swell of expansive soil *(6).* However, some soils show less potential to reach the target strength with RHA. Therefore, adding other materials such as lime to the RHA will help to enhance the soil properties *(7).*

The pozzolanic reaction can generally be defined as the chemical reaction between hydrated lime (an alkali), water, and a pozzolan *(8).* Based on the terminology used by the American Concrete Institute (ACI), a pozzolan is “a siliceous or siliceous and aluminous material that in itself possesses little or no cementitious value but will chemically react with calcium hydroxide (hydrated lime) at ordinary temperatures to form compounds having cementitious properties.” Accordingly, RHA is considered a pozzolan as it has a significant amount of amorphous silica. In this report, the literature review is documented by elaborating on the basic chemical interaction of RHA, lime, and clay.

1.1.1. Dissolution of Calcium Hydroxide

When quicklime (CaO) interacts with water (H_2O), calcium hydroxide [$Ca(OH)_2$] or CH is produced in an exothermal reaction as in Equation. 1.

$$CaO + H_2O \rightarrow Ca(OH)_2 + \text{Heat} \qquad (1)$$

While it is a common practice to use quicklime for highly wet soils so that the generated heat helps to reduce the soil moisture, solid evidence for a direct role of the generated heat in the stabilization process, apart from the latter "drying" benefit, was not found in the literature. Hydrated lime dissolves in water and produces calcium and hydroxide ions as shown in Eq. 2.

$$Ca(OH)_2 + H_2O \rightarrow Ca^{+2} + OH^{-1} \ (p^H\uparrow) \ (2)$$

The presence of OH ions in the pore water of soils will make an alkaline aquatic environment with a p^H of about 12.5. The covalent bonds in clay minerals, the bonds of Si-O and Al-O, are unstable at pH above 10.5, at which clays start breaking down into aluminum hydroxide and silicic acid (*9-10*). The decomposition of alumina and silica will lead to the reaction with the calcium ions in the solution. The reaction of the free calcium ions with alumina and silica can be referred to as the pozzolanic reaction that ultimately produces the cementitious products, calcium silicate hydrate (C-S-H), and calcium aluminate hydrate (C-A-H). Thus, calcium hydroxide has double roles in the pozzolanic reaction; first, it creates the alkaline environment that activates the pozzolan for the reaction, and second, it releases calcium ions that become part of the reaction to produce C-S-H and C-A-H.

Both C-S-H and C-A-H are well-known products resulting from the hydration of Portland cement. C-S-H results from the hydration of the raw materials tricalcium silicate (C_3S) and dicalcium silicate (C_2S) to promote the early (the case of C_3S hydration) and the late (the case of C_2S hydration) strength and durability in concrete. C-A-H results from the hydration of tricalcium aluminate (C_3A) in the absence of gypsum. The presence of gypsum leads to the formation of ettringite. There is a broad agreement in the concrete research community that the cementitious material C-A-H has little or no contribution to the strength development but does contribute to the setting (the process of rigidity gain of fresh concrete paste) and durability of concrete.

1.1.2. Pozzolanic Activity

It is the reaction rate between a pozzolan and calcium hydroxide in the presence of water. The rate of the reaction depends on the physical (e.g., the specific surface area) and the chemical composition of the pozzolan. The pozzolanic reaction is a long-term process that occurs over months or years. In the case of soil stabilization, the pozzolanic reaction consumes the soil pore water to form cementitious materials. The cementation product of this reaction depends on the pozzolan active phase. If the pozzolan is silica-based, which is the case of RHA, the pozzolanic reaction leads to C-S-H production. In summary, the pozzolanic reaction of the RHA-hydrated lime-clay-water system follows two paths:

Path I: The supply of silica and alumina comes from the clay which reacts with calcium ions from the hydrated lime (CH) to produce the cementation products C-S-H and C-A-H.

Path II: The supply of silica comes from the RHA (the pozzolan) which also reacts with the calcium ions from the CH to produce C-S-H.

The pozzolanic reactions explained above may generally be expressed in the two geochemical forms (Equations 3 and 4):

$$Ca(OH)_2 + SiO_2 + H_2O \rightarrow C\text{-}S\text{-}H \quad (3)$$

$$Ca(OH)_2 + Al_2O_3 + H_2O \rightarrow C\text{-}A\text{-}H \quad (4)$$

The first path is the well-known mechanism of calcium-based stabilizers, i.e., lime, Portland cement, and class C fly ash. Intuitively, the interest of this study goes along the second path of the pozzolanic reaction. RHA is one of the widely used pozzolans in the concrete industry. That is because it contains a high amount of reactive amorphous silica and has a high surface area. A recent review by Aghajanian *(11)* on fourteen research studies reported that on average RHA has 89.13% SiO_2, 0.85% Al_2O_3, 1.12% CaO, 1.98 K_2O, and less than 1% of Fe_2O_3, MgO, and Na_2O. RHA can be produced to have a specific surface area of up to 60 m^2/g and a very porous structure with a mean particle size of about 50μm *(12).*

1.2. Problem Statement

Globally, many countries including the United States are major rice producers. Arkansas produces the largest amount of rice in the United States with an annual production of about 200 million bushels. Besides Arkansas, Louisiana and Texas are two other major rice-producing states in the country. Around 20% of the paddy is rice hull (RH). When burnt, 20% of RH is transformed into rice husk ash (RHA). A significant portion of RHA generated by local milling companies such as Riceland Foods is being treated as waste. RHA is a cementitious material, and it contains about 75% silica in an amorphous form and has an extremely high surface area. RHA is also economically beneficial, but its performance as a construction material has been investigated very little. RHA can potentially be used as a stabilizing agent for poor subgrade and embankment soils, which are very common in Arkansas, Oklahoma, and other states. Even though the prospect of using RHA in stabilizing soft and expansive subgrade soils is high, no performance data of such initiatives is available in the public domain.

The main objective of the proposed collaborative study between Arkansas State University (A-State) and Oklahoma State University (OSU) is to assess the feasibility of the use of RHA in stabilizing poor subgrade soils through laboratory investigation. Based on the laboratory testing and results of this project, the investigators of this project will have a good understanding of the important features and efficacy of RHA as a stabilizing agent for poor soils. In particular, if there are short-term and long-term reactions, whether new minerals form as a result of the reactions, and whether the stabilization/modification processes are temporary or permanent will be understood.

2. OBJECTIVES

The main objective of this research is to evaluate the performance of RHA, lime, and a combination of RHA and lime on poor soils. Specifically, the following aspects are investigated in this study:

1) Evaluate selected physical, chemical, and mechanical properties of RHA and hydrated lime-modified soils.
2) Determine optimum dosages of the selected stabilizing agents.
3) Determine the optimum percentages of RHA, hydrated lime, or a combination of these two stabilizing agents.
4) Perform life cycle cost analysis of RHA and hydrated lime-modified subgrade soil.

3. LITERATURE REVIEW

3.1. Soil Stabilization

Conducting a feasibility study for a construction project is the first step before starting the site work. The step is typically followed by site surveying and soil investigation. Conducting geotechnical laboratory tests is essential to determine the soil properties before the design stage. The important criterion in a geotechnical report is the bearing capacity of the site. Traditionally, when poor soil is found at construction sites, several techniques are taken into consideration to strengthen the soil. Changing the design of the structure to be adequate for the poor soil, replacing the in-situ soil layer with stronger material, and abandoning the site location are a few common practices. These traditional methods are quite expensive and time-consuming as well. Stabilizing the poor soil with recycled material to enhance its properties can return the most benefit for all the project parties *(13)*. The main aims of soil stabilization are to increase strength, stiffness, and durability. Furthermore, it mitigates undesirable behavior in presence of water such as swell potential and compressibility. In general, ground improvement methods can be classified into 5 categories, which are densification, replacement, hydraulic modification, chemical modification, and reinforcement *(1)*. Chemical modification or stabilization is a process of mixing chemical agents such as quicklime, fly ash, cement, bitumen, or other byproducts and industrial products with poor soil to stabilize the subgrade.

3.2. Stabilization Agents

3.2.1. Rice Husk Ash

The process of producing rice involves many milling steps. Around 227.6 million hundredweight of rice was produced by the United States in 2020 *(14)*. Roughly, 58 percent of American long rice is produced in Arkansas *(14)*. Approximately, 20% of the rice weight is husk *(15)*, which is normally burnt or dumped as waste. When the rice husk is burnt in specific conditions it becomes RHA, which is rich with silica that makes it a cementitious or pozzolanic material. Researchers stated that RHA has the potential to improve soil properties because of its cementitious properties *(16,17)*.

RHA can be used as a soil stabilizer, however, determining its optimum percentage to enhance the soil characteristic is complicated and complex at the site. Thus, a series of laboratory experiments can be conducted in the lab to determine the optimum percentage of RHA. Alhassan (2008) *(18)* used 2-12% of RHA in a study to stabilize lateritic soil classified as A-7-6. Three tests namely compaction, un-soaked soils CBR, and unconfined compression strength were carried out at the lab for untreated and treated soils. The results showed improvement in the CBR by using 6% RHA. Additionally, the unconfined compressive strength test results showed an increase in strength by when 8% RHA was used.

Sivapullaiah et al. (2004) *(19)* used RHA as a stabilizer for expansive soils such as Indian black cotton soil. It was observed that the soil was effectively stabilized when using RHA and 3-9% lime together. The mixture can increase the strength of the soil and reduce the potential swelling by 5%.

Some other researchers examined a wide range of RHA to stabilize poor soil and reported that it would increase the strength and reduce the density. For instance, Rahman (1987) *(20)* conducted a study on stabilizing the lateritic soil with RHA in highway projects. The percentages used in this research were 6%, 12%, and 18% of RHA by weight. The specimens were cured for 7, 14, and 28 days for CBR and unconfined compressive strength. The researcher found that 18% RHA was optimum for a better performance. Roy (2014) *(21)* used 10% RHA only to improve the characteristic of poor soil. Some researchers used mixtures of RHA and other materials such as cement, fly ash, and/or fiber. Brooks (2009) (*22)* focused on improving the expansive soil as a construction material by blending the soil with RHA and fly ash. The mixture showed a reduction in swelling potential between the foundation and subgrade layers. It was observed that adding 12% RHA would increase the CBR and unconfined compressive strength by 47% and 97%, respectively. Ashango and Patra (2016) *(23)* suggested using RHA, steel slag, and/or quick lime to improve the geotechnical properties of the soil. The results showed improvement in the unconfined compressive strength by 45% and 90% for uncured and cured specimens, respectively.

3.2.2. Lime

Besides RHA, many scholars tried to use different percentages of lime to stabilize the soils. Kavak and Akyarlı (2007) *(24)* used 5% of lime to stabilize green clay soil. Their results showed a great improvement in soil strength; the CBR value increased by 16 times when mixing 5% lime with green clay soil. Negi et al. (2013) *(25)* observed an increase in CBR value for untreated soil by 10 times when the soil was stabilized by using lime. The addition of an adequate amount of lime with water would help to improve the soil characteristic. For using a combination of RHA and HL to stabilize the expansive soil, the blending ratio of RHA and HL was 4:1 (by weight) *(26).* In this research, several laboratory tests such as swelling test, unconfined compression test, consolidation test, and direct shear test were conducted to measure the improvement of the properties of the tested soils. The researchers found that by increasing the percentage of RHA and the period of curing, there was a remarkable improvement in the soil resistance to deformation and an increase in the strength of the soil.

3.3. Stabilization Practice

3.3.1. National Lime Association (NLA)

The National Lime Association (NLA) established Lime-Treated Soil Construction Manual for lime stabilization and lime modification *(27).* Soils treated chemically with lime can transform poor soils into usable soils. Lime can be used to treat subgrade in different forms such as quicklime (Calcium Oxide), hydrated lime (Calcium hydroxide), or lime slurry. Quicklime can be manufactured by transforming calcium carbonate into calcium oxide. However, hydrated lime can be produced by adding water to quicklime. Hydrated lime has a high potential to react with clay particles and produce strong cementation bonds between the small clay particles. Lime can be either alone or mixed with other materials to stabilize soils. Several factors affect the lime-treated subgrade, and they include the soil’s mineralogical properties, sulfate content, organic material, and soil plasticity index. Generally, the subgrade soil shall be mixed with 3 to 6 % of lime by dry soil weight, however, the adequate percentage of lime is subjected to laboratory test results.

3.3.2. Federal Aviation Administration (FAA)- Lime-Treated Subgrade

The Federal Aviation Administration (FAA) has introduced a specification for lime-treated subgrade soils *(28).* As presented in FAA Standard Specification Item P-155: *Lime-Treated Subgrade,* it is recommended to use lime for clay soil to reduce the plasticity index. Stabilization by using lime has the potential to increase the optimum moisture content and make the soil dry rapidly. More importantly, using lime can increase soil bearing and soil stability. Generally, using a dosage of 3-7% of lime would be suitable to bring the clay soil p^H to greater than 12, which helps the clay fine particles to break down. Samples of the in-situ subgrade should be tested at a laboratory. Per the FAA guidelines, engineers should specify the lime dosage and the depth of the treated soil required for the specific design load. Lime can be used as quicklime, hydrated lime, and either magnesium lime or high calcium dolomitic according to ASTM C51. Lime can easily react with carbon dioxide and moisture. Therefore, for reliable results, lime shall not be used after 6 hours exposed to the air. Besides, special cares need to be taken to make sure the lime-treated subgrade soil has enough moisture. Therefore, during the mixing, moisture needs to be provided 3% to 5% higher than the optimum moisture content obtained from the laboratory experiments.

3.3.3. Arkansas Department of Transportation (ARDOT)

The Arkansas Department of Transportation (ARDOT) has introduced a specification for using lime as a subgrade stabilizer *(29).* Section 301: Lime-treated subgrade present the procedure of treating the soil with lime. The types of lime used for soil treatment should be either quicklime or hydrated lime and comply with the requirement of AASHTO M 16. Prior to stabilizing the soil, the subgrade surface layer should be cleaned of all contaminated materials. Then, the surface should be compacted to an adequate density to prevent deformation. The ARDOT specifications state the depth of subgrade compaction shall be 8 inches when lime or Portland used as soil stabilizers (*29*).

The subgrade soil shall be mixed with water and lime. The water should be cleaned from any kind of contamination like oil, salt, or other materials. The amount of lime should not exceed 8% of lime by weight. The adequate percentage of lime will be determined based on the laboratory tests. The depth of treated soil with lime is a critical factor. The treatment depth varies from one soil to another depending on the moisture content and soil characteristic. According to Elsayed et al. *(30,31),* the depth of treatment with lime should be 16 inches for most types of soils. Stabilizing the soil with lime is highly effective when the soil has high plasticity. The recommended lime dosage is 4 to 8%. Furthermore, these researchers have come up with guidelines and recommendations for the adequate percentage of different stabilizing agents for different AASHTO soil classifications (A1 through A7).

3.4. Summary of Existing Literature

The findings of some major pertinent studies are summarized in Table 1. As explained earlier and from the data presented in Table 1, up to 20% RHA was used in stabilizing poor subgrade soils *(32).* Most studies considered binary stabilizing systems such as RHA+lime and RHA+cement since a unary system (e.g., RHA alone) was not very effective *(33, 40).* Besides lime, other stabilizing agents such as cement or plastic fiber in combination with RHA were investigated by some researchers *(35, 41).* Most of the studies reported increased strength properties (e.g., increased CBR), index properties (e.g., decreased shrinkage and PI), or a combination of strength and index properties when RHA alone or a combination of RHA and another stabilizing agent was used to stabilize poor subgrade soils.

Table 1. Summary findings of existing studies.

Type of Soil	Stabilizing Agent (s)	Optimum Dose of RHA (%)	Improvement of Soil Properties	Ref.
Laterite soil	RHA	18	Increase the CBR	(32)
Granite soil	RHA + Cement	20	●Reduced plasticity ●Decreased (MDD) ●Increases the optimum moisture content (OMC)	(33)
Clayey soil	RHA	20	●Enhance mechanical properties (compressive and tensile strength). ●Increase modulus of elasticity, and CBR ●Increase durability in terms of water resistance, water sorptivity, and shrinkage	(34)
Silty soil	RHA + Lime + Plastic fiber	12	●Increase compressive, tensile, and shear strength, ●Enhance CBR	(35)
Sandy soil	RHA + Lime	20	●Decreases MDD ●Increases the OMC	(36)
Clayey soil	RHA + Lime	10	● Increase unconfined compressive strength (UCS).	(10)
Clayey soil	RHA + Steel Slag + Lime	10	● Increase stiffness and durability ● Increase CBR and compressive strength ● Reduce PI	(37)
Silty soil	RHA + Lime	25	● Decrease shrinkage and PI	(38)
Clayey soil	RHA + Lime	20	● Improved CBR ● Reduce the plasticity and free swell	(39)
Alluvial soil	RHA	7.5	● Increase CBR and UCS	(40)
Laterite soil	RHA + Sisal fiber	8	● Decreases MDD ● Increases the OMC ● Increase UCS	(41)

4. METHODOLOGY

This chapter describes the material sources, equipment and test methodologies followed in this project. Four subgrade soils (two from Arkansas and two from Oklahoma) were collected and tested in the laboratory. To achieve the objectives of this project, several laboratory tests were conducted on untreated and treated soils. A detailed explanation of soils and the stabilizing agents along with an experimental design flow chart is provided in this chapter.

