

**ASSESSMENT OF HEJAZ STABILIZED EARTH'S THERMAL
AND ACOUSTICAL CHARACTERISTICS FOR SUSTAINABLE
CONSTRUCTION IN SAUDI ARABIA.**

BY

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A Thesis Presented to the
COLLEGE OF GRADUATE AND INTERDISCIPLINARY STUDIES
KING FAHD UNIVERSITY OF PETROLEUM & MINERALS
DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE
In
ARCHITECTURE AND CITY DESIGN

MAY 2024

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN- 31261, SAUDI ARABIA

DEANSHIP OF GRADUATE STUDIES

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[Dedication]

To my beloved mom, Saynab Mohamud Abdulle, my brothers, my sisters, and my fiancée, Basma Abdullahi, whose unwavering support, encouragement, and love have been my constant source of strength and inspiration throughout this journey. This thesis is dedicated to you, with heartfelt gratitude for your endless faith in me.

ACKNOWLEDGMENTS

First and foremost, my deepest gratitude is to Allah, the Most Merciful and Beneficent, who provided me with the perseverance and strength needed to pursue and complete this journey.

I would like to express my profound appreciation to my beloved mother, whose boundless support and prayers have been my foundation. Her sacrifices, love, and unwavering belief in my abilities have fueled my aspirations and achievements. This thesis is not only a product of my work but also a testament to her immeasurable contribution to my life.

My sincere thanks go to my advisor, Dr. Mohammad Sharif Zami. His expertise and insightful critiques have been invaluable to this research. Dr. Zami's dedication and meticulous attention to detail have significantly shaped and refined my work, pushing me to reach greater heights. I am also incredibly grateful to my thesis committee members: Dr. Ahmed Abd El Fattah and Dr. Ismail Mohammad Budaiwi. Their expert feedback and constructive suggestions have been crucial in enhancing the depth and quality of my research. Each meeting and discussion with them brought new insights and encouraged a more comprehensive approach to my subject matter. I extend a heartfelt thank you to Dr. Adel A. Abdou, whose expertise in acoustics has been instrumental in the success of this work. Dr. Abdou's profound knowledge and innovative approach significantly enhanced the acoustic analysis portion of my research. His willingness to share his insights and his enthusiastic support throughout the research process have been both inspiring and deeply appreciated.

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LIST OF ABBREVIATIONS

CKD :	Cement Kiln Dust
OPC:	Ordinary Portland Cement
AC:	Acoustical Characteristics
AC :	Acoustical Characteristics
HSE:	Hejaz Stabilized Earth ()
ASTM:	American Society for Testing and Materials
CSEBs:	Stabilized Earth Blocks
OMC:	Optimum Moisture Content
MDD:	Maximum Dry Density
K:	Thermal conductivity
EKS:	Electrokinetic Stabilization
TLS-100:	Transient Line Source
ISO:	International Organization for Standardization
SPM:	Sugarcane Press Mud
GGBS:	Ground granulated blast furnace slag
FA:	Fly Ash
LKD:	Lime Kiln Dust

CKD:	Cement Kiln Dust
CBPD:	Cement By-Pass Dust
MPa:	megapascal,
OSA:	Oil Shale Ash
AEA:	air-entraining additives
RAP:	Reclaimed Asphalt Pavement
AABs:	alkali-activated binders
CSMs:	cement-stabilized materials
AE:	Acoustic Emissions
DAS:	Distributed Acoustic Sensing
SNR:	Signal-to-Noise Ratio
CO₂:	carbon dioxide
IEEE:	Institute of Electrical and Electronics Engineers)
EN ISO:	European Norm (EN) and International Organization for Standardization (ISO).

ABSTRACT

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Thesis Title : Assessment of Hejaz Stabilized Earth's Thermal and Acoustical characteristics for Sustainable Construction in Saudi Arabia.
Major Field : Architecture And City Design
Date of Degree : May 2024

Abstract

In a strategic transition towards sustainable development, Saudi Arabia is exploring the use of indigenous materials for green construction, particularly in the historic Hejaz region. This research evaluates the effects of stabilizers such as ordinary Portland cement (OPC), lime, and Cement Kiln Dust (CKD) on Hejaz soils (Soil A and Soil B) in concentrations from 0% to 15%. Over 12 weeks, the study analyzed the thermal and acoustical characteristics (AC) of the soils. Thermal analysis revealed that a 12.5% cement concentration in Soil A increased thermal conductivity by 164.54%, while a 15% CKD application led to a 213.55% rise. Acoustically, untreated soils exhibited superior characteristics, with Soil A and Soil B achieving high AC values, placing them in the highly absorptive Class A. However, stabilization affected acoustic properties; for example, a 2.5% lime addition decreased AC from 0.9 to 0.07 in Soil A at 500 Hz. These findings highlight the potential of soil stabilization to improve the thermal and acoustic characteristics of Hejaz soils, emphasizing the importance of soil-specific methods. This study offers insights into optimizing soil-based materials for sustainable construction and lays the groundwork for future research on eco-friendly building practices.

ملخص الرسالة

الاسم الكامل: عبدالله عبدالرحمن محددين

عنوان الرسالة: تقييم الخصائص الحرارية والصوتية للأرض المثبتة في منطقة الحجاز للبناء المستدام في المملكة العربية السعودية

التخصص: العمارة وتصميم المدن

تاريخ الدرجة العلمية: يونيو 2024 الموافق لشهر ذو القعدة 1445 هـ

الملخص في إطار التحول الاستراتيجي نحو التنمية المستدامة، تستكشف المملكة العربية السعودية استخدام المواد المحلية للبناء الأخضر، والجير وغبار أفران الأسمنت (OPC) خصوصاً في منطقة الحجاز التاريخية. تقيم هذه الدراسة تأثير المثبتات مثل الأسمنت البورتلاندي العادي بتركيزات تتراوح من 0٪ إلى 15٪. على مدى 12 أسبوعاً، تم تحليل الخصائص الحرارية (B والتربة A التربة) على ترب الحجاز (CKD) زاد من التوصيل الحراري بنسبة 164.54٪، بينما أدى A والصوتية للترب. كشف التحليل الحراري أن تركيز الأسمنت بنسبة 12.5٪ في التربة بنسبة 15٪ إلى ارتفاع بنسبة 213.55٪. من الناحية الصوتية، أظهرت الترب غير المعالجة خصائص متفوقة، حيث حققت التربة CKD استخدام العالية الامتصاص. ومع ذلك، أثرت عملية التثبيت على الخصائص الصوتية؛ على سبيل A قيمًا صوتية عالية، مما جعلها في الفئة B والتربة A عند 500 هرتز. تسلط هذه النتائج A المثال، أدى إضافة الجير بنسبة 2.5٪ إلى انخفاض الخصائص الصوتية من 0.9 إلى 0.07 في التربة الضوء على إمكانية تحسين الخصائص الحرارية والصوتية لترب الحجاز من خلال التثبيت، مع التأكيد على أهمية الطرق المحددة للتربة. تقدم هذه الدراسة رؤى حول تحسين المواد القائمة على التربة للبناء المستدام وتضع الأساس لأبحاث مستقبلية حول ممارسات البناء الصديقة للبيئة

CHAPTER 1

INTRODUCTION

The pursuit of sustainable construction materials has led to renewed interest in utilizing earth as a primary resource, recognized for its low environmental impact, availability, and energy efficiency. This study evaluates the thermal and acoustical characteristics of Hejaz Stabilized Earth, focusing on contributing to the understanding of sustainable construction materials like Compressed Stabilized Earth Blocks (CSEBs). These materials are pivotal in reducing the construction sector's carbon footprint and offer a cost-effective, environmentally sustainable alternative to conventional building materials. The burgeoning environmental challenges in urban landscapes call for an urgent integration of sustainable infrastructure solutions, particularly in the realm of construction, to foster sustainable urban development [1], [2]. In this vein, this research is twofold, examining the thermal and acoustic properties of soils from the Hejaz region in Saudi Arabia, treated with various stabilizers: cement, lime, and cement kiln dust (CKD). This exploration is underpinned by the global drive towards utilizing local materials for sustainable construction, spotlighting the Hejaz soils' potential for eco-friendly building practices. Central to this investigation is the role of soil properties in sustainable construction, focusing on thermal conductivity and acoustical characteristics (AC) as critical indicators of soil performance. Recent studies, emphasize the environmental advantages of utilizing CKD, highlighting its efficiency as a sustainable, cement-free stabilizer and its role in emissions reduction [3].

Nonetheless, the literature reveals gaps, particularly concerning the long-term environmental impacts of stabilization techniques [4], [5], [6], [7], [8]. The application of CKD not only aligns with sustainable waste management practices by mitigating disposal costs but also enhances the environmental profile of construction materials. However, questions linger regarding the scalability and effectiveness across varying soil types and conditions [9]. The variability in soil response to stabilization methods poses a significant challenge in achieving consistent and predictable improvements in soil properties. This variability is underscored by studies showing that the thermal conductivity of cement-stabilized earth blocks (CSEB) varies with bulk density and the proportion of cement and lime added [10], [11]. The benefits of lime stabilization depend on factors like lime percentage, soil pulverization level, curing duration, and stress state [12]. The economic feasibility of leveraging by-products for soil stabilization is well-noted [13], alongside the benefits of innovative stabilization techniques such as Electrokinetic Stabilization (EKS) for improving soil properties, a critical aspect for soils like Sabkha prevalent in Saudi Arabia [14]. This aligns with this research focus on effective methods for soil stabilization. Geospatial technology has also been employed to assess risks in development [15], underscoring the significance of understanding soil properties during construction. Addressing stabilization/solidification techniques for soils contaminated with oil remains a concern that highlights the need, for environmentally responsible construction practices [13]. Furthermore, the geographic distribution of earthen construction globally is illustrated in Figure 1, underscoring the widespread applicability and relevance of these materials in various environment [16].



Figure 1. Global Distribution of Earthen Construction. This map illustrates the widespread use of earth-based building techniques worldwide[17].

This study, therefore, bridges the gap in current research concerning the thermal and acoustic properties of stabilized soils, particularly those amended with cement, lime, and CKD. By dissecting the impact of these stabilizers on Hejaz soils— designated as Soil A and Soil B. Soil A is a light brown silty clay (CL) characterized by a fine content of 95.3%, higher water retention, and lower permeability. It was sampled from the northern of Jeddah part of the Hejaz region. Soil B, on the other hand, is a medium brown clayey silt (ML) with a fine content of 92.5%, balanced moisture retention, and better drainage properties compared to Soil A. This soil was collected from the southern part of Jeddah of the Hejaz region. these specific soils were chosen due to their differing physical and chemical properties, which provide a comprehensive representation of the soil variability within the Hejaz region. By examining these two soil types, this study aims to develop a robust understanding of how different stabilization techniques affect soil properties critical for sustainable construction. The visual characteristics of these soils are shown in Figure 2,

which illustrates the acoustic samples, thermal samples, and acoustic and thermal samples during the curing period. The study will discuss Soil-A and Soil-B into their influence on thermal conductivity and AC, employing TLS-100-meter measurements and BSWA SW series Impedance Tubes in compliance with ISO 10534-2 standards. The study is to unveil soil-specific stabilization methods that not only enhance sustainable construction practices in Saudi Arabia but also contribute significantly to the broader discourse on sustainable building materials by offering a dual perspective on thermal and acoustic soil properties.

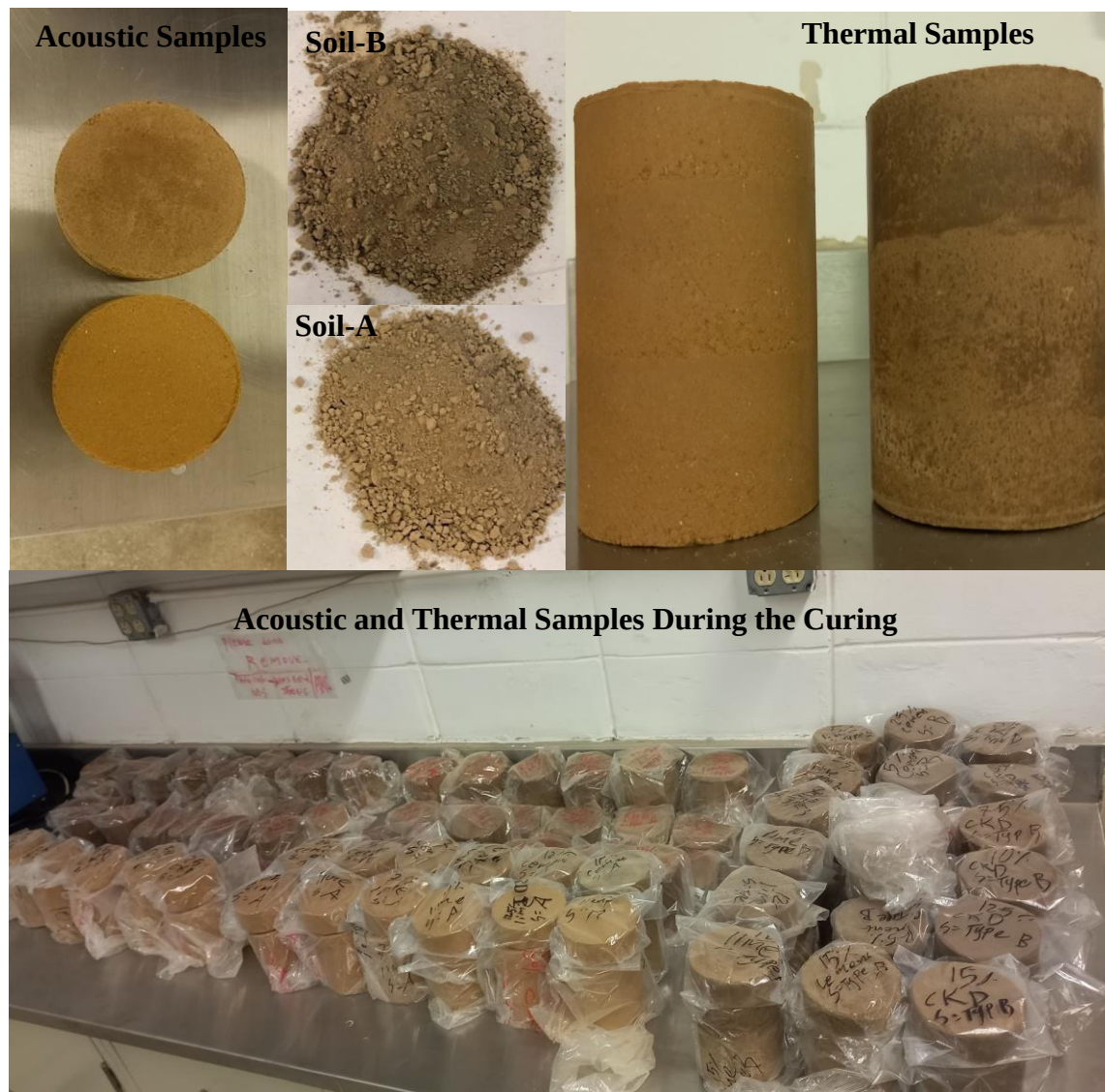


Figure 2. Soil A (Light Brown) and Soil B (Medium Brown) Acoustic and Thermal Samples During Curing Period

1.1 Problem Statement

The pursuit of sustainable construction materials has renewed interest in utilizing earth as a primary resource due to its low environmental impact, availability, and energy efficiency. This study evaluates the thermal and acoustical characteristics of Hejaz stabilized earth to contribute to the understanding of sustainable construction materials. These materials are pivotal in reducing the construction sector's carbon footprint and offer a cost-effective, environmentally sustainable alternative to conventional building materials. The Increasing environmental challenges in urban landscapes necessitate the integration of sustainable infrastructure solutions, particularly in construction, to foster sustainable urban development. Our research examines the thermal and acoustic properties of materials derived from Hejaz soils in Saudi Arabia treated with various stabilizers: cement, lime, and cement kiln dust (CKD). This exploration is driven by the global push towards utilizing local materials for sustainable construction, highlighting the potential of Hejaz soils for eco-friendly building practices. Central to our investigation is the role of soil-derived materials in sustainable construction, focusing on thermal conductivity and acoustical characteristics (AC) as critical indicators of material performance. The effectiveness of different soil stabilization methods—including cement, lime, and Cement Kiln Dust (CKD)—in improving the acoustic and thermal properties of sustainable construction materials presents significant challenges. These methods are crucial for enhancing the mechanical properties of construction materials, thereby increasing their strength, durability, and overall performance, which are essential for sustainable building practices

[17], [18] For instance, lime is effective in stabilizing clay soil for construction purposes[19], while the use of industrial waste like CKD is noted for its potential in enhancing soil quality and reducing environmental impacts and construction costs [20]. However, the effectiveness of these stabilization methods in specifically improving the thermal conductivity and acoustic properties of sustainable construction materials has not been thoroughly explored. The impact of stabilization methods on thermal properties, especially thermal conductivity, is critical and requires detailed investigation to develop efficient and sustainable construction materials [17], [18], [20], [21]. Traditional stabilizers like cement and lime not only improve engineering properties such as maximum dry density and plasticity of soils [22], but also may influence their thermal behavior. CKD, a by-product waste material, enhances soil properties like durability and permeability, which could impact thermal conductivity [23]. The introduction of recycled plastics as soil admixtures shows improvements in strength, durability, and thermal conductivity, suggesting potential contributions to the thermal efficiency of construction materials [24], [25]. Given the rising demand for sustainable materials that efficiently manage thermal energy, a systematic evaluation of how these stabilization methods affect the thermal conductivity of stabilized soils is necessary.

1.2 Objectives of the Study

1.2.1 Evaluate the Thermal Conductivity of Stabilized Hejaz Soils:

Assess the impact of different soil stabilization methods (cement, lime, and Cement Kiln Dust - CKD) on the thermal conductivity of Hejaz soils. This includes measuring the changes in thermal properties with varying stabilizer concentrations and environmental conditions, using the TLS-100 Thermal Conductivity Meter.

1.2.2 *Determine the Acoustic Properties of Stabilized Hejaz Soils:*

Investigate how soil stabilization affects the acoustic properties of Hejaz soils. This involves measuring the sound absorption coefficients of soils treated with different concentrations of cement, lime, and CKD, and understanding the implications for noise reduction in sustainable building environments.

1.3 Significance of the Study

This research addresses the potential use of soil stabilization in Saudi Arabia's Hejaz region, focusing on the thermal and acoustic performance of materials. By examining the performance of common stabilizers such as cement, lime and CKD in Hejaz soil stabilization, the study aims to contribute to the development of sustainable construction materials suitable for the regional demands of thermal and acoustic efficiency. The findings could influence policymakers, academicians, and construction practitioners, particularly those focused on sustainable materials. Insights from this study could guide decisions regarding the use of natural resources for soil stabilization in construction projects within the Hejaz area and could serve as a valuable resource for researchers globally interested in the application of natural materials for soil stabilization.

1.4 Scope of the Study

The scope of this study is limited to laboratory evaluations of the thermal and acoustic performance of Hejaz soil stabilization using natural materials, specifically cement, lime and CKD. The research will involve laboratory experiments to measure the thermal conductivity and acoustic characteristics of stabilized soil samples. This study will not conduct field tests or construct actual structures using stabilized Hejaz soil. The focus will remain strictly on the Hejaz region of Saudi Arabia as shown in Figure 3, aiming to provide

a controlled and detailed examination of the materials' properties within a laboratory setting.