4.1. Soil Sample Collection

With the help of ARDOT District 10 engineers and crews, adequate amounts (about 500 lb. of each sample) of soil were collected from two different sites in Arkansas. The first Arkansas soil (AR-1) was collected from an ongoing construction project on I-555 near Jonesboro in Craighead County, Arkansas. The second Arkansas soil (AR-2) was collected from Mississippi county, Arkansas. The locations of these sites are shown in Figure 1 and Table 2

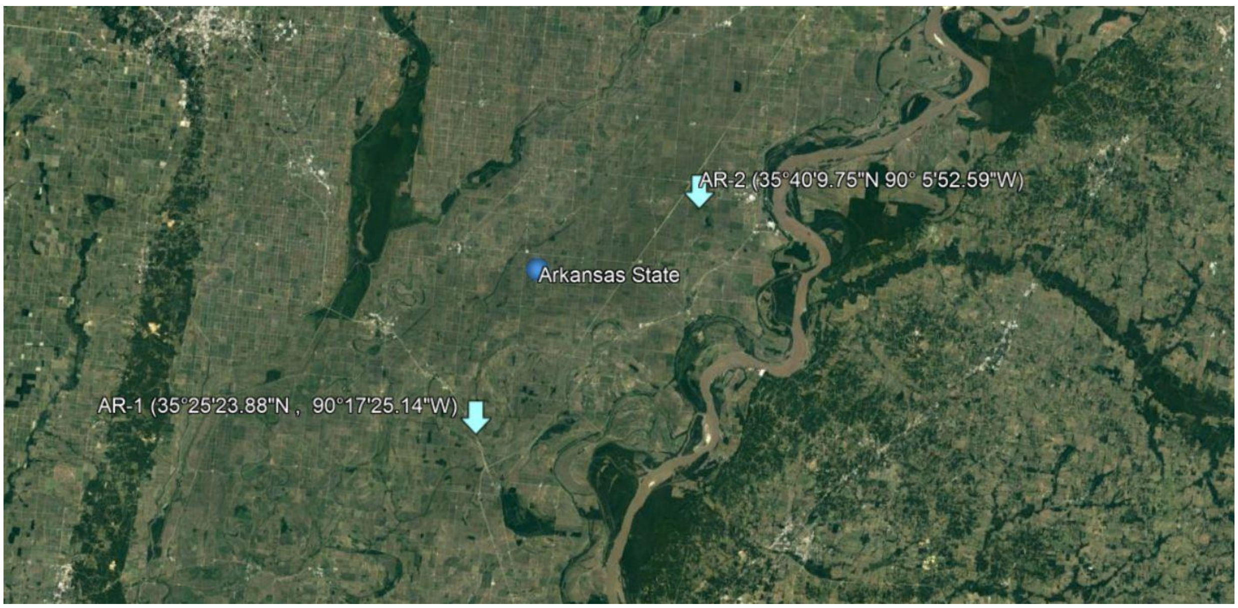


Figure 1. Sample locations for soils AR-1 and AR-2.

In the beginning, the surface soil was removed to make sure there were no organic materials such as grass and tree leaves. By using an excavator, as shown in Figure 2, the AR-1 soil sample was taken at a depth of 5-7 ft from the ground level. The AR-2 sample was retrieved from a depth of 10-12ft from the ground surface. The bulk samples of these soils are shown in Figures 3 and 4. Based on the Unified Soil Classification System (USCS), AR-1 and AR-2 soils are classified as lean clay with sand (CL) and elastic silt (MH), respectively. Other basic properties of these soils are provided in Table 3.

Table 2. The coordination of the sampling locations for AR-1 and AR-2.

Sample No	County	Latitude	Longitude
AR-1 (Red Soil)	Craighead (I-555)	35°30'54"N	90° 24'6.5"W
AR-2 (Black Soil)	Mississippi (AR-181)	35°40'9.75"N	90° 5'52.59"W

Figure 2. Soil collection.

Figure 3. Soil AR-1 sample (Red Soil).

Figure 4. Soil AR-2 sample (Black Soil).

The other two soil samples tested in this study were obtained from two sites in Oklahoma using push-tube sampling. Both sites have high plasticity soils. The first site is located in Ottawa County (OK-1), and the second site is located in Carter County (OK-2). The soil samples collected from the sites were processed into small pieces and spread out on table benches in the laboratory for one week to air dry. The remains of plant roots were removed while the soil was drying. The soil was broken into small pieces and further broken into much smaller sizes using a crusher. The basic geotechnical properties of this soil were obtained by following the relevant ASTM standards: ASTM D7928 (particle size distribution), ASTM D698 (Proctor), and ASTM D4318 (plastic and liquid limits). The results are given in Table 3 Additional information about these soils is provided in Appendix A. Based on the Unified Soil Classification System (USCS), both soils are classified as high-plasticity clay.

Table 3. Basic geotechnical properties of the soil samples

Index Property	Soil AR-1	Soil AR-2	Soil OK-1	Soil OK-2
Liquid Limit, LL, %	35.60	78.5	53	55
Plastic Limit, PL, %	24.55	46.83	24	24
Plasticity Index, PI, %	11.05	31.63	29	31
Gravel (Larger than 4.75 mm), %	2	0	0	0
Sand (0.075 to 4.75 mm), %	43	8.25	16	13
Silt (0.005 to 0.075 mm), %	21	79.13	41	47
Clay (Less than 0.005 mm), %	34	12.62	43	40
Maximum dry density (MDD), gm/cm^3	1.76	1.39	1.85	1.72
Optimum moisture content, %	16.3	27.5	24.0	27.0
Soil classification (USCS)	CL-Lean clay with sand	MH – Elastic silt	High plasticity clay	High plasticity clay

4.2. Additive Material

4.2.1. Rice Husk Ash

The RHA sample was obtained from Agrilectric® Research Co. located in Lake Charles, Louisiana. It was in black powder form, as seen in Figure 5. The chemical compositions of RHA are provided in Table 4 The major chemical component of RHA is silica (about 90%), which is followed by carbon (about 5%), potassium oxide (about 2%), and calcium oxide (about 2%).

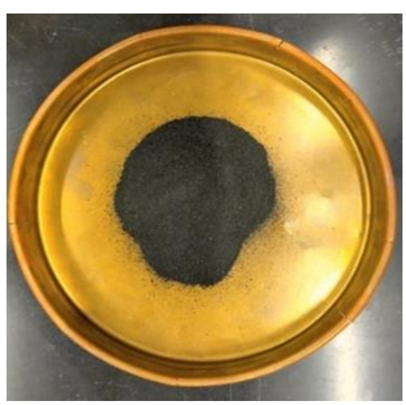


Figure 5. Rice Husk Ash.

Table 4. Oxide composition of RHA.

Name	Constituent	Composition
Silicon Dioxide	SiO_2 (Amorphous)	93.0 ± 4.0%
Silicon Dioxide	SiO_2 (Crystalline)	< 1.0%
Carbon	C	5.0 ± 1 %
Magnesium Oxide	MgO	0.2 ± 0.2%
Aluminum Oxide	Al_2O_3	1.1 ± 0.4%
Potassium Oxide	K_2O	2.20 ± 0.1 %
Ferric Oxide	Fe_xo_y	0.4 ± 0.1 %
Calcium Oxide	CaO	2.0 ± 0.1 %
Sodium Oxide	Na_2O	0.14 ± 0.04 %

4.2.2. Hydrated Lime

The lime sample used in this project was obtained from Arkansas Lime Co, located in Batesville, Arkansas. The collected lime was in white powder form, as shown in Figure 6. The primary soil reactions of soil and lime are the pozzolanic reactions which are formed in the pozzolan paste. The primary reaction will lead to secondary reactions with other active substances within the soil. Therefore, the secondary pozzolanic reactions will depend on the amount of alumina and silica in untreated soil minerals, which are the main mineral to produce the cementitious gel *(42)*. To prepare hydrated lime in the laboratory, different de-ionized water to quicklime mixtures were made. It was found that the quicklime to water ratio of 1:3 (by weight) was optimum such that lime had enough water to make a paste with no excessive water. While the 1:3 ratio was used, even if the quicklime was hydrated with excessive water, it should not be a problem since the goal is to create the calcium hydroxide as a final product. A ceramic pan was used, filled with 300 gm water, and poured 100 gm lime inside. Then, waited for 30 minutes until all the heat was produced. After that, the pan was covered with plastic wrap to prevent carbonation from the atmosphere. The next day, the solution was dried using a hair dryer, for around 30 minutes, and stored the powder of the hydrated lime in a sealed can.

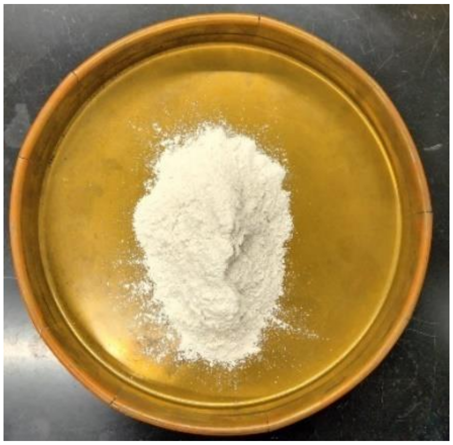


Figure 6. Hydrated Lime.

4.3. Laboratory Tests

4.3.1. Experimental Plan

An extensive literature review was done to develop an experimental plan for this study, as shown in Figure 7. Firstly, a series of laboratory tests were conducted on untreated soils. Secondly, the experimental procedure was extended to include adding different percentages of RHA and HL. Thirdly, the soils were treated with selective combinations of RHA+HL.

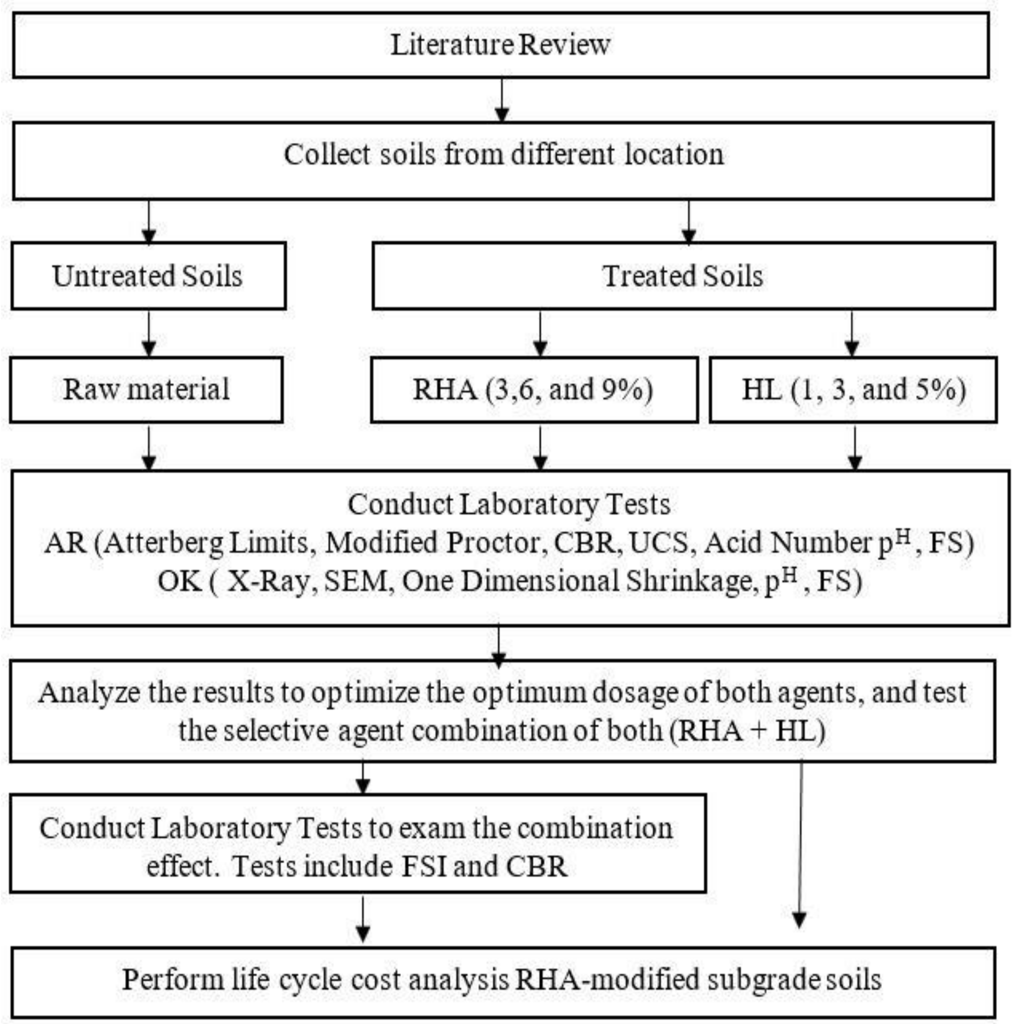


Figure 7. Experimental flow chart.

4.3.2. Gradation

The soil gradation was conducted according to ASTM D422-63 *(43)*. Figure 8 shows the apparatus used for soil gradation. The soil was classified according to the USCS (ASTM D2487-11) *(44)* and the AASHTO Soil Classification System (ASTM D3282-15) *(45)*.

Figure 8. Gradation (a) Sieve shaker (left) and (b) Hydrometer (right).

4.3.3. Atterberg Limits

ASTM D3418-98 (46) was followed to obtain the liquid limit and plastic limit. Around 150 gm of soil was thoroughly mixed with water equal to the optimum water content for the soil. A Casagrande apparatus was used to determine the liquid limit, as seen in Figure 9.

Figure 9. Atterberg limit apparatus.

4.3.4. Modified Proctor

The modified Proctor test results are used to obtain the relationship between the moisture content and dry density of the soil. The modified Proctor was carried out by taking a specific amount of soil which was poured into the compaction mold in five layers. Each of these layers was compacted by a Proctor hammer with 25 blows. From the compaction curve, the optimum moisture content (OMC) and maximum dry density (MDD) were calculated. For each natural soil and soil mixture, the modified Proctor test was carried out according to ASTM D1883-07 *(47)* to define the compaction proctor parameter. The compactor and the mold for the modified Proctor test are shown in Figure 10.

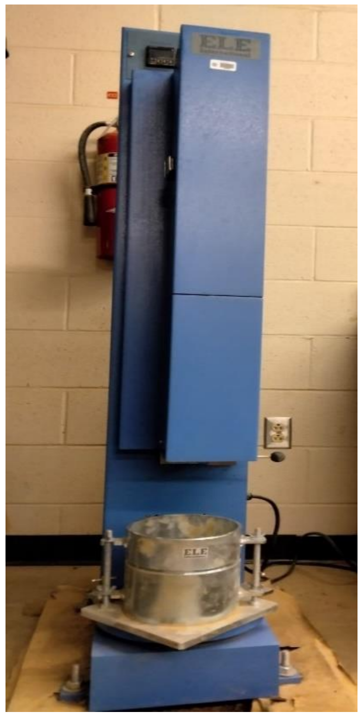


Figure 10. Modified proctor.

4.3.5. Unconfined Compressive Strength (USC)

Compacted soil specimens were prepared by mixing the dry soil and appropriate stabilizing agent with deionized water close to the optimum water content and compacted in layers in a Harvard miniature (HM) mold (42). The mold dimensions are 71.5 mm in height and 33.4 mm in diameter. ASTM D2166-16 *(48)* was followed in preparing and testing the soil samples. The HM apparatus used in this study is shown in Figure 11. The soil was compacted in the HM by a miniature drop hammer to reach a dry density very close to the maximum dry density in the standard Proctor compaction method. After being extracted from the mold, the compacted specimens were weighed and sealed with plastic wrap and aluminum foil and then stored in an ice chest for 7 days of curing in a room of constant humidity (70%) and at 22±1 °C.

4.3.6. California Bearing Ratio (CBR)

The value of the California Bearing Ratio (CBR) is the most essential soil parameter for structural design. It is also used as an indicator of soil strength as a subgrade or embankment. The CBR test can be carried out by applying load with the specific rate on the specimens by a standardized penetration piston. The natural soil was mixed with specific quantities of the stabilized agents and cured for 7 days before the CBR test. The un-soaked CBR was carried on the different soil mixtures according to ASTM D1883 *(49).* The CBR machine used in this study is shown in Figure 12.

Figure 11. Harvard Miniature Compaction apparatus.

Figure 12.California Bearing Ratio machine.

4.3.7. Soil p^H Measurement

The soils were prepared for p^H tests based on ASTM D6276 *(50)*. The air-dried soil was passed through sieve No. 40 and weighed to have 25 gm of the corresponding oven-dried soil. The soil was then mixed with the desired agent content and 100 mL of deionized water inside a sealed plastic bottle. The pH of the solution was measured by the Oakton® p^H 110 Meters as seen in Figure 13. The p^H meter was calibrated using a buffer solution (p^H = 7.00) at 25 °C. Before reading the p^H, the solution bottles were shaken for at least 30s every 10 min for 1h. For both treated and untreated soils, the same procedure was followed to measure the p^H values.

Figure 13. The probe for measuring the soil p^H.

4.3.8. Free Swelling Test (FST)

ASTM D4546-14 (35) was followed to conduct one-dimensional free-swell tests. The free-swell test was conducted on reconstituted soils compacted inside a stainless-steel ring of 6.40 cm in diameter and 2.54 cm in height as shown in Figure 14. Deionized water was used for all free-swell tests. The mixture of soil and stabilizer was compacted with the optimum water content in three layers. The mixture of soil and stabilizer was mixing n the dry state through manual mixing of the materials. Each layer received 25 blows using a wooden rod with a rubber cap (diameter =2.54 cm) to reach a dry density close, i.e., ±3% for untreated specimens, to the maximum dry density of the soil obtained from the standard Proctor compaction test. The compacted specimen with the ring was weighed, sealed with plastic wrap and aluminum foil, and then stored in an ice-chest for curing in a room of constant humidity of 45% and 22°C ± 1°C temperature. The soil specimens for the free-swell test were cured for 7 days. Then, the one-dimensional free-swell test was carried out under a pressure of 1 kPa as recommended by ASTM D4546-14, as shown in Figure 15. The swelling test was conducted after curing the prepared soil specimens for 7 days to allow for initial chemical interactions between the soil, RHA, and/or hydrated lime when the mixture was at the optimum moisture content.

Figure 14. Free Swell specimen.

Figure 15. Free Swell.

4.3.9. One-Directional Shrinkage Test

Since the specimens were tested in consolidometer rings, only the shrinkage in one direction was measured. The one-directional shrinkage was measured by a dial gauge set on a porous stone placed on the top of the specimen. The soil specimen was air-dried in the laboratory at a temperature and a relative humidity equal to 22±1 °C and 45%, respectively.

4.3.10. Microstructure Analysis

Samples from the stabilized soils were collected and analyzed by X-ray diffraction (XRD) and scanning electron microscopy (SEM). These tests were conducted in the Microscopy Laboratory at Oklahoma State University. The SEM analysis was conducted using the FEI Quanta 600 SEM, and the XRD using Bruker D8 Advance with a Lynxeye detector.

5. ANALYSIS AND FINDINGS

5.1. Effect of Additives on Soil Samples from Arkansas

5.1.1 Atterberg Limit

Figure 16 illustrates the relationship between the LL and the soil's moisture content. The LL of RHA-treated AR-1 increased as the percentage of RHA increased. For instance, the untreated AR-1 has its LL to be 35.6% but at 9%RHA treated soil, it was observed to be 41.1%. For AR-2, the RHA-treated soil's LL decreased slightly as the percentage of RHA increased. The LL for untreated AR-2 was 78.5%, while the LL dropped to reach 73.91% when the soil was mixed with 9%RHA.

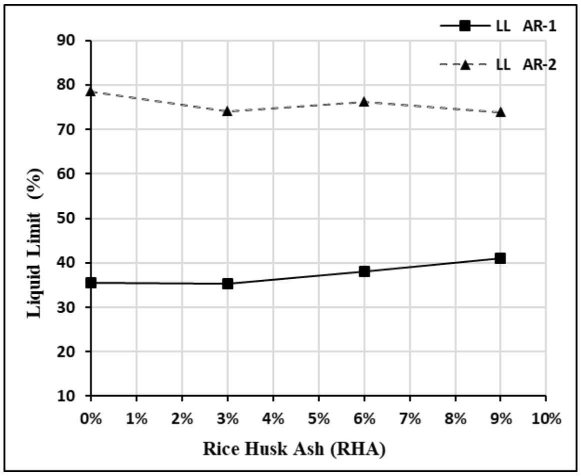


Figure 16. Effect of RHA on liquid limit of AR-soils

In the case of HL, from Figure 17, it is seen that the LL of AR-1 soil increased with a very small (1%) addition of HL. The LL for untreated AR-1 is 35.6% meanwhile the LL of treated AR-1 with 5%HL is 43.5%. Afterward, the LL decreased slightly with a further increase in HL. On the other hand, for AR-2, the LL decreased while adding HL. For example, the LL of mixing AR-2 with 1%, 3%, and 5%HL were 71.2%, 64.18%, and 60.32%, respectively.

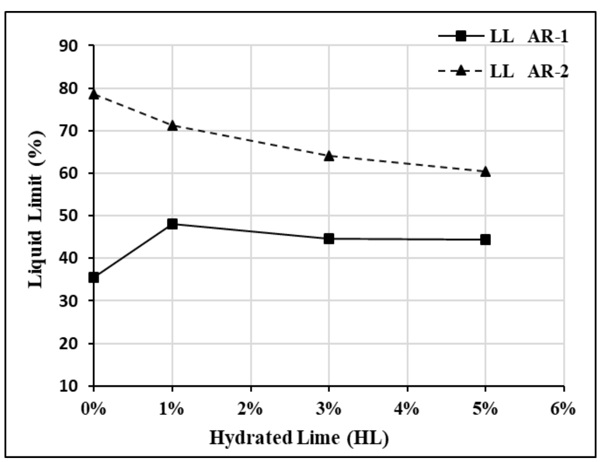


Figure 17. Effect of HL on liquid limit of AR-soils.

The effect of RHA on PI with different soils is shown in Figure 18. It is illustrated that there is a moderate reduction in the plasticity of RHA-treated soil. However, there is a significant decrease in the plasticity of AR-2 when it is mixed with RHA.

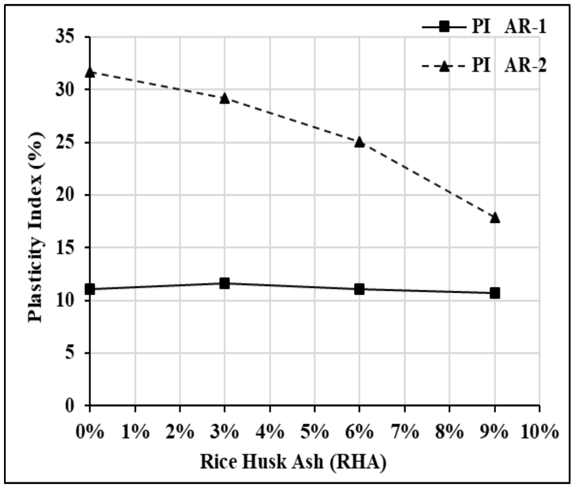


Figure 18. Effect of RHA on plasticity index of AR-soils.

From Figure 19, it is observed that the HL reduces the PI sharply for both soils. By using 3%HL, the AR-1 behaved like a non-plastic material. However, for untreated AR-2, the PI was 31.66. The PI of AR-2 soil decreased to 16.9%, 15.08%, and 9.12% by adding 1%, 3%, and 5% HL, respectively.

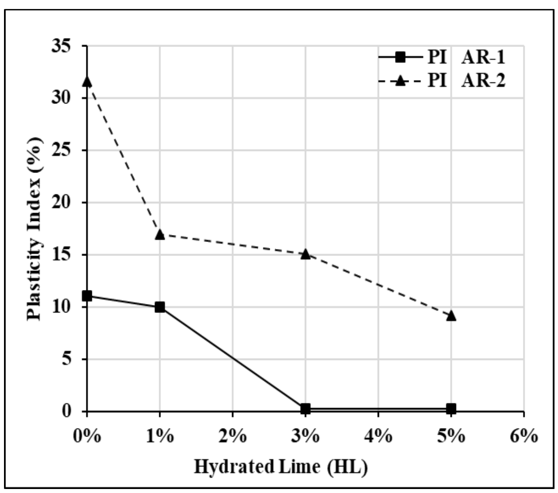


Figure 19. Effect of HL on plasticity index of AR-soils.

5.1.2 Effect on Optimum Moisture Content and Maximum Dry Density

The relationship between the density and additive material is shown in Figure 20. In general, the trend shows a reduction in the dry density with the addition of RHA. The decrease in MDD from 1.76gm/cm^3 to 1.56gm/cm^3 by adding 9%RHA to AR-1. Similarly, the MDD decreased from 1.39 gm/cm^3 to 1.33 gm/cm^3 by mixing 9%RHA with AR-2. The reduction in the dry density may be explained by using the lower specific gravity of RHA than the natural soil.

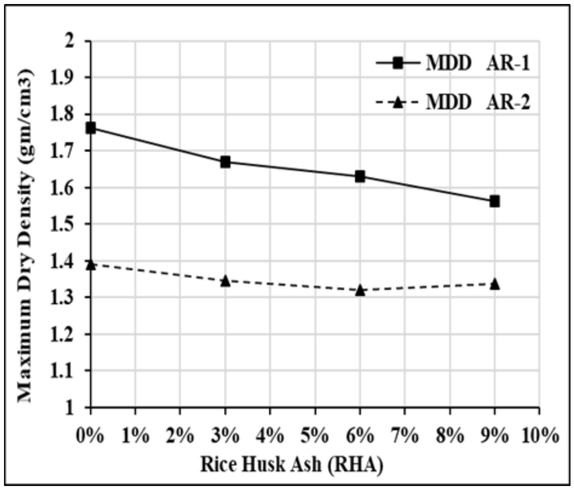


Figure 20. Effect of RHA on MDD of AR-soils.

From Figure 21, it is seen that for untreated AR-1, the MDD was 1.76 gm/cm^3. For 1%HL, 3%HL, and 5% HL, the MDD of AR-1 soil reduced to 1.68 gm/cm^3, 1.69 gm/cm^3, and 1.64 gm/cm^3, respectively. Similarly, there was a decreasing trend of MDD of AR-2 soil when HL was used as a stabilizing agent. The least MDD was observed at 5%HL, which was 1.34 gm/cm^3, while the MDD of the untreated AR-2 soil was 1.39 gm/cm^3.

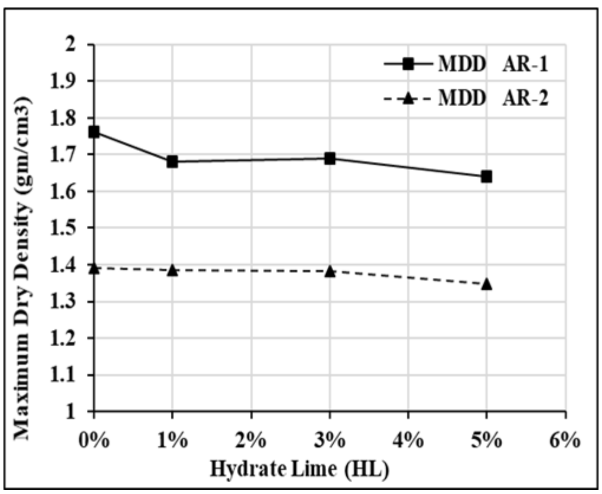


Figure 21. Effect of HL on MDD of AR-soils.

Using RHA as additive material can increase the OMC of the soils. For AR-1, the OMC for untreated soil was 16.10%, and the OMC increased to 20.3% with 9%RHA. On the other hand, AR-2 showed an increased OMC of 31.2% with 3%RHA, then it decreased to 30.2% and 27.9% with 5% and 9% RHA, respectively, as shown in Figure 22. For both soils, increasing the percentage of RHA will increase the percentage of OMC required to reach the MDD.

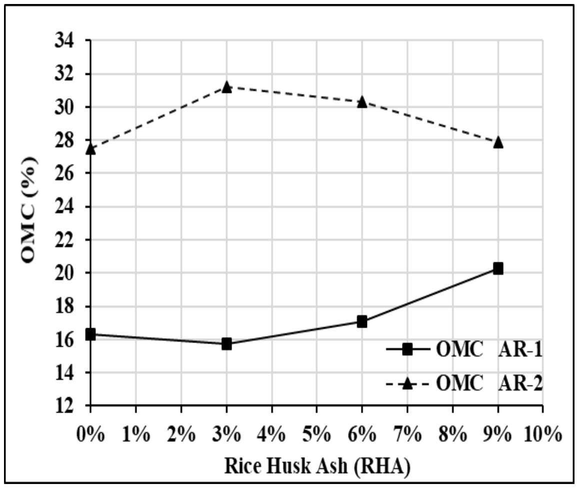


Figure 22. Effect of RHA on OMC of AR-soils.

From Figure 23, an increase in the OMC is observed with an increase in the amount of HL. For AR-1, the OMC increased gradually; with 1%, 3%, and 5% HL the OMC is found to be 17.2%, 18.1%, and 19.1%, respectively. In the case of AR-2, 1%, 3%, and 5% HL samples have OMC values of 32.2%, 29.8%, and 31.1%, respectively.

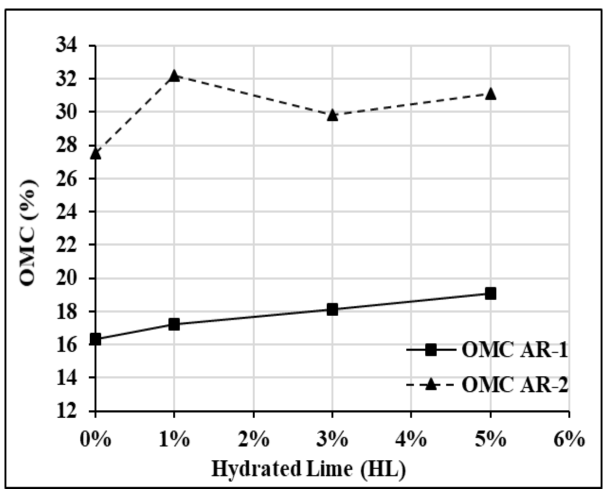


Figure 23. Effect of HL on OMC of AR-soils.

5.1.3 Effect on Unconfined Compressive Strength

From Figure 24, it is seen that in general, the soil's UCS improved with the addition of either RHA or HL. At 9% RHA, the soil's UCS is the maximum for both AR-1 and AR-2. It is also observed that the increase of UCS is significantly more for RHA than HL in the case of AR-1. As expected, except for AR-1 soil with 1%HL, the HL increases the UCS and the maximum UCS is observed when 5% HL is used as the stabilizing agent. In the case of AR-1 soil, 3% HL was found to be the optimum dosage to get the highest UCS value.