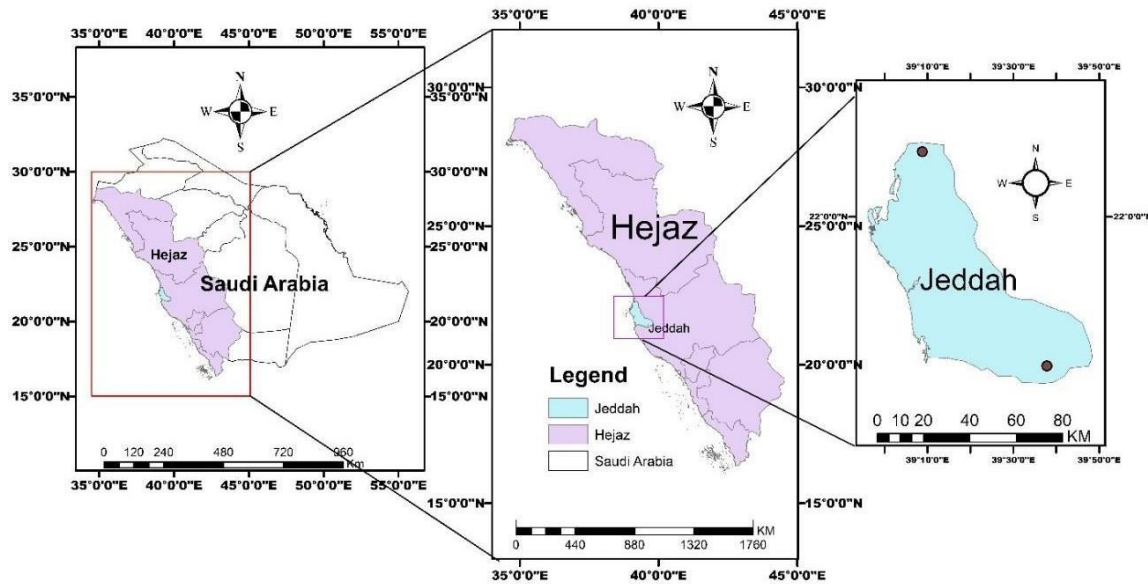


Figure 3. Hejaz Region Indicating the Soil's Location for the Research Study

CHAPTER 2

LITERATURE REVIEW

2.1 Geotechnical Soil Stabilization

Soil stabilization is essential in geotechnical engineering, enhancing soil's physical properties for construction and engineering applications. This enhancement is achieved through the integration of various additives, which serve to bolster soil strength, diminish compressibility, and augment durability. Predominantly, Portland cement, lime, and cement kiln dust (CKD) have emerged as the preferred materials for soil stabilization. The process of cement stabilization involves the admixture of Portland cement into the soil, triggering a hydration reaction that culminates in the formation of cementitious compounds, effectively binding the soil particles together. This method has demonstrated its efficacy in fortifying the soil's bearing capacity, thereby rendering it more resilient against external loads [26]. The typical values and percentages of cement used in these techniques can vary based on the soil type and the desired improvement. For instance, lateritic soils, which are prevalent in tropical regions, have shown significant improvement in unconfined compressive strength (UCS) and durability with cement contents ranging from 3% to 12% as shown in Figure 4 [27]. , the addition of oil palm ash and cement in clay soil stabilization has demonstrated that 5% oil palm ash and up to 10% cement can effectively increase soil compressive strength as depicted in Figure 5 [28]. Concurrently, lime stabilization utilizes quicklime or hydrated lime, which interacts with the soil's clay particles, resulting in enhanced soil strength, reduced plasticity, and improved workability,

thus facilitating ease of manipulation during construction activities [29]. CKD, a byproduct of cement production, has also found its niche in soil stabilization. This approach offers a sustainable solution by repurposing industrial waste to enhance soil properties.

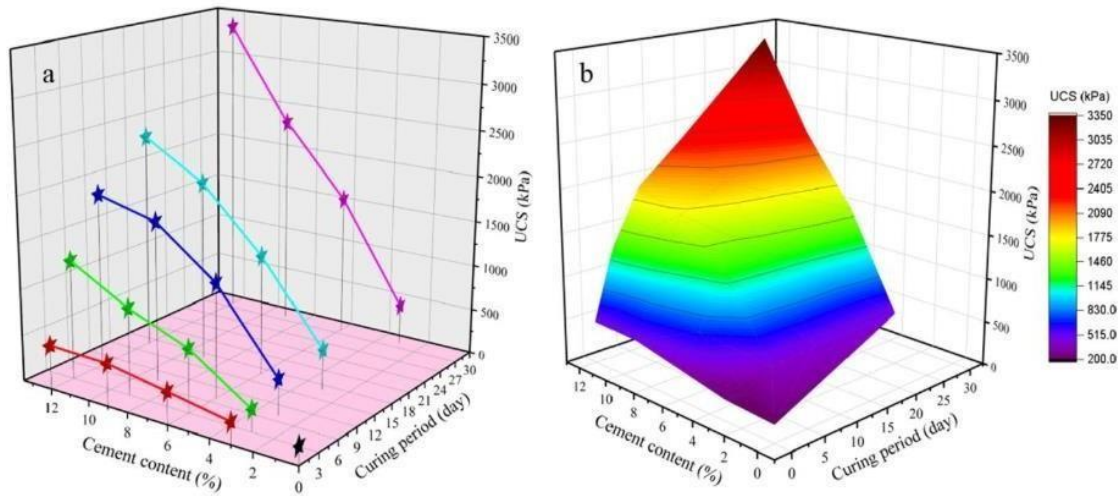


Figure 4. (A)UCS results versus cement content (0, 3, 6, 9, 12%) and (B)curing time (0, 3, 7, 14, 28 days) a scatter plot [28].

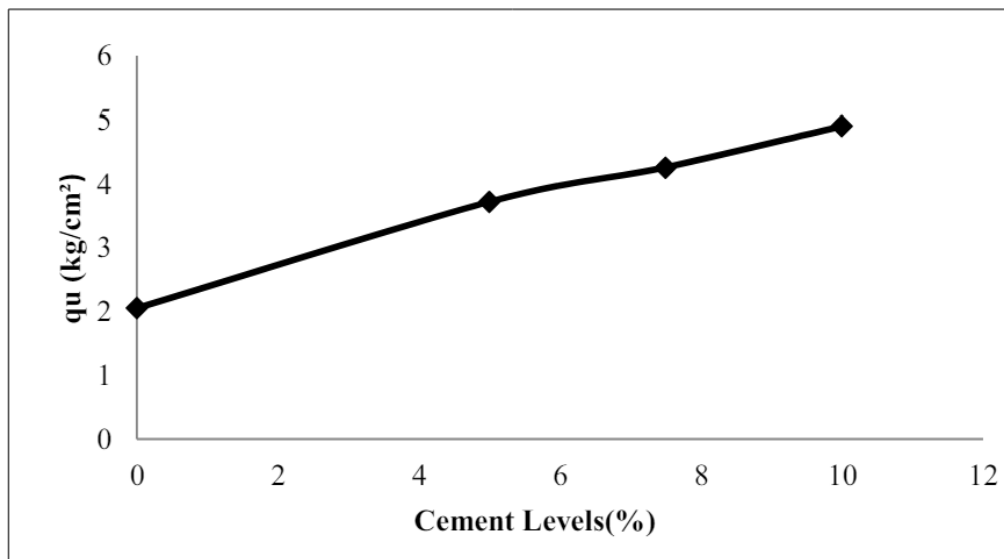


Figure 5. Effect of adding 5% ash of oil palm bunches and 0%, 5%, 7.5%, and 10% of cement to the value of free compressive strength [29].

Studies have concluded that soil stabilization is an effective and economical method for improving road pavement for engineering benefits [30]. The synergistic application of

cement and lime in soil stabilization capitalizes on the immediate strength conferred by cement and the prolonged benefits afforded by lime, culminating in a comprehensive enhancement of soil properties [31]. Moreover, the environmental and economic dimensions of soil stabilization are indispensable, Utilizing industrial byproducts like CKD provides an eco-friendly and cost-efficient alternative to conventional methods, supporting sustainable construction practices [32]. In essence, the practice of soil stabilization, through the use of cement, lime, and CKD, plays a crucial role in augmenting soil properties for engineering applications, simultaneously promoting sustainable practices via the utilization of industrial byproducts. Soil stabilization, crucial for enhancing soil properties for engineering applications, heavily relies on materials like cement, lime, and Cement kiln dust (CKD), a by-product of cement manufacturing, enhances soil workability, increases bearing capacity, and reduces clay settlement evident through decreased pH, electrical conductivity, and total dissolved solids in CKD-clay systems over time (lime . When mixed with polypropylene fibers, CKD not only strengthens soil but also enhances its ductility [34]. Additionally, its combined use with lime offers an economical solution for road pavements [30]. Blending CKD with lime kiln dust and fly ash further stabilizes soil subgrades [32]. Cement-lime stabilization, especially with Sugarcane Press Mud (SPM), significantly enhances strength, outperforming lime alone [35], with 1% SPM identified as the optimal amount for strength gain [35]. The combination of cement, lime, and bitumen has been identified as optimal for road construction [36], Furthermore, adding silica fume to this mixture significantly reduces soil swell and swelling pressure [37]. Bagasse ash, lime, and cement together increase soil strength, lower its plasticity, and reduce swelling, with bagasse ash serving as a substitute for cement due to its high silica content [38].