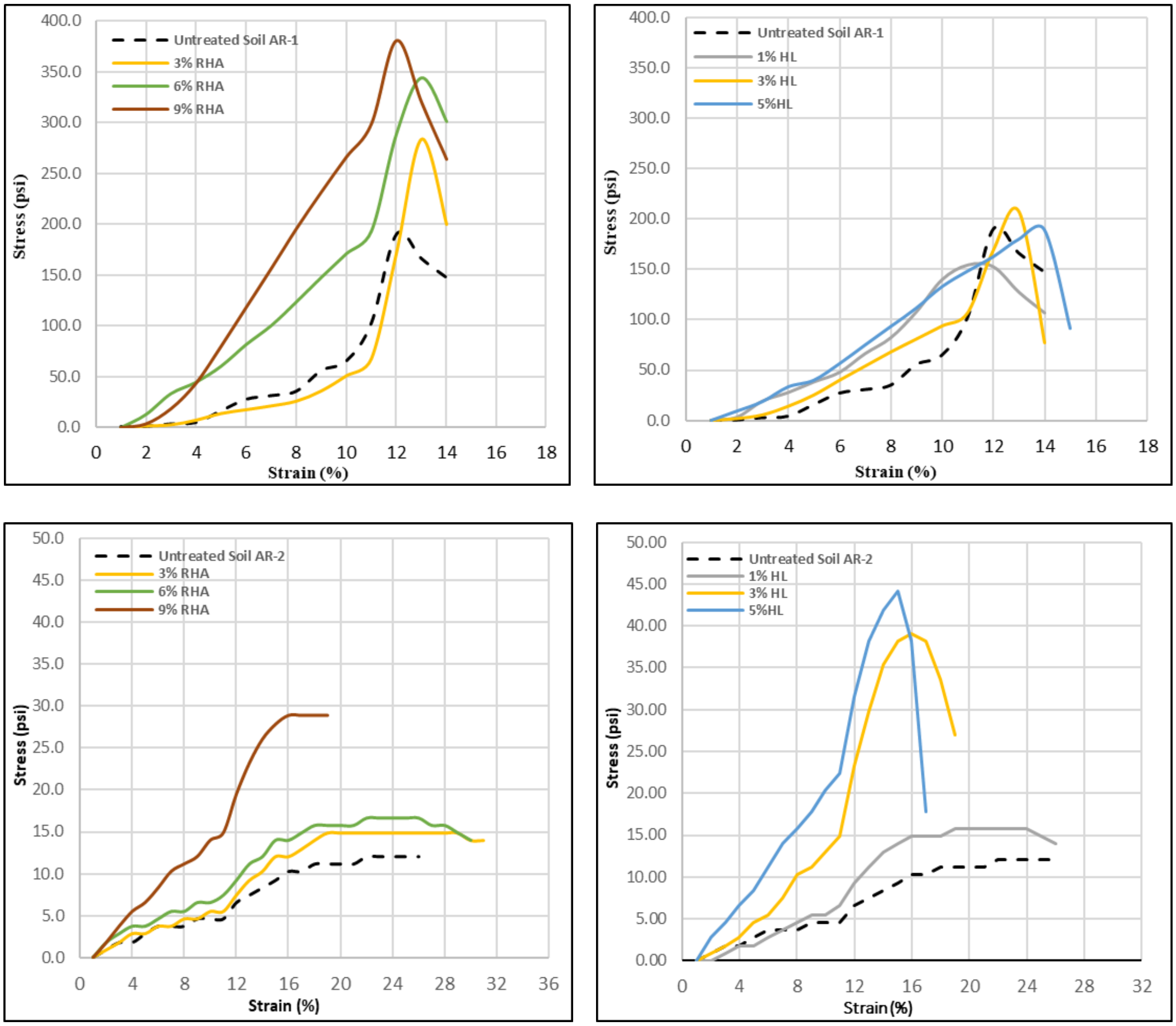


Figure 24. Effect of RHA and HL on UCS *of AR-Soils: (a)AR-1 with RHA(left-top), (b) AR-1 with HL(right-top), (c) AR-2 with RHA(left-bottom), and (d) AR-2 with HL(right-bottom).*

5.1.4 Effect of California Bearing Ratio

The CBR values of AR-1 and AR-2 soils treated with RHA ranging from 0% to 9% are shown in Figure 25. In general, there is an increased improvement in the CBR value of both treated soils. The CBR value for untreated AR-1 was 2.52%. The CBR values for AR-1 were 2.70%, 3.40%, and 5.61% when mixed with 3%, 6%, and 9% RHA, respectively. The CBR value for untreated AR-2 was 3.12%, and it increased to 3.71%, and 5.84% when mixed with 3% and 6% RHA, respectively. However, the CBR value decreased to 5.09% when the RHA amount was increased to 9%. Thus, 6% RHA appears to be the optimum dosage for the AR-2 soil.

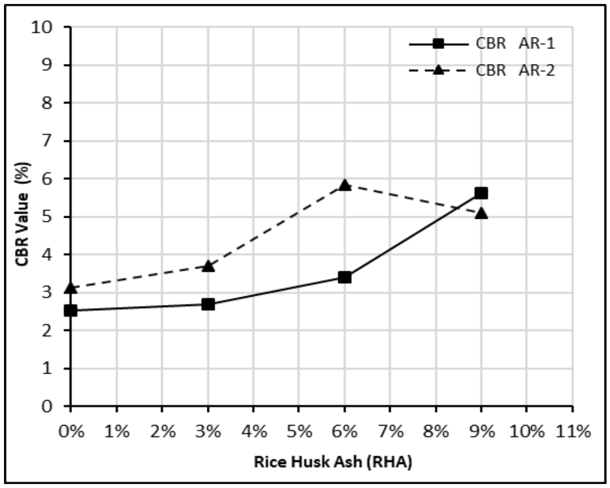


Figure 25. Effect of RHA on CBR of AR-soils.

Using HL as additive material shows an increase in CBR, as seen in Figure 26. The AR-1 soil treated with 1%, 3% and 5% HL increased the CBR value to 2.81%, 5.51%, and 7.82%, respectively. On the other hand, the AR-2 soil treated with 1%, 3%, and 5% HL increased the CBR value to 4.1%, 6.45%, and 8.13%, respectively.

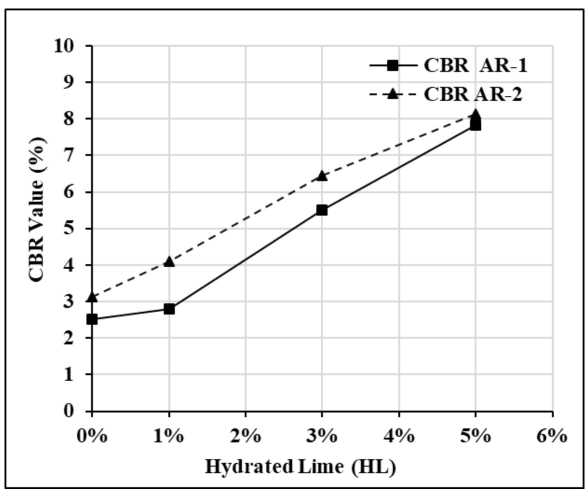


Figure 26. Effect of HL on CBR of AR-soils.

5.1.5 Effect of Soil p^H

The RHA has a moderate effect on the p^H of the tested soils. The p^H value of the soil increased gradually with a higher dosage of RHA. The maximum pH value was observed as 7.75 at 9% RHA, as shown in Figure 27. On the other hand, HL significantly affects the soil p^H. There is a sharp increase in the p^H value with an increase in the HL dosage. The p^H value reached to10.66 at 1% HL. Then the p^H value steadily increased to a higher percentage of HL to 12.95 at 5% HL.

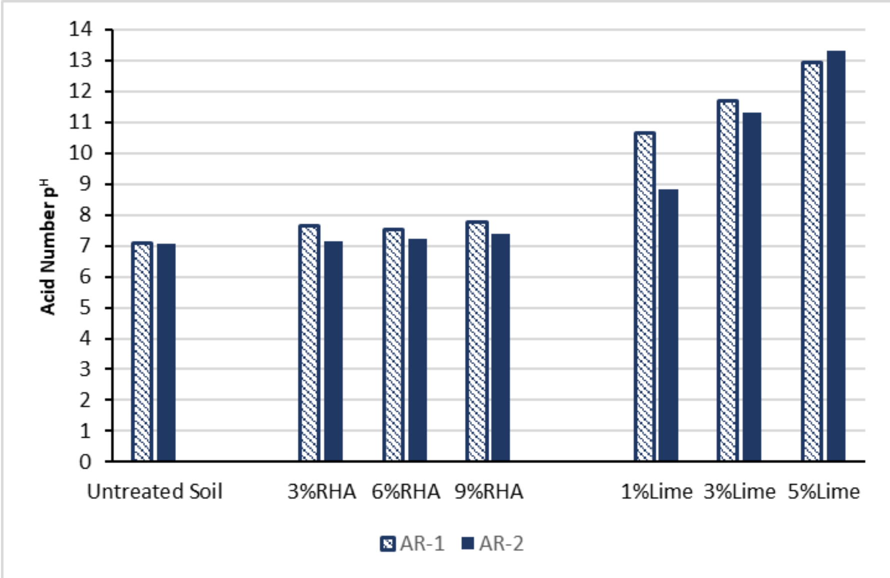


Figure 27. Effect of RHA and HL on p^H of AR-soils.

5.1.6 Optimum Dosages of RHA and HL

Considering test results (PI, UCS, and CBR), a 6% RHA was found to be optimum. On the other hand, a 3% HL was found to be optimum. It can be noted that the use of HL as a stabilizing agent is not a new concept. As seen from the laboratory test results of the current study, 3% lime has exhibited superior performance as a stabilizing agent compared to 6% RHA. Thus, the research team strived to find a suitable binary system (RHA+HL) that would give comparative results of HL alone while using a lesser amount of HL so that the former would be more economical than the latter. The next section discusses selected binary systems along with their laboratory test results.

5.1.7 Effect of Blended Stabilizing Agents on CBR

Keeping the overall objective of this study (e.g., use of RHA as a stabilizing agent), the research team strived to focus on a combination of lime and RHA together (i.e., binary systems) to understand their efficacy without jeopardizing the beneficial effects too much. Thus, the research team tried 1% HL (e.g., below its optimum dosage of 3% as a unary system) and three different percentages of RHA while staying below its optimum dosage of 6% as a unary system. Also, 1% HL was chosen from an economical perspective as RHA is less expensive than HL.

As seen in Figures 28 and 29, 1%HL shows a remarkable improvement in the CBR value AR-1 and AR-2 with 2.84% and 4.1%, respectively. The combination of mixing RHA and HL with both soils shows a better improvement in the soil strength at a lower cost. The CBR result for the combination agents showed using 1%HL+5%RHA gives the highest CBR strength for the AR-1 and AR-2 soils at 142.3% and 127.56%, respectively. However, using 1%HL + 4%RHA gave slightly low improvement strength compared to the 1%HL+ 5%RHA sample. The CBR improvement for the 1%HL+4%RHA soil AR-1 and AR-2 is 113.09% and 121.79%, respectively. This combination is appropriate in terms of strength at a lower cost than either 3%HL or 1%HL+5%RHA.

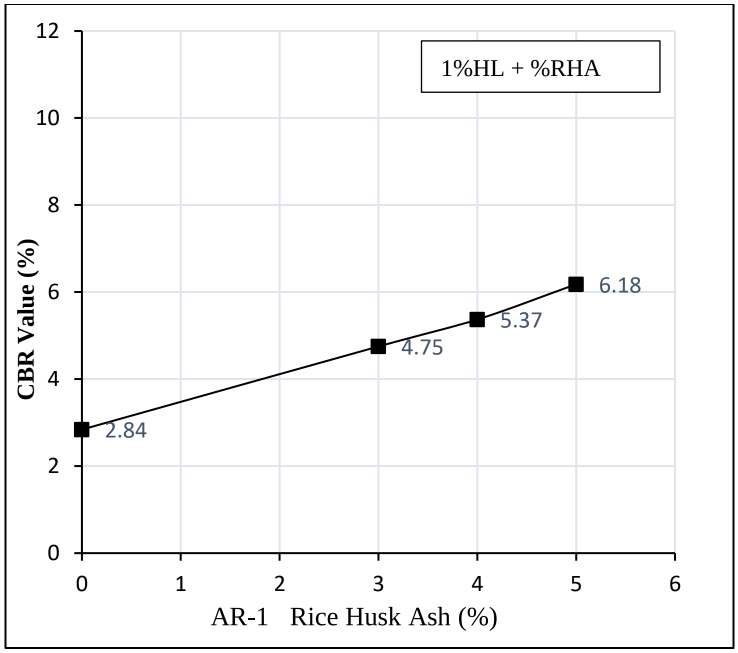


Figure 28. Effect of agents combination on CBR of AR-1 soil.

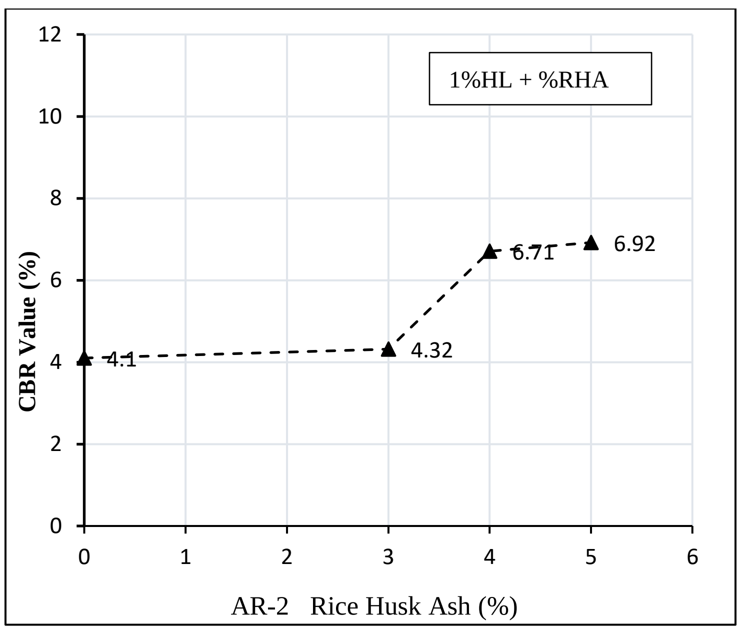
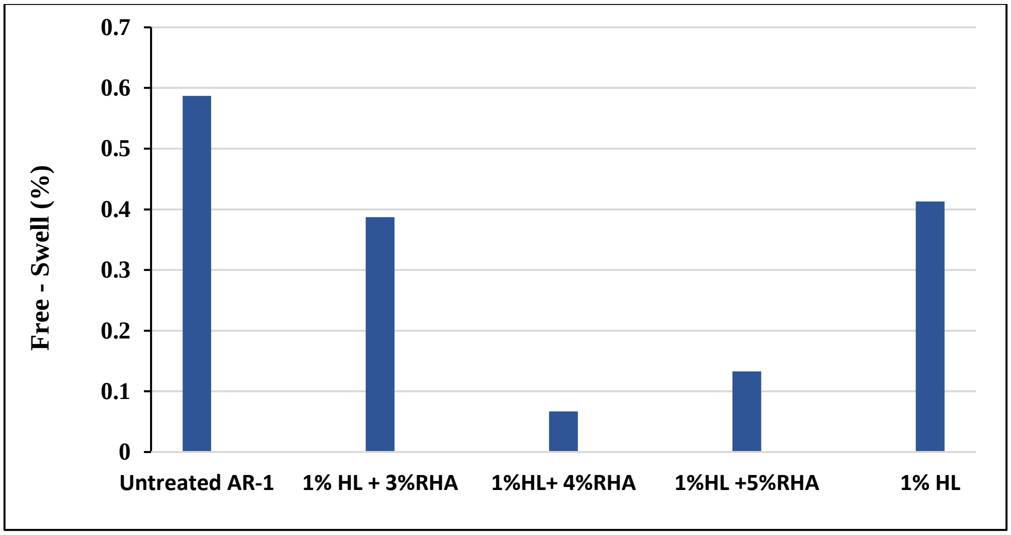


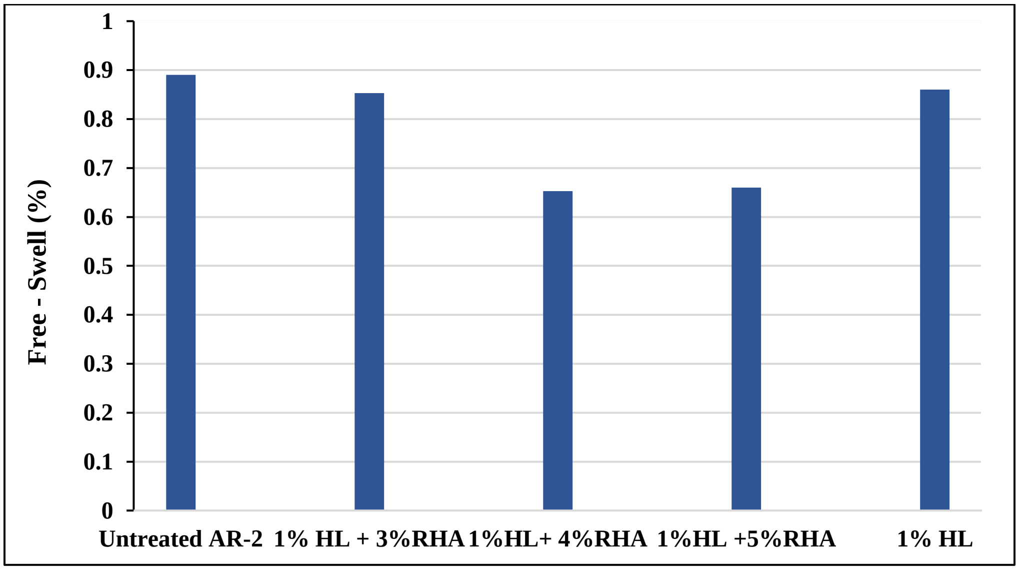
Figure 29. Effect of agents combination on CBR of AR-2 soil.

5.1.8 Effect of Blended Stabilizing Agents on Free Swell

Four samples of soil mixtures were tested for free-swell tests to examine the effectiveness of stabilized agents in mitigating the soil swell potential. Free swell tests were assessed to have 1%HL mixed with 3%, 4%, and 5% RHA. Besides, the Free swell test was conducted on the soil mixed only with 1%HL. The results of the free swell tests for AR-1 and AR-2 are presented in Figure 30. From the Free swell result, using the combination of 1%HL +4% RHA showed a significant reduction in the swell potential. The Free swell value for AR-1 reduced sharply from 0.587% to 0.065% when treated with 1%HL+4%RHA. Likewise, for the treated AR-2 with 1%HL+4%RHA, the reduction in the free swell potential dropped from 0.88% to 0.65%. Thus, a combination of 1%HL+4%RHA is the optimum dosage among the three binary systems considered in this study.



(a)



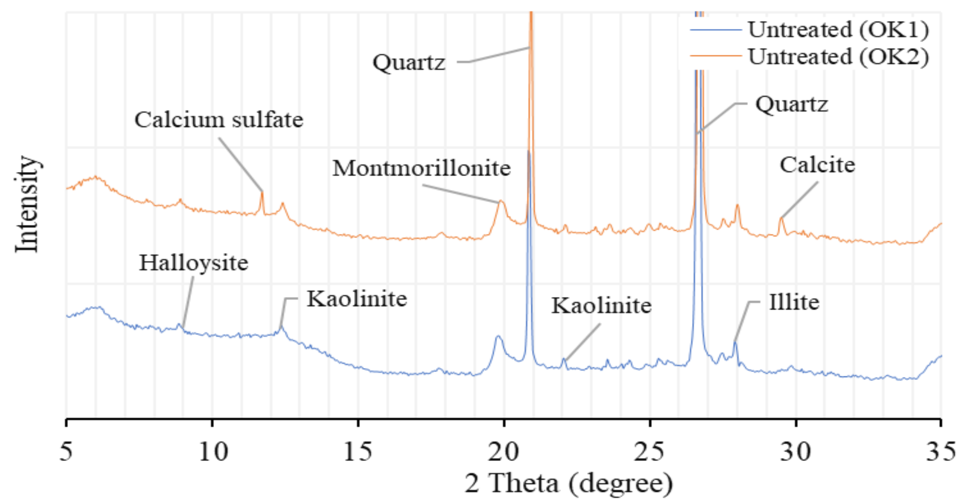
(b)

Figure 30. Effect of agent combination on free- swell of AR-soils: (a) AR-1 soil and (b) AR-2 soil.

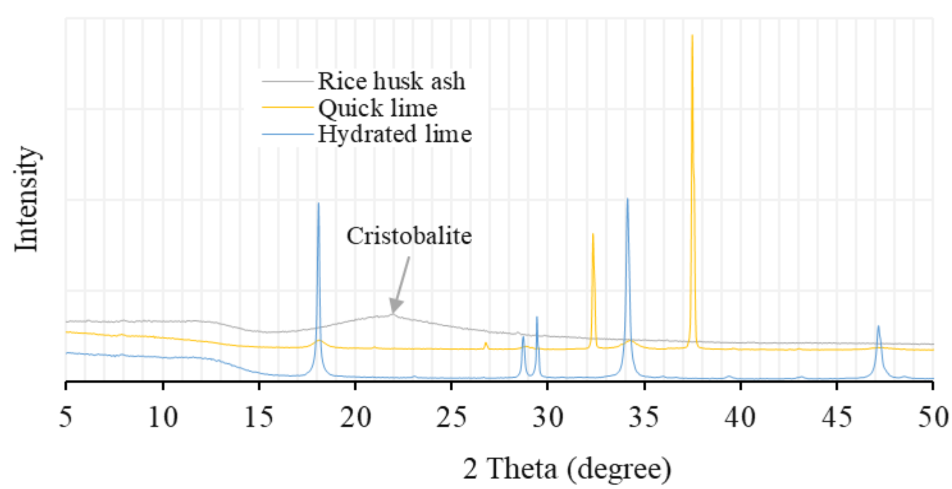
5.2. Effect of Additives on Soil Samples from Oklahoma

5.2.1. X-Ray Diffraction and Morphology of Materials

Applying X-ray diffraction (XRD) on samples from quicklime, HL, RHA, and native untreated soils gave the peaks shown in Figure 31. The morphology of the stabilizers, quicklime, hydrated lime, and RHA is shown in Figure 32. The XRD indicates the presence of different clay minerals in both soils. The XRD also indicates the presence of calcium sulfate in only OK-2 soil. In the case of stabilized soils, a new mineral of silica "cristobalite" is formed due to the addition of RHA at very high temperatures.



(a)



(b)

Figure 31. The XRD results of (a) the native soils, and (b) the stabilized soils.

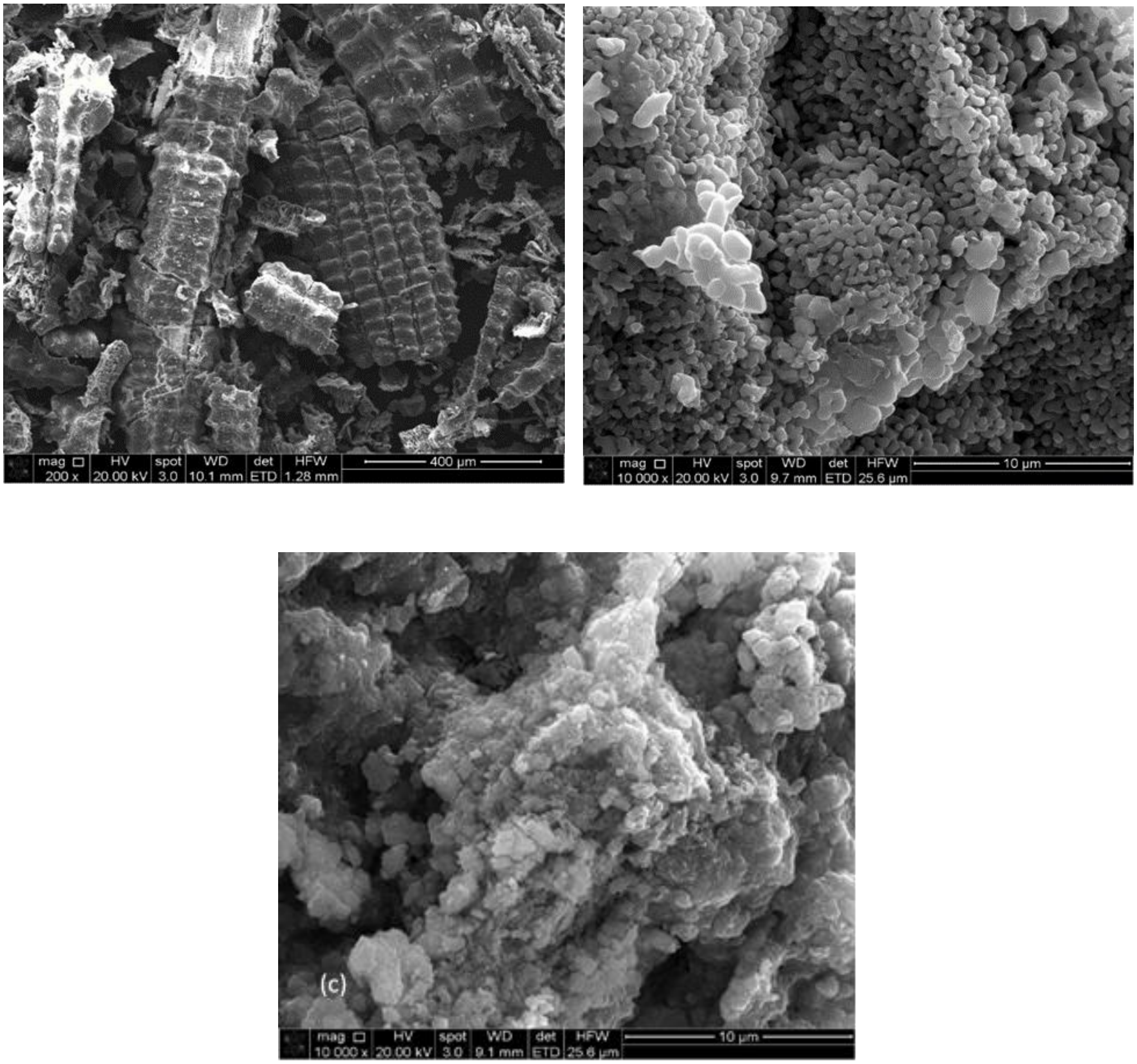


Figure 32. SEM images of the stabilizers: (a) RHA(left-top), (b) quicklime(right-top), and (c) hydrated lime(ceter-bottom).

5.2.2. Free-Swell Tests

At first, the research team decided to investigate the Oklahoma soils with either lime or RHA. As mentioned earlier, the mix design of the 1st selection includes adding 3%, 6%, 9% RHA or 1%, 3%, 5% HL. The results are shown in Figure 33. The results reveal that HL treatment is more effective in reducing the swelling potential of both soils. The treatment with 1% HL was enough to almost vanish the swelling potential for both soils. However, in the case of RHA, the reduction of percent swell ranges from 21% to 73%. The addition of both stabilizers led to a slight reduction in the dry density. For lime treatment, the increase in the stabilizer dosage from 1% to 5% lowered the dry density by 5.0% and 4.6% for OK-1 and OK-2 soil, respectively. Based on the results presented in Figure 33, the research team decided to investigate the effectiveness of blending both stabilizers: HL and RHA.

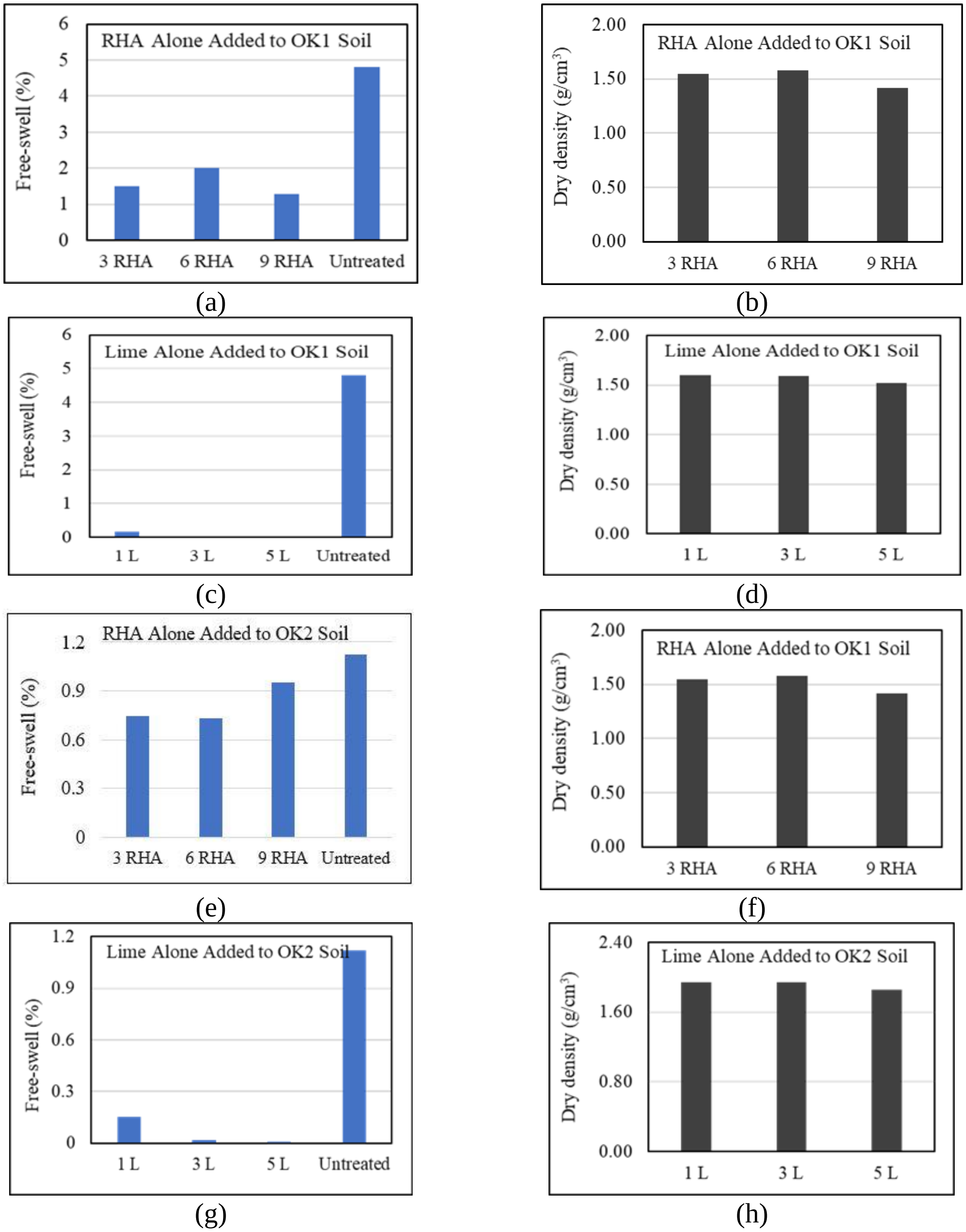


Figure 33. Results of free-swell tests from the 1st selection of mix design for (a) RHA with OK-1, (c) HL with OK-1, (e) RHA with OK-2, (g) HL with OK-2, and result of dry density test for (b) RHA with OK-1, (d) HL with OK-1, (f) RHA with OK-2, (h) L with OK-2

The next mix design of free-swell tests was assessed to have RHA equal to 2, 4, and 6% blended with 1 or 2% lime. The results of this mix design are presented in Figure 34 together with the results of the dry density. This mix design revealed that the improvement of free-swell by adding RHA was not significant enough if compared with the untreated native soil. The free-swell of the untreated soil exceeded 4% and that of only 1% lime was about 0.62%. However, adding 6% RHA with 1% lime reduces the free-swell to 0.35%. Therefore, in a general perspective, the addition of lime alone may be sufficient enough to reduce swelling behavior.