Portland cement and lime effectively improve the shear strength in soils contaminated with organic compounds such as anthracene and glycerol [39], They are also successful in

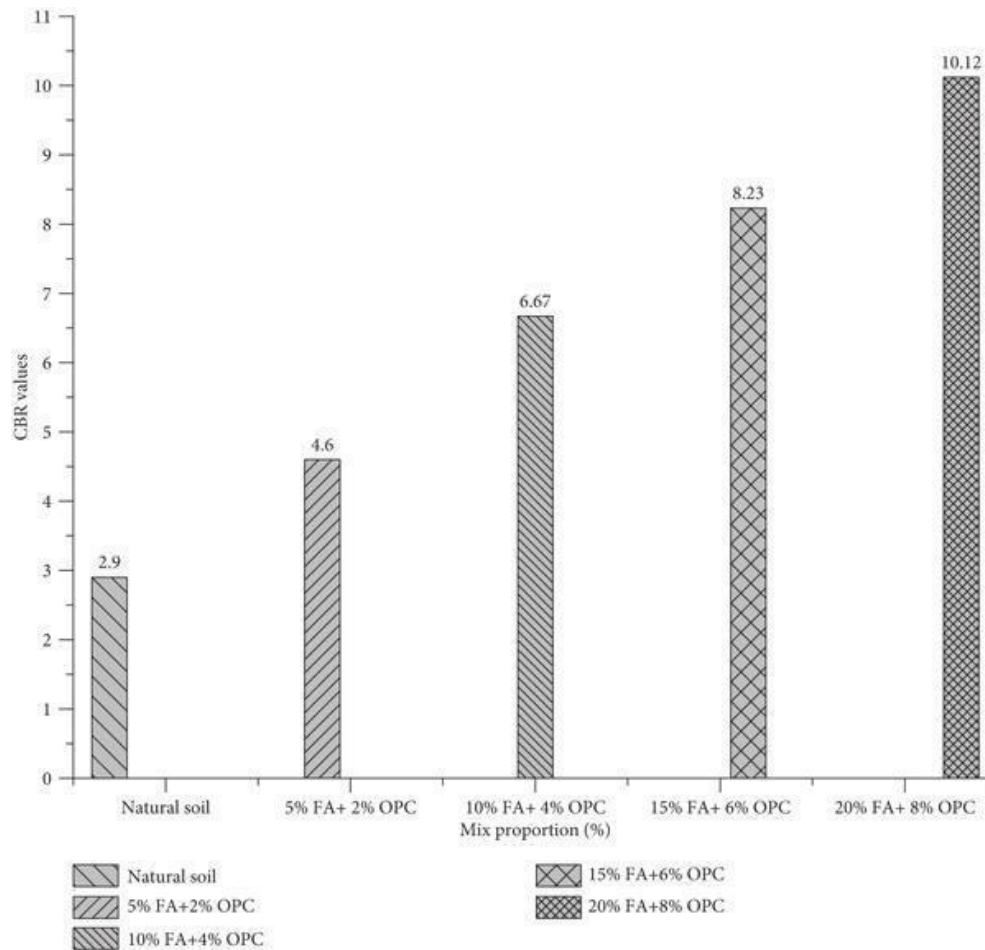


Figure 6. California bearing ratio of fly ash and cement mixture [41].

stabilizing peat soil, increasing its shear strength by 14% [40]. Moreover, the combination of fly ash (FA) and cement in subgrade soil stabilization has shown that 8% cement, along with 20% fly ash, significantly improves the California bearing ratio (CBR) and UCS values As Shown In Figure 6 [41].

Ground granulated blast furnace slag (GGBS) and CKD are employed to improve the physical and mechanical properties of soils. The optimal binder composition is found to be 6% of a mixture comprising 25% GGBS and 75% CKD, and 75% CKD enhanced the

strength of soft soil by 3.3 times in 7 days and 5.5 times in 28 days, attributed to the formation of hydration products as shown in Figure 7 [42]. The exploration of industrial wastes, such as cement kiln dust (CKD), lime kiln dust (LKD), and fly ash (FA), for soil stabilization, contributing to improved soil stability and sustainability [1], [5].

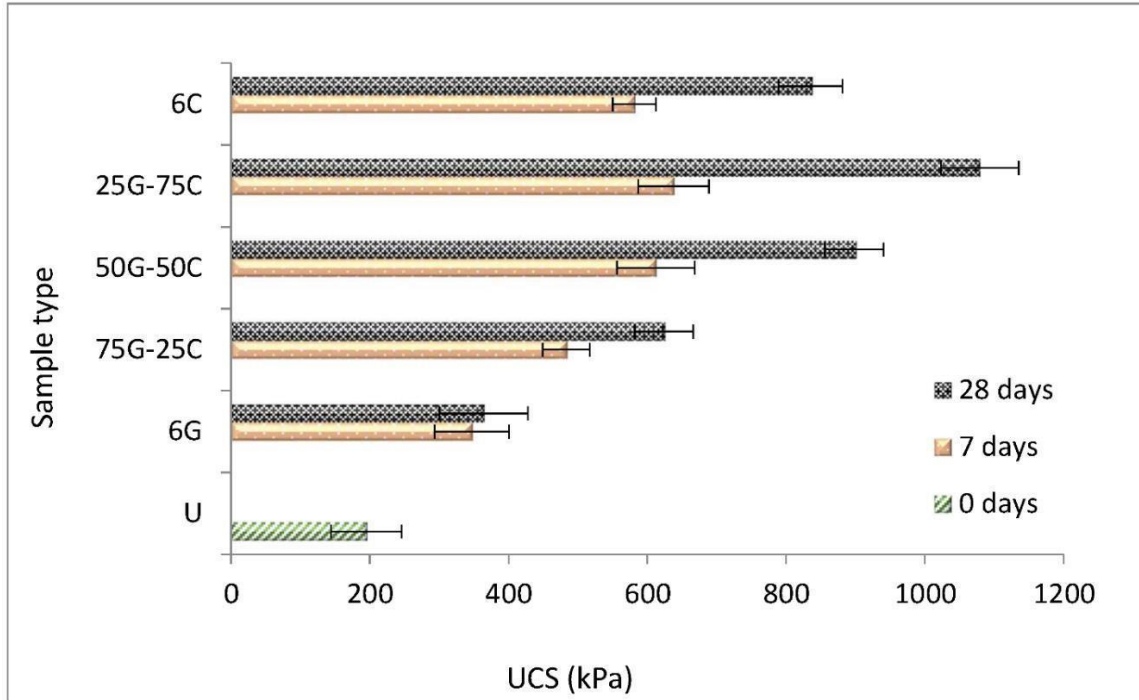


Figure 7. UCS of both treated and untreated soil samples at 7 and 28 days [42].

These materials not only provide an eco-friendly alternative to traditional stabilizers but also enhance the long-term stability of soil subgrades [26]. CKD and lime effectively reduced the swelling potential of the soil and improved its geotechnical properties [31].

CKD significantly enhanced the engineering properties of clayey soils, making them more suitable for use as pavement subgrades [43]. This exploration of various soil stabilization techniques and materials, especially cement, CKD, and lime, signifies significant advancements in the field. For instance, In the stabilization of expansive subgrade soils, lime percentages range from 5% to 20%, with significant improvements in the California

Bearing Ratio (CBR) values observed at higher lime contents as illustrated in Figure 8 [44]. In addition, Gypsum clay soils show optimal stabilization with 6% lime, resulting in significant increases in unconfined compressive strength and modulus of elasticity after 28 days of curing as shown in Figure 9 [45].

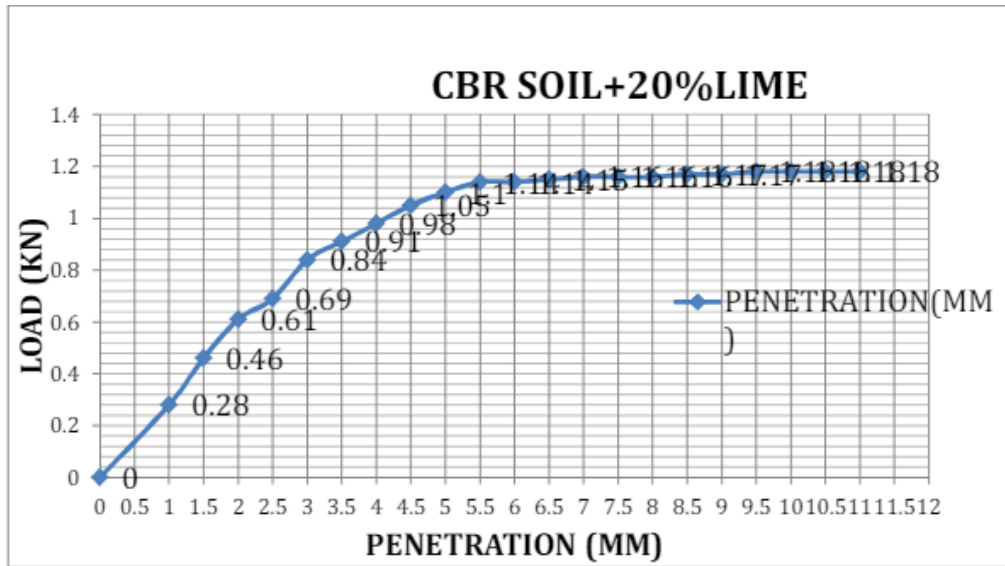


Figure 8. CBR Graph Soil & Lime [44].

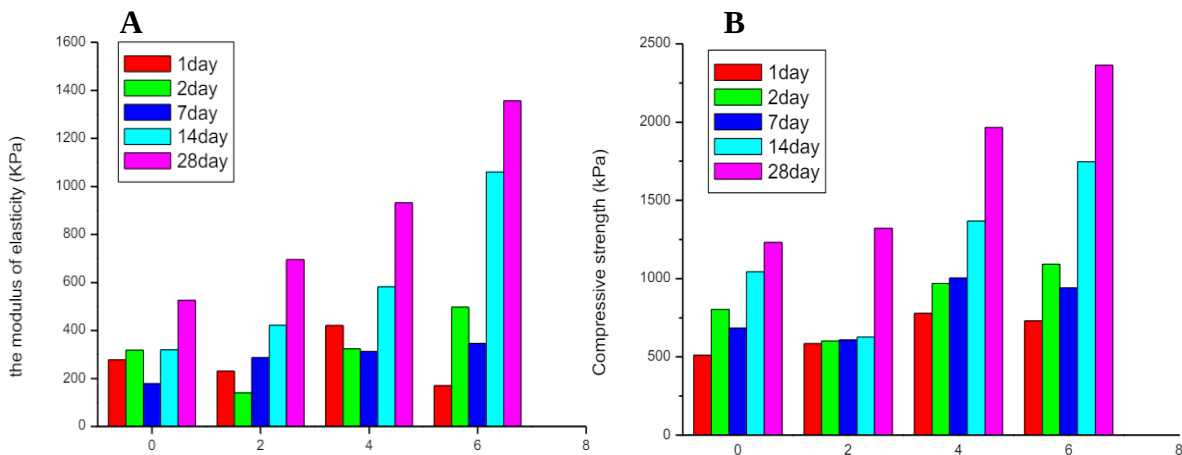


Figure 9. (a) Results of compressive strength development with increasing cure time. (b) . Development of modulus of elasticity with increasing cure period [45].