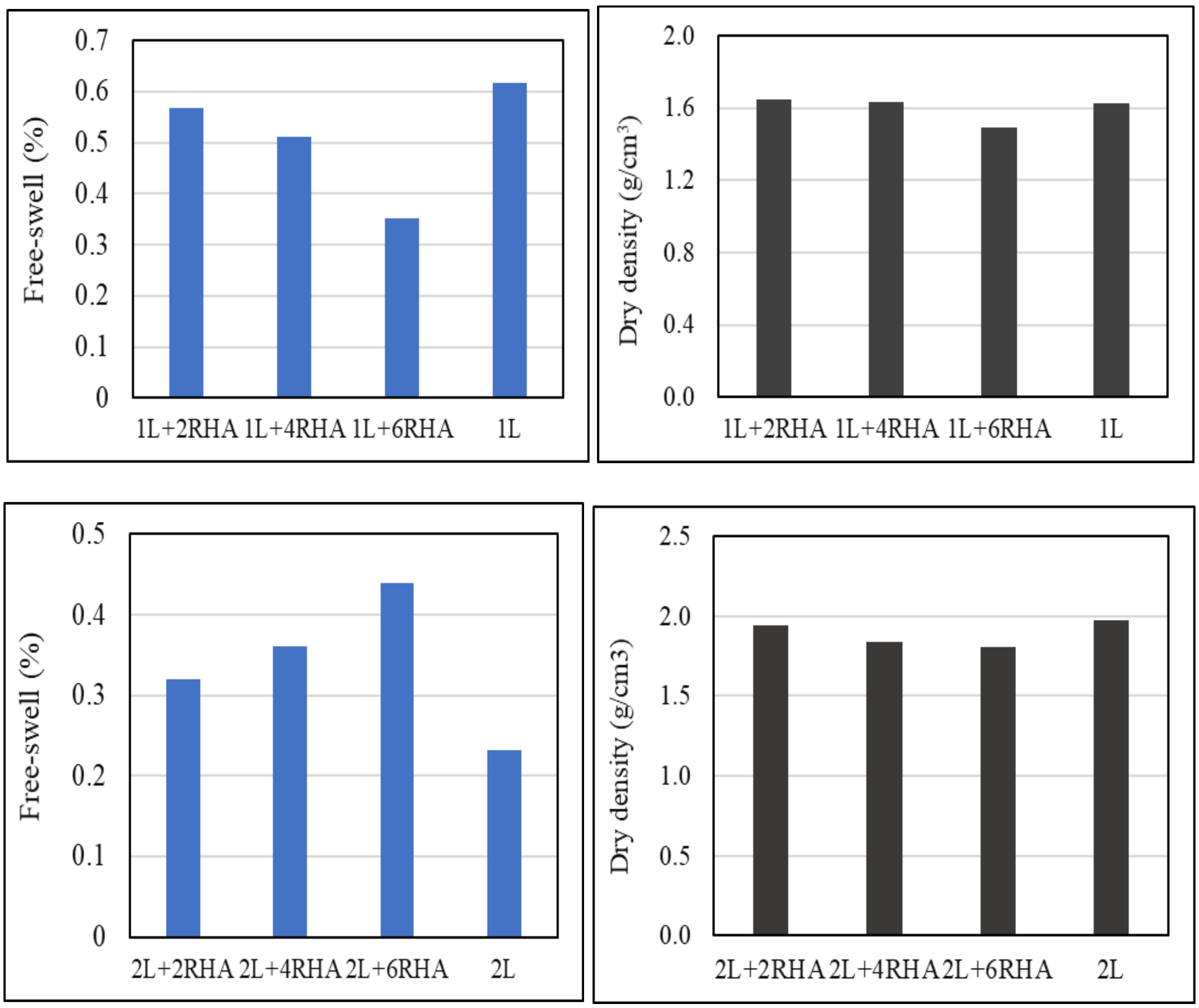
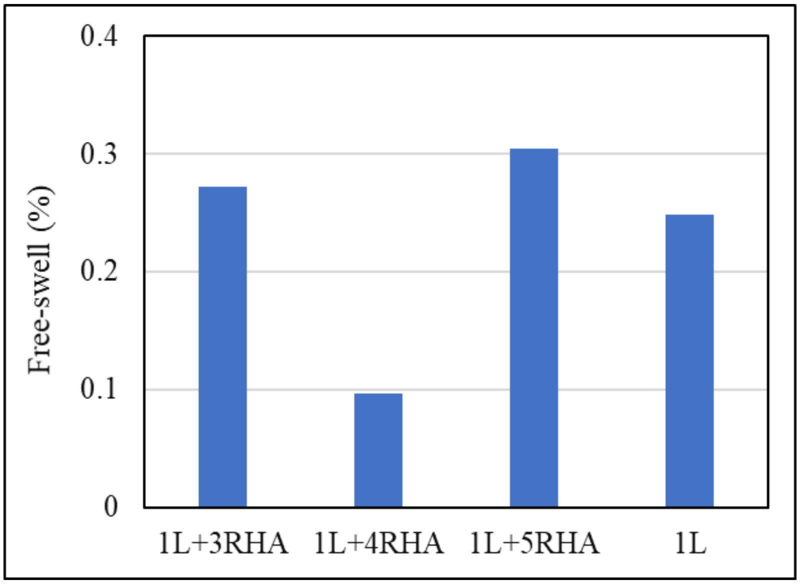
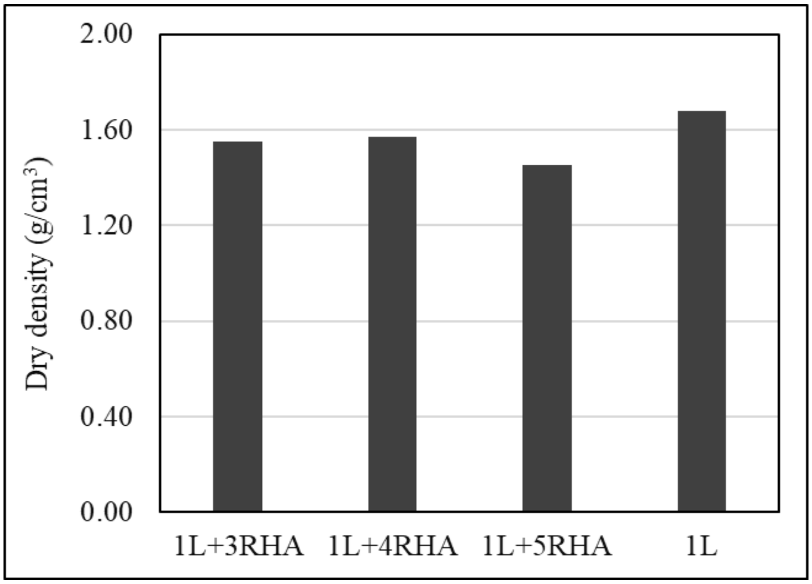


Figure 34. Results of free-swell tests from the 2nd selection of mix design for OK-1 (a) 1%L with different %RHA(left-top), (c) 2%HL with different % RHA(left-bottom), and results of dry density tests for (b) 1% L with different % RHA(top-right), and (d) 2% HL with different %RHA(bottom-right).

Based on the swelling results shown in Figuer 34, the research team decided to mix OK-1 soil with 1% lime and 3, 4, and 5% RHA. The same procedure of the free-swell test was followed. The results provided in Figure 35 show that 4% RHA added to 1% lime can provide some mitigation on free-swell behavior. A summary of the overall swelling results is presented later in this report. The next section presents the microstructural examination of the swelling specimens using XRD and SEM.



(a)

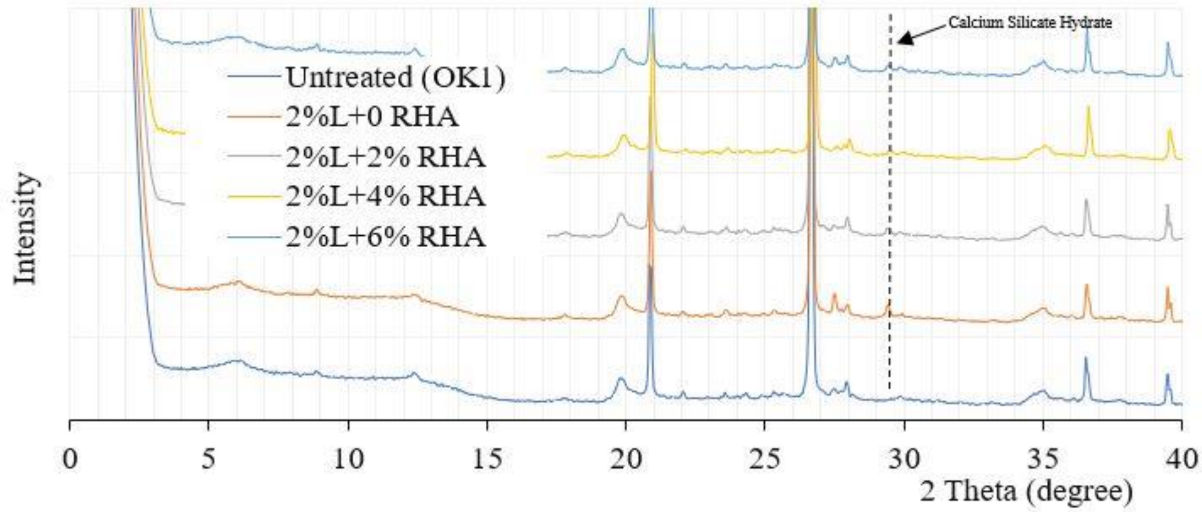


(b)

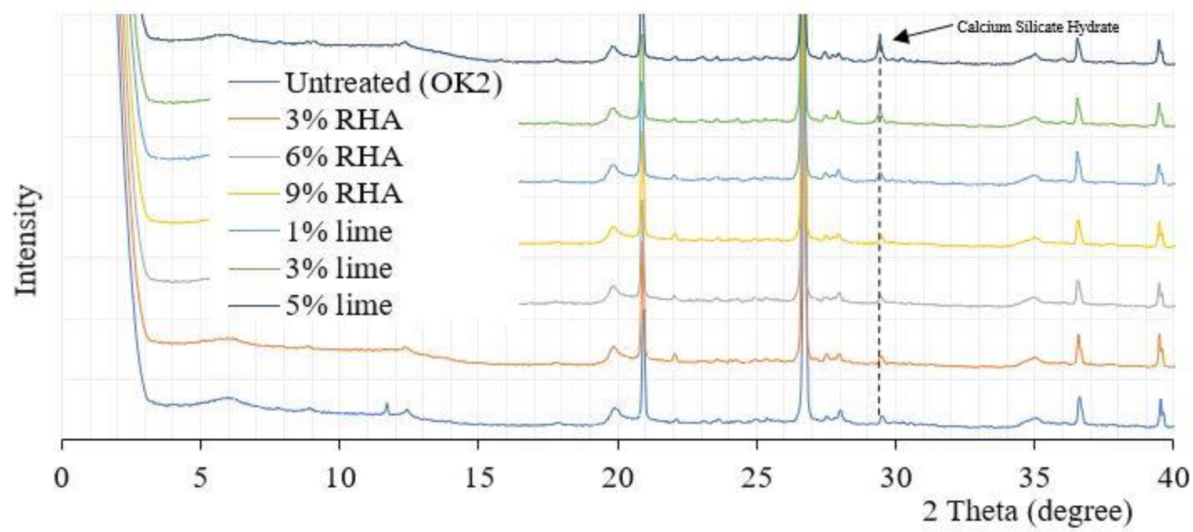
Figure 35. Results of free-swell tests from the 3rd selection of mix design, (a) free-swell results and (a) dry density results.

5.2.3. Microstructural Investigation by XRD and ESEM

After the swelling tests were over small samples were cut and subjected to air drying in the laboratory. After drying, they were crushed into powder and investigated using the X-ray diffraction (XRD) and environmental scanning electron microscope at the Oklahoma State University (OSU) Microscopy Facility. XRD results indicate a peak at 2 Theta around 29.5º as shown in Figure 36. This peak can reflect the presence of calcium silicate hydrate. The results of other XRD analyses are given in Appendix B.



(a)



(b)

Figure 36. Results of XRD: (a) OK-1 soil and (b) OK-2 soil.

The scanning by SEM provided more explanation on the treated soils as discussed below. Several SEM images of both Oklahoma soils treated with RHA are shown in Figures 37a and 37b. These images indicate that RHA worked as a filler material. Other images of lime-treated soils (Figures 37c and 37d) show the formation of cementitious materials owing to the lime treatment. One interesting observation is the formation of ettringite in OK-2 soil treated with 5% lime. EDX spectroscopy was taken on certain spots of the samples. All the EDX results are provided in Appendix B.

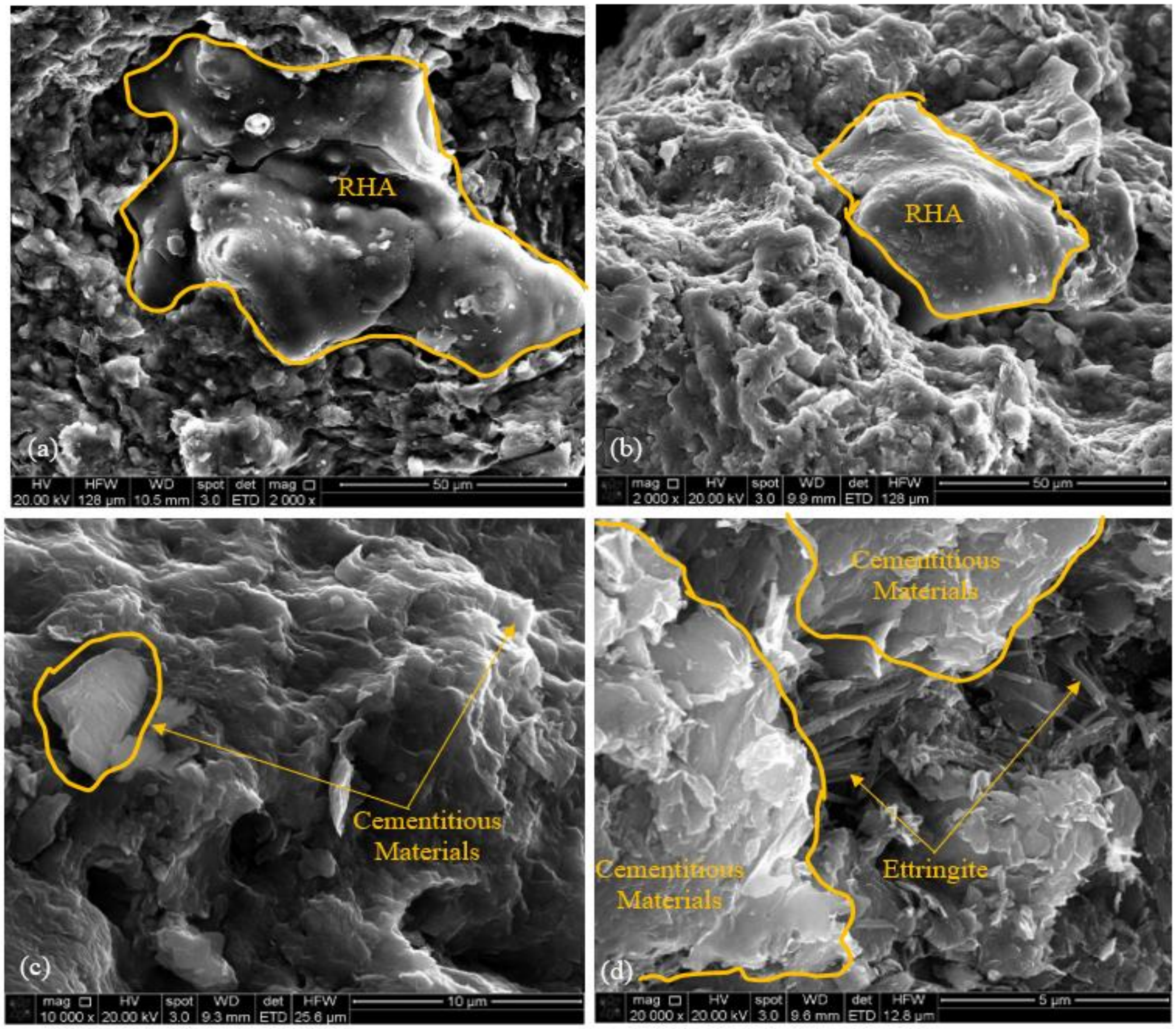


Figure 37 SEM images of treated soils, (a) OK-1 treated with 1% lime with 6% RHA, (b) OK-1 treated with 9% RHA, (c) OK-1 treated with 5% lime, and (d) OK-2 treated with 5% lime

5.2.4. Summary of the Free-Swell Tests Microstructural Investigation

Three mix designs were selected for free-swell tests to examine the effectiveness of RHA in reducing swelling potential. RHA was added in both conditions, i.e., alone and blended with the hydrated lime. In general, it was found that the RHA did not provide significant mitigation to the swelling behavior as compared with the hydrated lime. One percent lime was enough to introduce a high reduction in percent swell. The addition of 1% lime reduced the percent swell by at least 85% for both Oklahoma soils. However, the optimum mitigation of the percent swell in the case of RHA alone was 3%. Three percent RHA reduced the percent swell by 69% and 33.6% for OK-1 and OK-2 soil, respectively.

Microstructural examination by XRD and SEM was carried out for all the samples tested for swelling. The results indicated that the RHA particles worked as a filler material within the structure of the soil. However, for the treatment with lime, both XRD and SEM indicated the formation of cementitious materials in both stabilized soils, i.e., OK-1 and OK-2 soil, such as calcium silicate hydrate. Another interesting observation was the presence of ettringite minerals in OK-2 soil treated with lime. This observation agrees with the XRD of the native untreated OK-2 soil. As shown in Figure 36, the XRD reflected a peak of calcium sulfate for OK-2 soil.

While there are signs from free-swell tests that RHA has contributed to mitigating the swelling behavior, its contribution is still not considerable as compared with the lime treatment only. For example, the treatment of OK-1 soil with only 1% lime reduced the free-swell from 4.8% to about 0.25%, while the addition of 4% RHA with 1% lime only improves the swelling potential by reducing it from 0.25% (the case of 1% lime only) to 0.1% (the case of 4% RHA added to 1% lime). According to the findings from this preliminary study, it is recommended for future studies to first investigate the chemical reactions between the pozzolan (i.e., RHA in this study) and the hydrated lime before the treatment with the candidate soil.

5.2.5. The p^H of the Swelling Test Solution

The p^H of the swelling solutions was measured. After the swelling tests were over the collected solutions were subjected to air drying in the laboratory to reach the initial water content of the samples. The average readings are listed in Table 5 and shown in Figure 38. The results indicated no clear trend of a correlation between the stabilizer content and the solution p^H.

Table 5. The results of the pH for the solutions of free swell tests.

Soil	Stabilizer	p^H
OK-1	0% L + 0% RHA	8.26
OK-1	1% L + 0% RHA	8.26
OK-1	1% L + 3% RHA	8.28
OK-1	1% L + 4% RHA	8.4
OK-1	1% L + 5% RHA	8.46
OK-1	0% L + 3% RHA	8.17
OK-1	0% L + 6% RHA	8.23
OK-1	0% L + 9% RHA	8.19
OK-1	3% L + 0% RHA	8.21
OK-1	5% L + 0% RHA	7.94
OK-2	0% L + 3% RHA	8.43
OK-2	0% L + 6% RHA	8.41
OK-2	0% L + 9% RHA	8.21
OK-2	1% L + 0% RHA	8.23
OK-2	3% L + 0% RHA	8.06
OK-2	5% L + 0% RHA	8.32

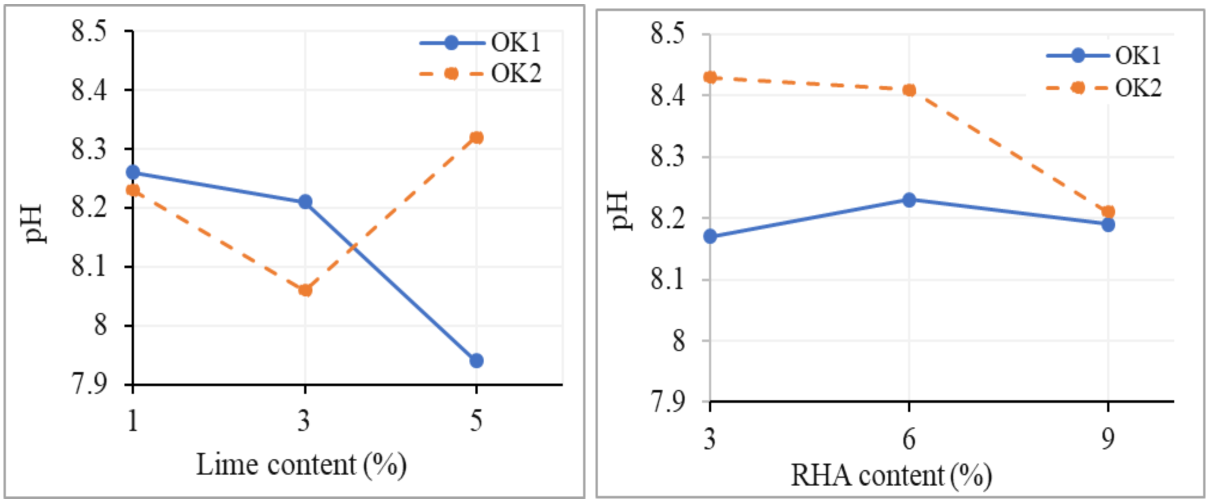


Figure 38. The pH of the solutions of swelling tests for OK-1 and OK-2: (a) HL(left) and (b) RHA(right).

5.2.6. One-Directional Shrinkage Test

The samples of the last selection of mix designs were subjected to air drying in the laboratory. The one-directional shrinkage was measured by a dial gauge set on a porous stone placed on top of the specimen. The soil specimen was air-dried in the laboratory at the temperature and relative humidity equal to 22±1 °C and 45%, respectively. The results are shown in Figure 39. The results show that the addition of 3% RHA increased the shrinkage potential by around 16%, but the addition of 4 or 5% RHA reduced the shrinkage potential by around 20%.

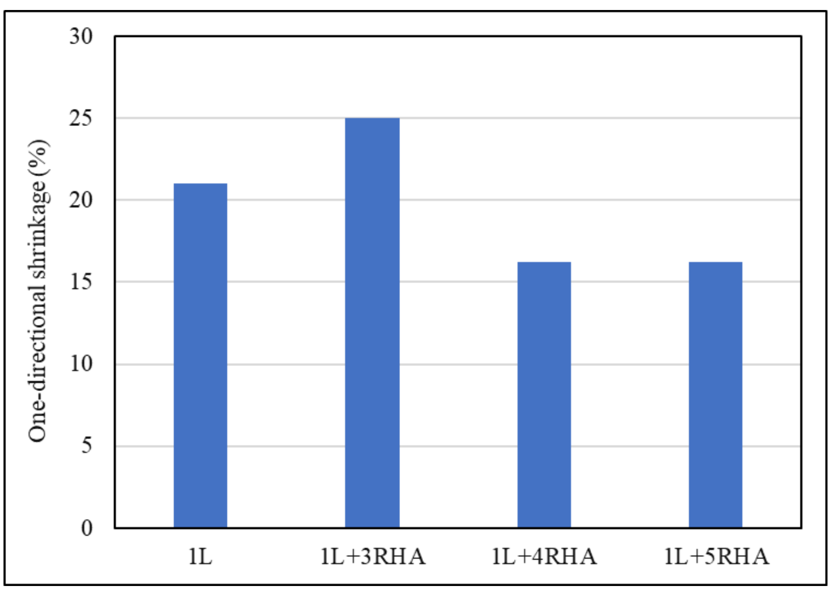


Figure 39. Results of one-directional shrinkage tests.

5.3. Cost Analysis

The cost analysis was performed for the treated subgrade soil. The material cost analysis helped to determine the effectiveness of using soil stabilizers in terms of economic benefit returns along with the improvement of the soil characteristics. To this end, a comparative treated subgrade cost analysis was done by using a standard 1.0-mile length with a 12 ft width (one lane). The cost estimate was prepared for an assumed density of 109 lb/ft^3 for treating 16 inches of subgrade soils *(30)*. Based on data available in the public domain, one ton of RHA costs US$75.0 *(52)* and one ton of HL costs US$165.0 in the local market. The result of the cost analysis is shown in Figure 11. From the cost analysis, it is shown that 6% RHA and 3% HL cost $20,730 and $22,800, respectively. The combination of 1% HL+4% RHA cost $21,420. The optimum dosage of the combination system would be less expensive and would give a higher CBR value than a 3% HL. As part of saving the cost, the environmental impact of using the RHA should not be forgotten. It was estimated that for each 1-mile treated subgrade with a 6% RHA about 276 tons of RHA were required. Increasing the demand for using RHA as a soil stabilizer would help to recycle the RHA sustainably.

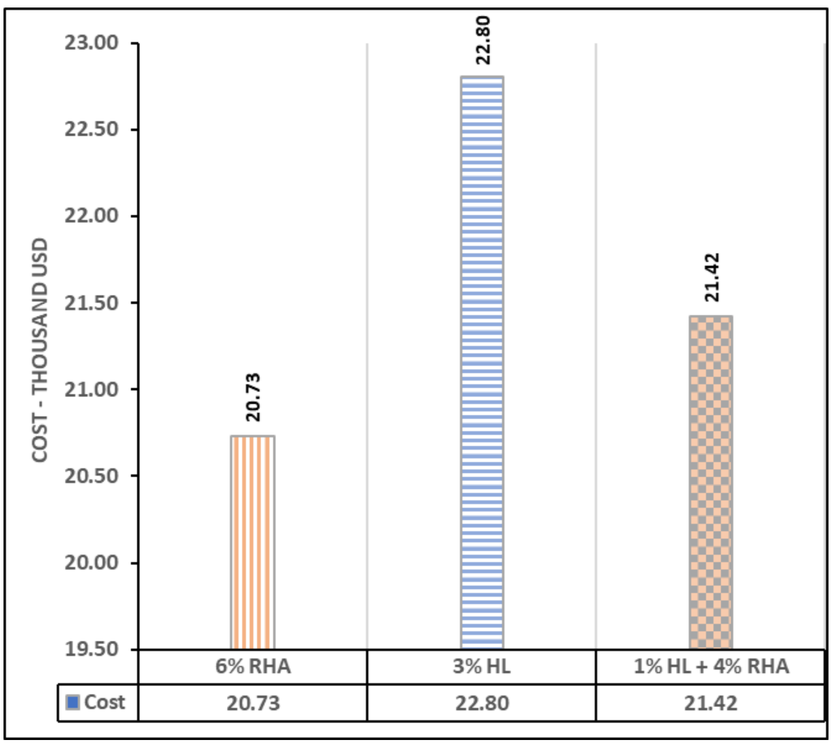


Figure 40. Estimation of cost of stabilization using treated soil

6. CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusions

Four subgrade soils (two from Arkansas and two from Oklahoma) were collected and tested in the laboratory to meet the objectives of the research. A series of experiments were conducted to study the effective varying dosages of two stabilizing agents: Rice Husk Ash (RHA) and Hydrated Lime (HL).

Firstly, two soil samples collected from ongoing construction projects in northeast Arkansas were evaluated in this study. One of these soils was classified as clay soil, CL (AASHTO Type A-6), with a LL of around 35% and a PI of around 11%. The other soil was classified as silty soil, MH (AASHTO Type A-7-5), with a LL of around 78% and a PI of around 31%. The effects of the stabilizing agents on the engineering properties of the soil were examined. The optimum dosages of the two stabilization agents and the combination of both agents were determined based on laboratory-based experimental data.

Secondly, for the two soils collected from Oklahoma, three mix designs were selected for free-swell tests to examine the effectiveness of RHA in reducing the swelling potential of two subgrade soils from Oklahoma. RHA was added in both conditions, i.e., alone and blended with the hydrated lime. In general, it was found that the RHA did not provide significant mitigation to the swelling behavior as compared with the hydrated lime. 1% lime was enough to introduce a high reduction in percent swell. The addition of 1% lime reduced the percent swell by at least 85% for both Oklahoma soils. However, the optimum mitigation of the percent swell in the case of RHA alone was 3%. 3% RHA reduced the percent swell by 69% and 33.6% for OK1 and OK2 soil, respectively.

Microstructural examination by XRD and SEM was carried out for all the samples tested for swelling. The results indicated that the RHA particles worked as a filler material within the structure of the soil. However, for the treatment with lime, both XRD and SEM indicated the formation of cementitious materials in both stabilized soils, i.e., OK1 and OK2 soil, such as calcium silicate hydrate. Another interesting observation was the presence of ettringite minerals in OK2 soil treated with lime. This observation agrees with the XRD of the native untreated OK2 soil. The XRD reflected a peak of calcium sulfate for OK2 soil. According to the findings from this preliminary study, it is recommended for future studies to first investigate the chemical reactions between RHA and HL before the treatment with the candidate soil.

Based on the limited experimental test results, the following conclusions can be drawn from this study:

1- Treatment of the poor subgrade soil with RHA and HL showed a reduction in the maximum dry density and plasticity index.

2- RHA has a moderate effect on soil pH, the soil pH increased to reach the highest pH of 7.75 with 9% RHA. On the other hand, 5% HL had a remarkable effect on the pH of the soil to get beyond 12.95.

3- It was observed that there was a considerable influence on strength characteristics. The CBR and UCS showed enhancement by increasing the percentage of RHA and HL.

4- The optimum dosages for using RHA and HL as unary modifiers were 6% and 3%, respectively, for the evaluated soils.

5- Among the binary systems, 1% HL+4% RHA was the optimum dosage for treating the tested soils. It increased the soil strength (CBR) by 113.0% compared to the untreated soils. At the same time, this optimum binary system reduced the potential swell significantly.

6- Regarding cost-effectiveness, 1% HL+ 4% RHA costs $21,420/lane-mile with 16 inches subgrade treated. On the other hand, a 6% RHA and a 3% HL cost $20,730/lane-mile and $22,800/lane-mile, respectively. More importantly, the CBR values for the combination of 1% HL+4% RHA was higher compared to 3% HL alone.

6.2. Recommendations for Future Research

According to the findings from this preliminary study, it is recommended for future research to first investigate the chemical reactions between the pozzolan (i.e., RHA in this study) and the hydrated lime before the treatment with the candidate soil. Future research can specifically investigate the interaction given in Equation 5.

$$Ca(OH)2 + SiO2 + H2O \rightarrow C\text{-}S\text{-}H \quad (5)$$

An attempt was made to simulate the above interaction by mixing 1:1 RHA to hydrated lime with 1.2 by weight added de-ionized water to prepare a paste in the laboratory. The mixture was visually inspected over time. No formed gel was observed even after dry curing the mixture for more than a month. The mixture was loose with no clear change with time. Therefore, if such a case is encountered in future research, it is likely beneficial to introduce a catalyst that activates the reaction between the hydrated lime and RHA.

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APPENDIX A: Routine Test Data of Oklahoma Soils

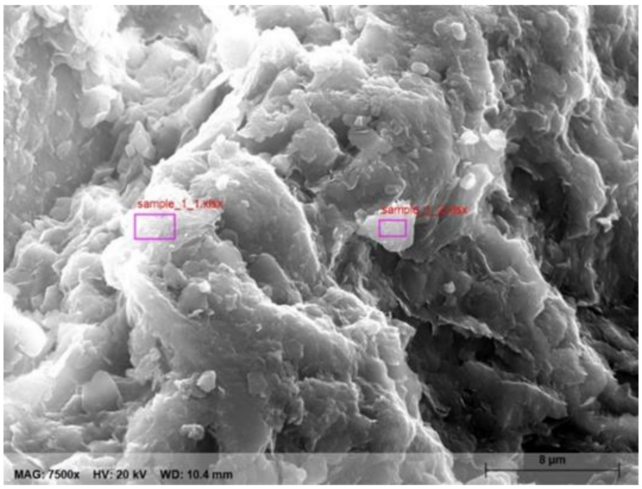
A_Table 1 Additional information on the soils sampled from Ottawa County

Site, Horse Creek	Depth, cm (ft)	Natural Density, g/cm^3 (lb/ft^3)	Natural Water Content, %	Liquid Limit, %	Plasticity Index, %	Passing 2Micron, %
Borehole 1	67 (2.2)	1.93 (120.9)	27.2	59	32	33.6
Borehole 1	137 (4.5)	2.04 (127.2)	15.0	36	19	47.4
Borehole 1	198 (6.5)	1.95 (121.5)	24.2	54	28	53.2
Borehole 1	268 (8.8)	2.03 (126.5)	24.3	54	29	54.0
Borehole 2	70 (2.3)	1.93 (120.8)	29.5	60	36	33.6
Borehole 2	140 (4.6)	2.03 (127.0)	21.5	27	10	53.2
Borehole 2	192 (6.3)	1.94 (121.4)	30.1	58	36	52.0
Borehole 2	253 (8.3)	2.00 (125.2)	28.7	52	29	52.0
Borehole 2	274 (9.0)	2.03 (126.9)	18.7	52	32	52.0
Borehole 2						
Borehole 3	67 (2.2)	1.96 (122.4)	29.1	54	27	43.9
Borehole 3	131 (4.3)	1.99 (124.2)	28.1	50	27	31.2
Borehole 3	198 (6.5)	1.93 (120.6)	28.4	61	38	44.0
Borehole 3	289 (9.5)	1.99 (124.2)	26.1	59	39	44.0
Borehole 3						
Borehole 4	40 (1.3)	1.93 (120.4)	20.2	57	21	54.7
Borehole 4	128 (4.2)	2.04 (127.3)	19.0	57	26	54.6
Borehole 4	189 (6.2)	1.87 (117.0)	27.0	58	32	35.5
Borehole 4	268 (8.8)	2.03 (126.5)	21.0	58	32	35.5
Borehole 4						
Borehole 5	189 (6.2)	1.94 (121.3)	28.5	59	34	54.7
Borehole 5	253 (8.3)	2.02 (126.3)	25.0	52	28	54.6

A_Table 2 Additional information on the soils sampled from carter county

Boring no.	Depth (feet)	Soil Description (Visual Inspection)
Borehole 1	0 to 0.95	Root fibers, black, slightly disturbed.
Borehole 1	0.95 to 1.95	Root fibers, black, disturbed.
Borehole 1	2.0 to 2.80	Traces of root fibers, brownish, disturbed.
Borehole 1	2.80 to 3.57	Root fibers, brownish, disturbed.
Borehole 2	0 to 0.90	Root fibers, black, disturbed.
Borehole 2	0.90 to 1.90	Root fibers, black with brown stains, disturbed.
Borehole 2	2.0 to 3.0	Root fibers traces, brownish, disturbed.
Borehole 2	3.0 to 3.45	Light brown, highly disturbed/collapsed.
Borehole 3	0 to 1.1	Root fibers, black, disturbed, moisture appears.
Borehole 3	1.1 to 1.85	Brownish, cracked, moisture appears.
Borehole 3	2.0 to 2.90	Brownish, disturbed, sample cross-section is not fully cylindrical.