This proves that the integration of cement, lime, and Cement Kiln Dust (CKD) in soil stabilization has become a central focus in geotechnical engineering, aiming to enhance the

mechanical and physical properties of soils for a variety of construction purposes. Cement, being a well-established binding material, enhances soil strength and diminishes its compressibility. Lime, a traditional stabilizer, induces pozzolanic reactions, leading to long-term strength gain and decreased soil plasticity [30], [46].

Moreover, the utilization of secondary raw materials, including waste and by-products from industries such as cement kiln dust (CKD), has emerged as a sustainable and cost-effective alternative in soil stabilization, particularly in challenging terrains like peatlands. This approach not only offers environmental benefits but also contributes to the sustainability of the cement manufacturing process [26], [32], [47]. The stabilization of lateritic soil using a combination of CKD and lime has proven effective, reducing plasticity, maximizing dry density, and decreasing swell potential, thereby classifying the soil as suitable for road pavement applications [30]. This improvement is attributed to changes in soil particle interactions and enhancements in compaction and strength [30]. Similarly, fresh CKD has been shown to effectively stabilize high swelling clays, reducing their tendency to swell and improving overall soil stability [33]. The utilization of industrial wastes, such as CKD, in soil stabilization underlines a shift towards sustainable practices, emphasizing the recycling potential of these materials [26]. CKD, along with Lime Kiln Dust (LKD) and Fly Ash (FA), has proven effective in stabilizing weak soil subgrades, recommending CKD or FA/LKD for long-term stabilization and FA and LKD for short-term applications, thus improving the soil's bearing capacity and stability and providing a sustainable alternative to traditional stabilizers [32]. Furthermore, the use of CKD in soil stabilization plays a critical role in addressing environmental concerns. An effective approach for mitigating arsenic contamination in soil is the application of lime dust and

cement kiln dust (CKD). The effectiveness of this methodology has been demonstrated in the immobilization of arsenic, the reduction of its mobility, and the enhancement of soil safety [48]. The efficacy of CKD in the process of soil stabilisation is heightened when employed in combination with additional substances, such as polypropylene fibres, which enhance the material's ability to undergo deformation without experiencing fractures and subsequently reinforce it. Furthermore, the inclusion of glass fibre in fine-grained soil results in the improvement of its physical and mechanical characteristics, thereby increasing its stability and ability to bear loads [34], [49]. The use of Cement By-Pass Dust (CBPD) in soil stabilisation has shown improvements in the properties of expansive clay, showing similar results to those achieved with lime or cement [46]. In the context of expansive soils, CKD has been utilized to reduce swelling and improve geotechnical properties, with the addition of lime further enhancing these effects [31]. Enhancing the stability of clayey subgrade materials with CKD stabilization has shown significant improvements in the engineering properties of clayey soils, making them suitable as pavement subgrades [50]. This demonstrates that using cement, lime, and CKD in soil stabilization offers a comprehensive method for improving soil properties in construction applications, contributing to safer and more sustainable construction practices, and showcasing the potential of utilizing industrial by-products in geotechnical engineering.

2.2 Soil Stabilization in Saudi Arabia

Soil stabilization is vital in geotechnical engineering, especially in Saudi Arabia. The unique geological and climatic conditions here require diverse stabilization techniques to support infrastructure such as roads, buildings, and bridges. The region's expansive clays, sabkha soils, and oil-contaminated areas require innovative stabilization solutions to ensure

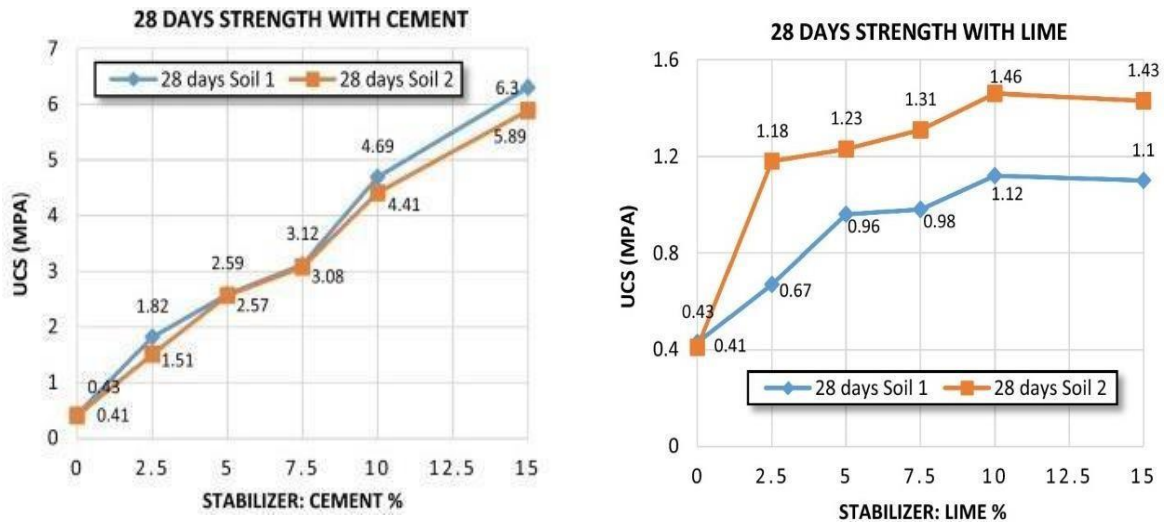


Figure 10. Enhanced compressive strength in Al-Hofuf soil with 15% cement versus 10% lime [51].

construction safety and longevity. Studies on soil stabilization with cement and lime indicate that cement generally surpasses lime in enhancing soil strength and durability [51], [52], [53]. In Al-Hofuf's 'Hamrah', a soil mixture with 15% cement attained a maximum compressive strength of 6.3 MPa, notably higher than the 1.46 MPa achieved with 10% lime as shown in Figure 10 [51].

This demonstrates cement's superiority in soil stabilization, offering a more durable solution. Also, a mix of Portland cement, limestone powder, and cement kiln dust has effectively improved soil properties in oil-contaminated areas [54], showing their potential in addressing contamination and enhancing soil compaction and strength. Cement Kiln Dust (CKD), a by-product of cement manufacturing, is acknowledged as an effective soil stabilizer. It notably enhances the geotechnical properties of clay soil used in road construction, such as increasing strength and improving compaction behavior, thus providing the dual benefits of repurposing industrial by-products and promoting sustainable construction practices [55]. Although generally less effective than cement in enhancing strength, lime stabilization has significant potential in improving soil

workability and strength for certain soil types compositions, underlining the necessity of selecting the appropriate stabilizing agent based on the soil's unique characteristics. For low-volume roads, a composite material of cement and bitumen has shown superior performance, enhancing soil compaction, strength, and durability, thereby highlighting the effectiveness of using multiple stabilizing agents to achieve desired soil properties for specific applications [56]. In Saudi Arabia, the challenge of expansive soils, prone to significant volumetric changes with moisture variation, is effectively tackled through chemical stabilization using lime and cement. This approach results in decreased expansion tendencies and increased soil strength, crucial for preserving construction integrity and preventing structural damage [57], [58]. Additionally, Sabkha soils, known for their high salt content and weak load-bearing capacity, especially in coastal regions, have shown improved load-bearing abilities after stabilization with cement and lime, rendering them more suitable for construction [59]. This underscores the vital role of tailored stabilization techniques in addressing the unique challenges posed by different soil types. Yet, the specific impact of stabilization on soil thermal behavior, especially in unique environments such as the Hejaz region, remains underexplored. This study aims to address this gap by examining the thermal properties of cement, lime, and cement kiln dust (CKD)-stabilized Hejaz soil. The study explores how different stabilization concentrations influence soil thermal properties, a crucial aspect for the development of sustainable infrastructure solutions. The results of this study could directly contribute to enhancing stabilization practices in Saudi Arabia, exploring sustainable materials, and promoting more sustainable construction practices. This research has significant potential to contribute substantially to environmental science, sustainable materials, and geotechnical engineering. Furthermore,

the applications of this research are not limited to Saudi Arabia but can be extended to other geotechnical contexts worldwide.

2.3 Soil /Soil Stabilization: Thermal and Mechanical Insights

The exploration of thermal properties in stabilized soil is a key aspect of geotechnical engineering, focused on enhancing the performance, sustainability, and resilience of construction materials. Over the last several decades, extensive studies have been conducted to better understand the effects of various stabilizing chemicals and procedures on the thermal, mechanical, and geotechnical properties of soils. Cement Kiln Dust (CKD), a byproduct of the cement manufacturing process, has been extensively researched for its potential in soil stabilization, demonstrating improvements in geotechnical qualities and construction suitability [60]. When combined with glass or polypropylene fibers, CKD impacts the physicochemical properties, geomechanically strength, and ductility of fine-grained soil. This addresses the brittle nature of CKD-stabilized soils and underscores the importance of considering mechanical and thermal properties in construction applications [34], [49]. The combination of traditional stabilizers like cement and lime with innovative materials such as sodium silicate, Oil Shale Ash (OSA), and Ordinary Portland Cement (OPC) has shown promising results in enhancing the mechanical properties, durability, and thermal insulation of soil [61], [62]. These combinations yield a resilient and long-lasting construction material, characterized by superior compressive strength, low water absorption, and minimal shrinkage. The use of alternative materials like Pottery Burnt Hull Ash (BHA) in combination with lime has demonstrated enhanced strength and reduced heat conductivity. This finding highlights the potential of integrating agricultural waste products into sustainable construction practices [63]. Moreover, air-entraining additives