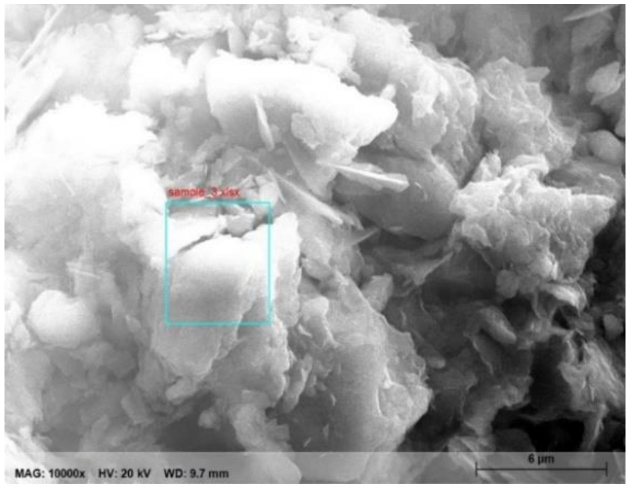
APPENDIX B: Results of SEM/EDX Tests



B_Figure 1: SEM of 1% lime added to OK1 soil

B_Table 1 EDX results of 1% lime added to OK1 soil

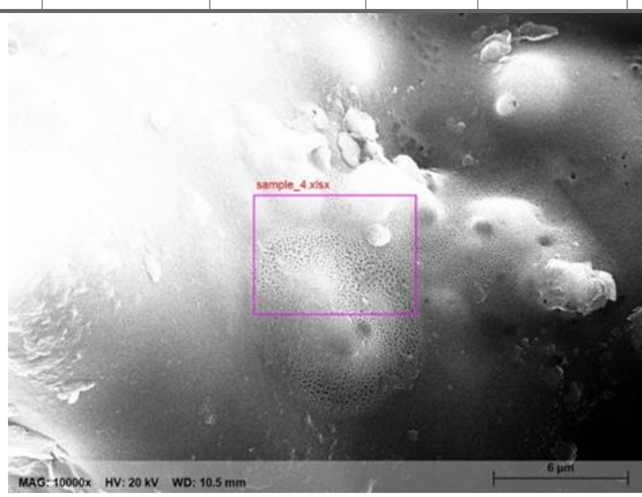
Spectrum	Sodium	Magnesium	Aluminum	Silicon	Potassium	Calcium	Iron
sample_1_1	**0.95**	**1.48**	**8.71**	**20.11**	**2.37**	**1.04**	**3.93**
sample_1_2	**0.68**	**0.94**	**8.68**	**18.13**	**5.53**	**0.59**	**2.12**



B_ Figure 2: SEM of 1% lime and 4% RHA added to OK1 soil

B_Table 2 EDX results of 1% lime and 4 % RHA added to OK1 soil

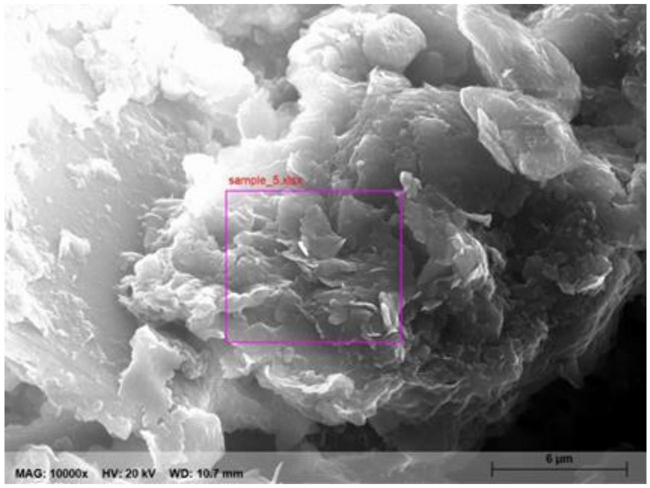
Spectrum	Sodium	Magnesium	Aluminum	Silicon	Potassium	Calcium	Iron
sample_3	0.35	1.01	5.16	23.04	1.08	1.05	2.48



B_Figure 3: SEM of 1% lime and 6% RHA added to OK1 soil

B_Table 3 EDX results of 1% lime and 6% RHA added to OK1 soil

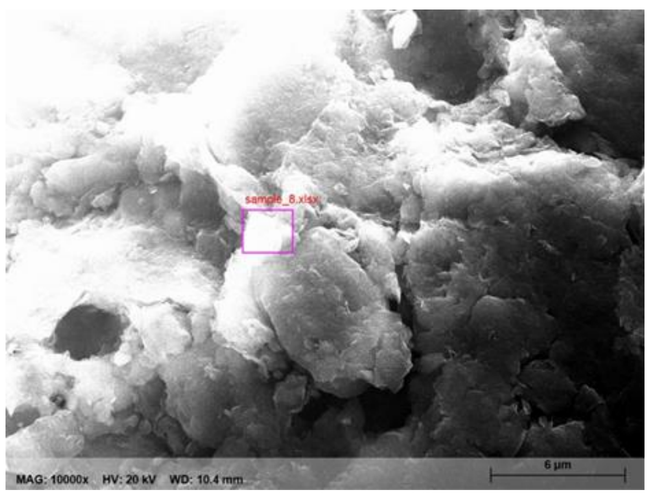
Spectrum	Sodium	Magnesium	Aluminum	Silicon	Potassium	Calcium	Iron
sample_5	0.43	1.33	7.83	15.98	1.56	9.64	2.74



B_Figure 4: SEM of 2% lime added to OK1 soil

B_Table 4 EDX results of 2% lime added to OK1 soil

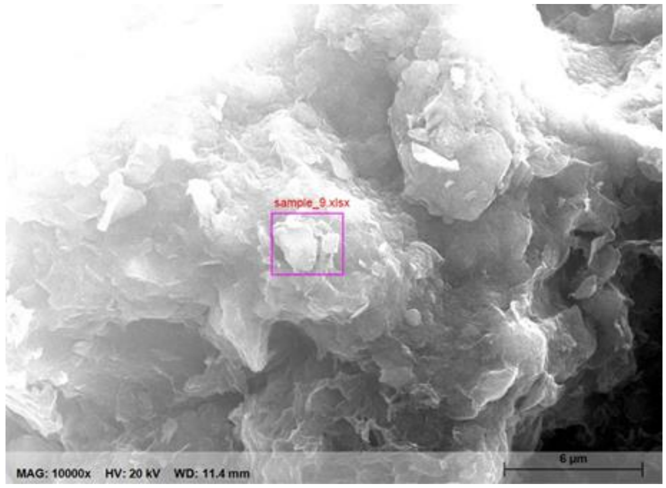
Spectrum	Sodium	Magnesium	Aluminum	Silicon	Potassium	Calcium	Iron
sample_5	0.43	1.33	7.83	15.98	1.56	9.64	2.74



B_Figure 5: SEM of 2% lime and 6% RHA added to OK1 soil

B_Table 5 EDX results of 2% lime and 6% RHA added to OK1 soil

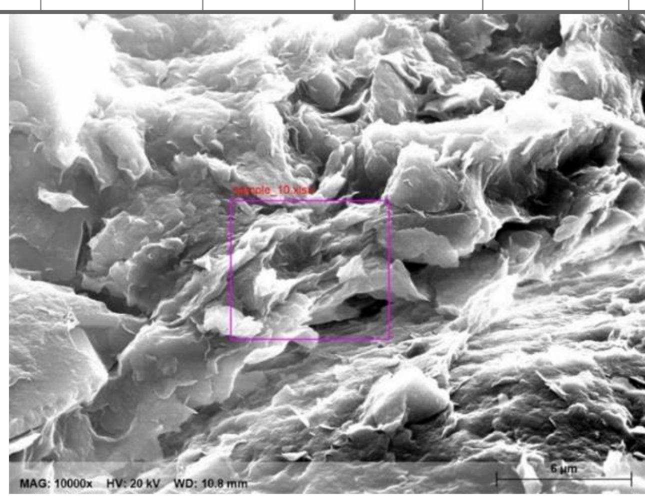
Spectrum	Sodium	Magnesium	Aluminum	Silicon	Potassium	Calcium	Iron
sample_8	0.11	1.00	5.99	30.53	1.45	0.86	2.49



B_Figure 6: SEM of 2% lime and 8% RHA added to OK1 soil

B_Table 6 EDX results of 2% lime and 6% RHA added to OK1 soil

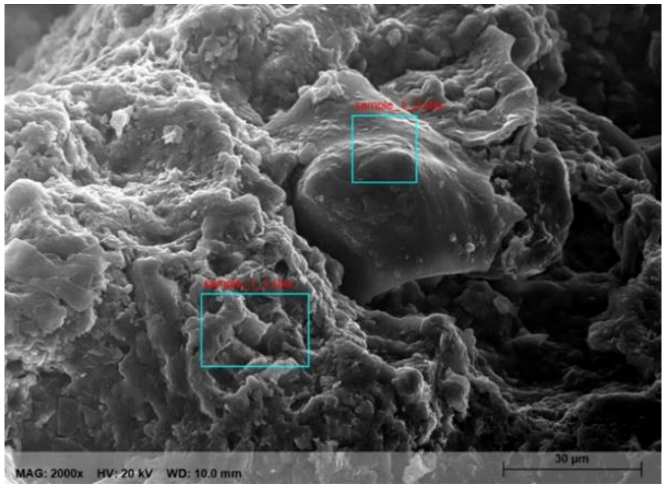
Spectrum	Sodium	Magnesium	Aluminum	Silicon	Potassium	Calcium	Iron
sample_9	0.23	2.01	10.79	20.75	2.23	1.78	5.92



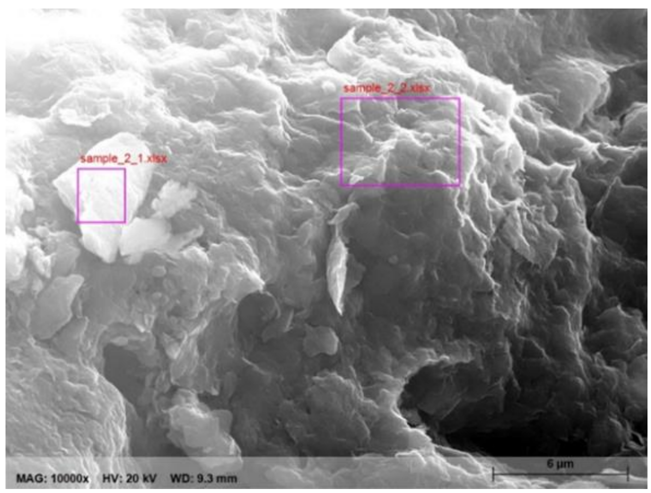
B_Figure 7: B_SEM of untreated OK1 soil

B_Table 7 EDX results of untreated OK1 soil

Spectrum	Sodium	Magnesium	Aluminum	Silicon	Potassium	Calcium	Iron
sample_10	0.42	1.83	10.29	19.20	3.33	0.61	4.16



B_Figure 8: SEM of 9% RHA added to OK1 soil

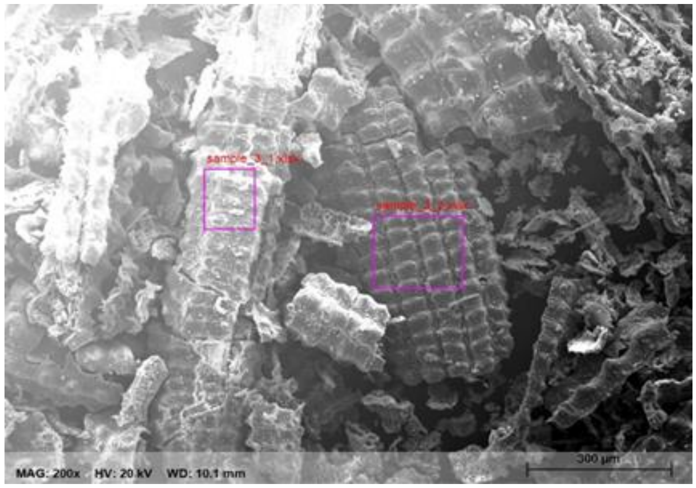


B_Figure 9: SEM of 5% lime added to OK1 soil

B_Table 9 EDX results of 5% lime added to OK1 soil

Spectrum	Sodium	Magnesium	Aluminum	Silicon	Potassium	Calcium	Iron
sample_2_1	0.477682	1.9207129	16.40045	40.76	12.78229	23.113	4.5
sample_2_2	0.755143	4.0322419	18.49386	35.87	3.198832	29.184	8.32

Spectrum	Sodium	Magnesium	Aluminum	Silicon	Potassium	Calcium	Iron
sample_1_1	0.47	4.99	22.34	51.83	6.23	1.70	12.25
sample_1_2	0.19	0.89	4.59	87.68	2.34	0.65	2.88

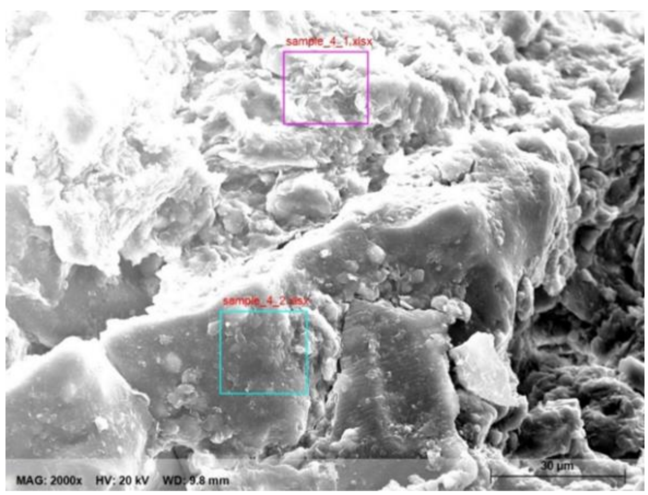


B_Figure 10: SEM of RHA alone

B_Table 10 EDX results of RHA alone

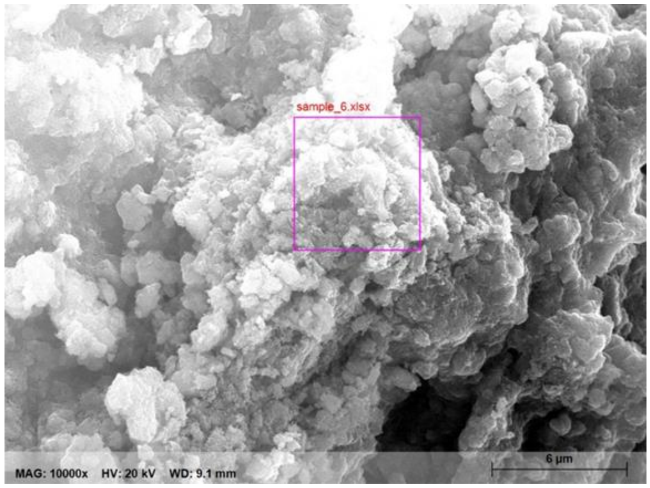
Spectrum	Sodium	Magnesium	Aluminum	Silicon	Potassium	Calcium	Iron
sample_3_1	0	0	0	95.77	3.37	0.47	0.04
sample_3_2	0	0	0	95.83	3.21	0.27	0.01

Spectrum	Sodium	Magnesium	Aluminum	Silicon	Potassium	Calcium	Iron
sample_4_1	0	0	0	95.77	3.37	0.47	0.04
sample_4_2	0	0	0	95.83	3.21	0.27	0.01



B_Figure 11: SEM of 9% RHA added to OK2 soil

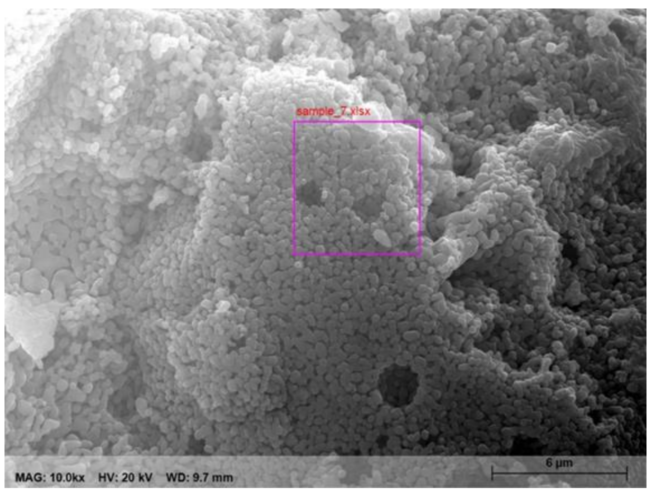
B_Table 11 EDX results of 9% RHA added to OK2 soil



B_Figure 12: SEM of hydrated lime alone

B_Table 12 EDX results of hydrated lime alone

Spectrum	Sodium	Magnesium	Aluminum	Silicon	Potassium	Calcium	Iron
sample_6_1	0.10	1.20	0.63	0.35	0.00	97.63	0.08



B_Figure 13: SEM of quicklime alone

B_Table 12 EDX results of quicklime alone

Spectrum	Sodium	Magnesium	Aluminum	Silicon	Potassium	Calcium	Iron
sample_7_1	0.05	0.48	0.26	0.16	0.03	98.93	0.04