(AEA) combined with cement, hydrated lime, fly ash, and metakaolinite affect the mechanical, thermal, and physical properties of earth mortars, leading to enhanced compressive strength, reduced water absorption, and modified thermal conductivity [64]. In pavement engineering, the use of CKD and Reclaimed Asphalt Pavement (RAP) significantly enhances the mechanical properties of subgrade soils, ensuring a stable and durable pavement structure that can withstand traffic loads and environmental conditions [65]. This proves that the comprehensive analysis of various soil stabilization techniques and materials has led to significant advancements in the field, providing numerous options for enhancing soil properties and ensuring stable, durable, and sustainable construction practices, as evidenced by the many studies. Various methodologies have been employed to investigate the thermal properties of soils without stabilization, revealing a common need for enhanced understanding and measurement techniques. Experimental studies have yielded valuable data on thermal conductivity and resistivity, crucial for predicting soil behavior under environmental stressors [66], [67]. Semi-empirical models have advanced this understanding by correlating thermal properties with soil density, a critical factor in soil stabilization [68]. The impact of soil composition on thermal behavior underscores the need for more detailed research in this area, especially for applications involving stabilized soils [69]. The development of new laboratory equipment highlights the existing gap in precise measurement tools, indicating a significant area for future innovation [70]. This collective body of work points towards a substantial need for advancing knowledge on the thermal properties of soils as well as stabilized soils. Concurrently, the development of specialized laboratory equipment such as the TLS-100 device addresses the need for precise measurement tools. This device, in particular, has been instrumental in advancing

the understanding of soil thermal properties. For example, a study on the thermal conductivity of Iraqi soils using the TLS-100 demonstrated how intrinsic soil composition influences thermal conductivity, providing valuable data for civil engineering applications [71]. Similarly, research on silty clay soils has demonstrated a clear relationship between thermal conductivity and resistivity, findings that are vital for the design of structures that must withstand temperature fluctuations [66]. Moreover, the use of bio-cementation techniques has significantly enhanced soil thermal conductivity, as measured by the TLS-100, suggesting improvements in the efficiency of energy piles[72]. Soil thermal conductivity is a critical parameter influencing various environmental and engineering applications, such as groundwater withdrawal, ground source heat pumps, and heat storage in soils. It is influenced by several factors including soil moisture saturation (SMS), soil organic matter (SOM) content, dry density, porosity, and mineralogical composition. For instance, soil thermal conductivity increases linearly with water content and dry density, as observed in silty clay soils from Fengxian County, where it decreases slightly when water content exceeds 17.65% due to decreased density as shown in Figure 11 [73]. The thermal conductivity of soils also varies with temperature, peaking in the range of -2 to

0°C for silty and organic-poor soils and -5 to 0°C for organic-rich soils due to phase changes of ice/water in warm permafrost as illustrated in Figure 12 [74].

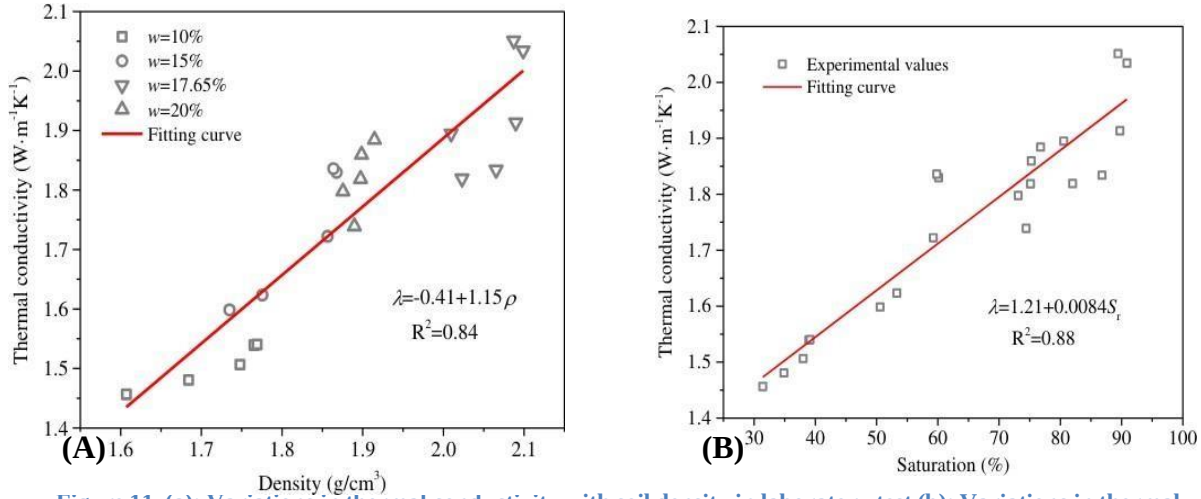


Figure 11. (a): Variations in thermal conductivity with soil density in laboratory test (b): Variations in thermal conductivity with saturation in laboratory [73].

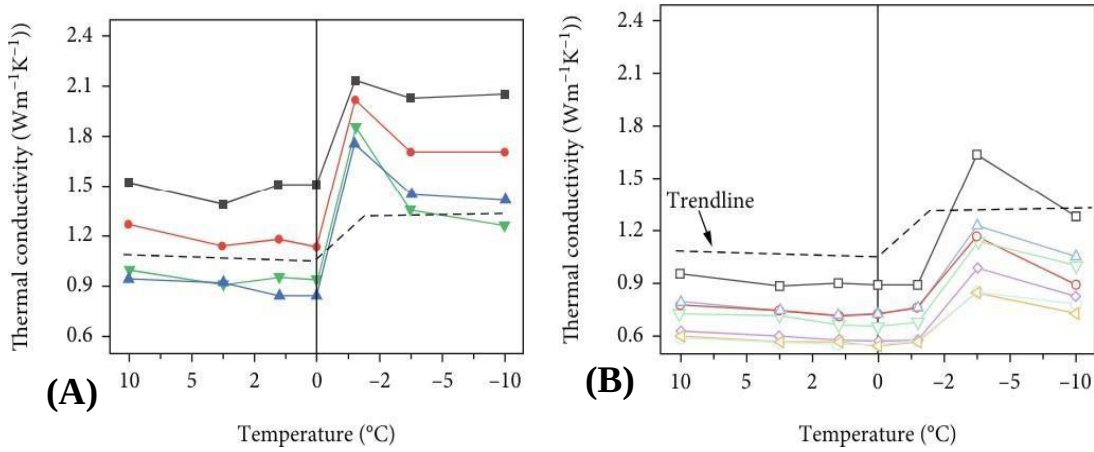


Figure 12. Changes in soil thermal conductivity with soil temperatures ((a) silt and organic-poor soil samples; (b) organic-rich soil samples [74].

Empirical models have been developed to estimate soil thermal conductivity more accurately. For example, a new model considering porosity, saturation, and quartz content showed a root mean square error (RMSE) of 0.098 and 0.096 $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ in field and laboratory tests, respectively [73]. Another model incorporating dry density, porosity, and mineralogical composition improved the coefficient of determination (R^2) from 0.83 to

0.95 [75]. Additionally, a new empirical model demonstrated a mean coefficient of determination (R^2) of 0.964 and a mean relative error (Re) of 7.335% across different soil textures [76]. In light of these significant findings, the current study will adopt the TLS-100 device to measure the thermal properties of Hejaz soil, following the same measurement tool used Iraqi soil study [71]. Unlike the Iraqi study, which was a field test, this study will be conducted in a laboratory. The Iraqi soil study, conducted by experts, did not use stabilizer materials, as shown in Figure 13. This study will extend the application of the TLS-100 to evaluate the effects of stabilization with cement, CKD, and lime on Hejaz soil.



Figure 13. TLS-100 measurements of thermal properties of unstabilized Iraqi soil (field test) [71].

2.4 Acoustic Properties of Soil

Soil acoustics involves the study of how sound waves propagate through soil, which can provide valuable insights into soil properties and conditions. Various studies have measured different acoustic parameters in soils, revealing significant variations based on soil type, moisture content, and other factors. For instance, ultrasonic velocity in soils can vary nonlinearly with soil texture and moisture absorbent media, with the lowest velocity observed in pure sand and higher velocities in soils with increased plasticity and clay

content [77]. Acoustic complexity in forest soils shows seasonal and diurnal patterns, with the highest values in spring and summer and the lowest during the night [78]. Geo-acoustic signals have been used to estimate shear wave velocity, porosity, and relative density, with correlations found between naturally produced acoustic signals and soil properties [79]. The high-frequency multi-channel analysis of surface waves (HF-MASW) method measures shear wave velocity up to 2.5 meters deep, reflecting soil variations due to weather and other factors [80]. Fibre optic Distributed Acoustic Sensing (DAS) systems have shown good response in different soil types, with signal-to-noise ratios indicating reliable performance even after a decade [81]. Sensitivity studies have identified shear modulus, Poisson's ratio, and coefficient of restitution as key parameters affecting acoustic wave velocity and frequency in soils [82]. Acoustic emissions from soil grains under compression and shear processes provide additional data for soil mechanics [83]. Challenges in acoustic communication through soils include attenuation and coupling issues, but data rates up to 300 MB/s have been achieved over short distances [84]. Ground impedance measurements in sandy and clay soils show significant frequency-dependent variations [85]. Finally, acoustic attenuation coefficients in soils range from 0.12 to 0.96 dB cm⁻¹ kHz⁻¹, with propagation speeds between 86 and 260 m/s, influenced by soil moisture and porosity [86]. These findings collectively enhance the understanding of soil acoustics and its applications in various fields.

2.5 Acoustical Characteristics of Stabilized Earth Materials

The acoustical characteristics of stabilized earth materials vary significantly based on the type and concentration of stabilizers used. For instance, the use of water hyacinth ash

(WHA) and sugarcane bagasse ash (SBA) as binders in earth blocks affects their acoustic properties differently. Increasing WHA concentration enhances the acoustic transmission coefficient and porosity but reduces airflow resistivity, whereas increasing SBA concentration decreases the transmission coefficient and porosity but increases airflow resistivity, indicating SBA's stronger binding properties [87]. NBRRI interlocking compressed stabilized earth blocks (ICSEB) made from silty sand exhibit high acoustic coefficient values ranging from 0.71 to 0.99 at octave bands of 500Hz to 4000Hz, with the highest value at 1000Hz, suggesting their viability for acoustic insulation, especially at lower frequencies [88]. The use of lime stabilization in rammed earth (RE) improves durability and unconfined compressive strength (UCS), with lime stabilized RE (LSRE) showing little to no erosion in wet conditions and higher UCS with increased curing time and temperature [89]. Ultrasonic pulse velocity (UPV) testing on hollow ICSEBs indicates that both moisture and cement content significantly affect their physical-mechanical properties, with higher cement content ($\geq 6\%$) recommended for durable blocks[90]. Additionally, the incorporation of polystyrene in stabilized earth blocks reduces mechanical properties but influences density and mechanical resistance [91]. Compaction pressure also affects intrinsic acoustic parameters, with high-density compressed earth blocks showing some discordance between model and experimental data at high frequencies [92]. Natural polymers like alginate, when used for soil stabilization, improve compressive and flexural strength, with UPV correlating well with mechanical properties [93]. P-wave velocities in stabilized soils increase with curing time and density, correlating with unconfined compressive strength and modulus, demonstrating the effectiveness of ultrasonic testing for evaluating stabilized materials [94], [95]. The use of dispersed

reinforcement in soil-cement-polypropylene fiber mixtures showed a decrease in ultrasonic pulse velocity by up to 18.5%, with immersion in water increasing results by about 6.3% [96]. The incorporation of natural polymers like alginate and wool fibers in soil composites improved compressive and flexural strength, with ultrasonic wave propagation aiding in the assessment of soil shrinkage and fiber-soil adherence capacity [93]. Lightweight granular materials mixed with polyurethane resin, such as perlite, arlite, and vermiculite, exhibited high structural strength and favorable acoustical properties, making them suitable for noise control applications [97].

2.6 Acoustic Properties in Soil Stabilization

The investigation into the acoustical characteristics of stabilized soils, specifically those treated with cement, lime, and Cement Kiln Dust (CKD), is pivotal for advancing sustainable construction practices. The stabilization of soils using a blend of binders, including cement and lime, has been shown to significantly improve the geotechnical properties and workability of soil, thereby enhancing its strength and durability for construction applications [98]. The environmental and economic benefits of utilizing industrial waste products, such as CKD, as stabilizing agents are well-documented, offering improved performance and reduced pollution [19]. The addition of Portland cement and lime to soils, as explored in rammed earth construction, demonstrates the potential for these materials to increase the mechanical properties of soils, making them suitable for sustainable construction [17]. This aligns with the broader industry goal of reducing greenhouse gas emissions through the use of alternative materials, such as alkali-activated binders (AABs), which can also stabilize soils with reduced environmental

impact [99]. The physical and mechanical behavior of lime-cement-stabilized compressed soil blocks further underscores the effectiveness of these materials in enhancing soil properties for construction [100]. Research on lime stabilization reveals its efficacy in improving the engineering properties of clayey soils, although moisture exposure can affect the longevity of such treatments [101]. The use of Ground granulated blast slag GGBS and CKD has shown promise in enhancing the physical and mechanical properties of soft soils, thereby improving their suitability for pavement construction [42]. The sustainable development of cement-stabilized materials (CSMs) benefits significantly from the incorporation of waste materials, promoting environmental sustainability [102]. Studies on the mechanical properties of subgrade soils stabilized with cement and lime have highlighted the role of these materials in improving soil characteristics, essential for sustainable construction [18]. Moreover, these advancements stem from a myriad of research efforts, each contributing unique insights into the multifaceted domain of soil mechanics and geotechnical engineering. Geo-acoustic signals, for instance, have been effectively used to estimate soil properties, indicating a correlation with the physical and mechanical characteristics of soils [79]. Similarly, the calibration of Acoustic-Soil Discrete Element Models has shown the sensitivity of soil parameters to different acoustic indicators, offering pathways to enhance construction accuracy through the refinement of acoustic wave-soil interaction models [82]. The development of an acoustic soil profiler utilizing surface wave methods represents a significant leap forward, enabling the profiling of near-surface soil layers for various applications, including agricultural land assessment and compaction studies. This tool's versatility underscores the expanding scope of acoustic methods in geotechnical investigations [80]. Investigation into the relationship between

acoustic emissions and energy dissipation in soil-structure interaction research provides insights into the mechanics of acoustic emissions generation, driven predominantly by friction and damping mechanisms. The results from this study provide insights into the behavior of granular materials under stress, serving as a predictive tool for assessing structural integrity. [103]. Acoustic Emissions (AE) Monitoring in soil compressibility and shear strength tests illustrates the initial phases of applying AE technology in soil mechanics, paving the way for more sophisticated diagnostic tools capable of identifying mechanical precursors to soil failure and landslides [83], [104]. Additionally, the application of Distributed Acoustic Sensing (DAS) systems for infrastructure monitoring highlights the effectiveness of acoustic techniques across different soil types, enhancing the Signal-to-Noise Ratio (SNR) and performance of Distributed Acoustic Sensing (DAS) systems in real-world settings [81]. Investigations into the behavior of acoustic waves in complex underground environments, such as tunnels within multilayer soils, reveal the significant impact of soil layer composition and tunnel geometry on acoustic wave propagation. Ultrasonic acoustical assessments have further demonstrated the potential of acoustic methods to evaluate soil texture and moisture content, critical factors in agricultural and environmental management [77]. The development of an underground through-soil wireless acoustic communication system opens new avenues for data transmission in challenging environments, underscoring the versatility of acoustic technologies [105]. Techniques for measuring acoustic wave speed in soils have also advanced, with high-sensitivity methods enabling in-situ observations of soil properties, facilitating a deeper understanding of soil behavior under various conditions [106]. Acoustic emission characteristics in soils subjected to triaxial compression offer a non-

destructive means to evaluate and predict the mechanical behavior of soils, providing a valuable tool for geotechnical engineering and disaster mitigation [107]. Sound source material recognition technology represents another innovative application, enabling the study of soil compaction and offering a method for assessing compaction levels without invasive testing [108]. Determining soil characteristic frequency using acoustic techniques has shown promise in measuring sandy soil properties, potentially determining soil permeability—a critical factor in both environmental and civil engineering projects [109]. The effect of foundation details and soil types on the airborne sound insulation of structures has also been explored, highlighting the role of soil properties in acoustic insulation and the potential for optimizing building designs. [110]. [The use of acoustic sampling methods for detecting insect pests in soil illustrates the broad applicability of acoustic techniques, extending beyond traditional engineering applications to include agricultural and environmental monitoring. This method shows promise for non-invasive pest management strategies, though further study is required to enhance data interpretation [111]. This The integration of acoustic techniques in geotechnical engineering significantly advances non-invasive soil analysis and structural monitoring. However, the application of these methods in soil stabilization, particularly with cement, lime, and Cement Kiln Dust (CKD), remains underexplored. This gap highlights an opportunity for research to expand into developing acoustic-based strategies for enhancing soil stabilization processes. Exploring this could lead to innovative solutions that improve soil strength and durability, essential for sustainable infrastructure development.

2.7 Importance of Sound Absorption in Building Materials

Utilizing suitable insulation is an economical approach to greatly enhance the energy efficiency of buildings and diminish their total impact on global CO₂ emissions [112]. Sound absorption characteristics of building materials, such as glass-wool panels, have been shown to align well with reverberation room measurements, indicating the reliability of these materials in real-world applications [113]. This underscores the importance of selecting materials with proven sound absorption capabilities for building construction. Furthermore, the sustainable approach for sound absorption assessment, as validated by small-scale reverberation room measurements, highlights the economic and environmental benefits of using materials with reduced size and cost-effective evaluation methods [114]. The study of sustainable materials, such as those derived from rice husk, reveals that compositions with high sound-absorption coefficients can also possess suitable compressive strength, demonstrating the feasibility of using eco-friendly materials without compromising structural integrity [115]. This aligns with the investigation of study's focus on using locally sourced soils and sustainable stabilizers like CKD in construction. In concert halls, the choice of building materials and their treatments significantly affects sound field characteristics. It has been observed that the use of acoustic materials in ceilings, as opposed to side walls, results in shorter reverberation times, enhancing the acoustic quality of the space [116]. This finding has significance in this research because it highlights the importance of where and how materials are placed and applied to achieve acoustic outcomes that vary with frequency. The development of impedance tubes, for testing absorbing materials further underscores the necessity, for measurement and analysis of the acoustic properties found in construction materials [117]. This is especially relevant

for this research as the Acoustical Characteristics (AC) of stabilized soils will play a role. Promising findings have emerged regarding the use of materials like foam-based composites and 3D printed structures in absorption. Research suggests that these materials exhibit absorption capabilities across a wide range of frequencies opening up exciting opportunities for acoustic design, in buildings [12]–[14]. This creates opportunities to investigate the characteristics of stabilized soils, which could potentially result in the development of building materials that have improved sound absorption capabilities. Additionally by measuring the Acoustical Characteristics (ACs) of building components, such, as elements like lightweight partition walls and windows it emphasizes the holistic approach to considering acoustics, in building design [121]. This study takes an approach by considering the acoustic performance of stabilized soils, in construction. The impact of absorption on building acoustics, occupant comfort and energy efficiency highlight the importance of building materials. This research aims to advance this field through an investigation into the sound absorption characteristics of soils stabilized with cement, lime, and CKD.

CHAPTER 3

Methodology

This comprehensive experimental methodology aims to evaluate both the thermal and acoustic properties of soil stabilized with traditional and industrial waste materials in the Hejaz region of Saudi Arabia. Using a structured approach, this study systematically examines how different soil stabilization methods affect these properties, adhering to established ASTM standards. The methodology section outlines the different approaches involved in conducting experimental research, with a focus on the thermal and acoustic performance of stabilized earth materials. A visual representation provided in Figure 14

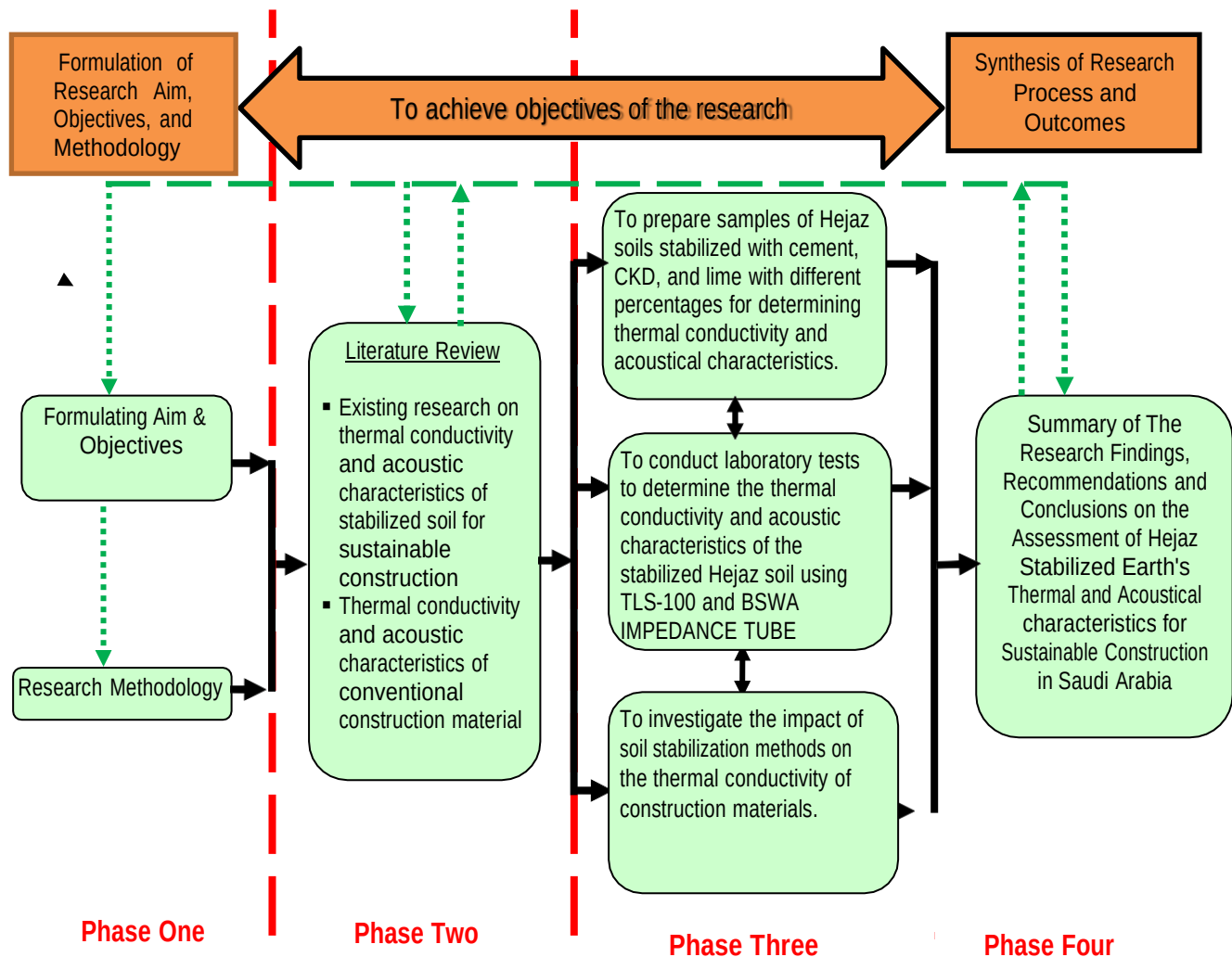


Figure 14. Research methodological framework: A graphical representation of interconnection of four phases and all methods going to be used in this research.

summarizes the methodology employed, illustrating the key stages and components of the research, including objectives and aims.

3.1 Sample Preparation and Stabilization Agent Selection

The initial stage of this study in the Hejaz region involves meticulously sourcing, collecting, and preparing soil samples to analyze their thermal and acoustic properties. The study will investigate two distinct types of soil, designated as Soil-A and Soil-B. These samples underwent rigorous preparation processes including pulverization, mixing to ensure homogeneity, and drying, followed by stabilization using a blend of Ordinary Portland cement, hydrated lime, and Cement Kiln Dust (CKD) in dosages ranging from 0% to 15%. This comprehensive experimental approach adheres to the ASTM D698 standards, essential for verifying the effectiveness of the stabilization and ensuring the reproducibility of the results. The preparation techniques aim to optimize the soil's physical properties necessary for detailed evaluation of moisture content, thermal conductivity, sound absorption coefficient, and impedance. The soil sampling procedure is critical and involves thoughtful consideration of factors such as soil type, composition, and specific location within the Hejaz region to ensure that the samples accurately represent the entire area [122], [30], [33], [48].

3.1.1 Soil Characterization Procedure

The soil samples from the Hejaz region were subjected to comprehensive characterization to determine their physical and chemical properties. The following standardized tests were performed as shown in Table 1:

Table 1. Soil Characterization Tests and Standards

Test	Standard	Description
Sample Collection	-	Soil samples were collected from northern (Soil A) and southern (Soil B) Hejaz.
Particle Size Distribution	ASTM D422	Sieve analysis and hydrometer tests to classify soil types.
Atterberg Limits	ASTM D4318	Measures liquid limit, plastic limit, and plasticity index.
Specific Gravity	ASTM D854	Determines the density and compaction characteristics of the soils.
pH and Electrical Conductivity	-	Measures chemical reactivity and salt content using pH and Electrical Conductivity testing kits.
Standard Proctor Test	ASTM D698	Determines optimum moisture content (OMC) and maximum dry density (MDD).

3.1.2 Stabilization Process

The stabilization process involved treating the soil samples with different stabilizers to enhance their thermal and acoustical properties. The following steps were undertaken as illustrated Table 2:

Table 2. Soil Stabilization Process Steps

Step	Description
Selection of Stabilizers	Chosen stabilizers: Ordinary Portland Cement (OPC), hydrated lime, and Cement Kiln Dust (CKD).
Preparation of Soil Samples	Air-dried and sieved soil samples, added stabilizers in varying percentages (0%, 2.5%, 5%, 7.5%, 10%, 12.5%, 15%) by weight.
Mixing	Thoroughly mixed soil and stabilizers; added water to achieve optimum moisture content.
Compaction	Compacted mixtures using Standard Proctor method; cured in airtight conditions for four weeks.
Curing	Exposed samples to natural weathering for six, eight, and twelve weeks.
Testing of Stabilized Soils	Conducted thermal conductivity tests (TLS-100, ASTM D5334) and acoustic measurements (BSWA SW series Impedance Tubes, ISO 10534-2).

3.2 Additive Ratios for Sustainable HSE Thermal and Acoustical Performance.

Hejaz Stabilized Earth (HSE) can gain popularity as a sustainable construction material owing to its minimal environmental effect, availability, and affordability. The inclusion of cement, lime, and CKD in varied ratios was tested in analyzing HSE's thermal and acoustical performance for sustainable constructions [123].

The addition of cement in percentages ranging from 2.5% to 15% has been observed to increase the Thermal and Acoustical and compressive strength of HSE [124]. Lime, in amounts ranging from 2.5% to 15%, has been proven to improve HSE's workability and minimize shrinkage. Lime also aids in the development of calcium silicate hydrates, which increase the strength and durability of HSE [125]. The addition of CKD in amounts ranging from 2.5% to 15% has been observed to increase HSE strength while decreasing permeability. CKD includes calcium oxide and silica, which react with water to generate calcium silicate hydrates like those formed by lime. The incorporation of CKD also helps to reduce carbon dioxide emissions linked with cement manufacture. Finally, altering amounts of cement, lime, and CKD may improve HSE's thermal and acoustic characteristics, as well as its strength and durability [126]. Nevertheless, while combining these chemicals into HSE to maximize its qualities for sustainable building in Saudi Arabia.

3.3 Standard Proctor Test:

The Standard Proctor Test is a generally used laboratory test for measuring the maximum dry density and optimal moisture content of a soil sample [127]. This test is useful in geotechnical engineering and building projects since it ensures that the soil is compacted

to the correct level and examines the soil's suitability for construction purposes. This protocol explains the processes necessary to administer the Standard Proctor Test. The preparation of samples is the first stage in administering the Standard Proctor Test. Soil samples from the field are gathered, with two typical samples obtained from the Hejaz region. After that, the samples are air-dried in a cool, dry location until they attain a constant weight. To assure accuracy, big particles, roots, and organic materials are removed from soil samples. The second step is the actual test procedure. Approximately 1800 grams of the air-dried soil sample is weighed into a mixing bowl, and water is added to the soil in increments of 2.1-2.7%, with thorough mixing after each addition [128]. The moisture content of the soil sample is measured using a moisture content tester, and water is incrementally added until the optimum moisture content is reached [129]. The moist soil sample is then compacted in the Proctor mold using a standard compaction procedure, with the soil being compacted in layers with a specified number of blows per layer [130]. The mold is removed from the compacted soil, and the specimen is trimmed to the desired height before sealing them in airtight plastic bags and labelling them with the sample ID, and type of the soil [131]. It is important to understand that the Standard Proctor Test should be performed in accordance with ASTM D698-12 requirements and suggestions. The Standard Proctor Test should be carried out in compliance with ASTM standards and recommendations, it is crucial to highlight [132]. ASTM International is an abbreviation for the American Society for Testing and Materials (ASTM) [133]. The ASTM standards provide guidelines for performing laboratory testing, such as the Standard Proctor Test, in ensuring the accuracy, consistency, and reliability of the results. ASTM D698-12, Standard Test Methods for Laboratory Compaction Properties of Soil Using Standard Effort [12,400

ft-lbf/ft³ (600 kN-m/m³)], describes the ASTM standards for the Standard Proctor Test [134]. This standard specifies soil sample preparation and compaction using a Proctor mold with a capacity of about 944 cm³ and a predefined number of blows per layer [135]. According to ASTM D698-12, the soil sample should be placed in the Proctor mold in three equal layers, with each layer being subjected to 25 blows from a standard hammer with a mass of 2.5 kg, while the drop height of 304.8 mm and the diameter of the mold is

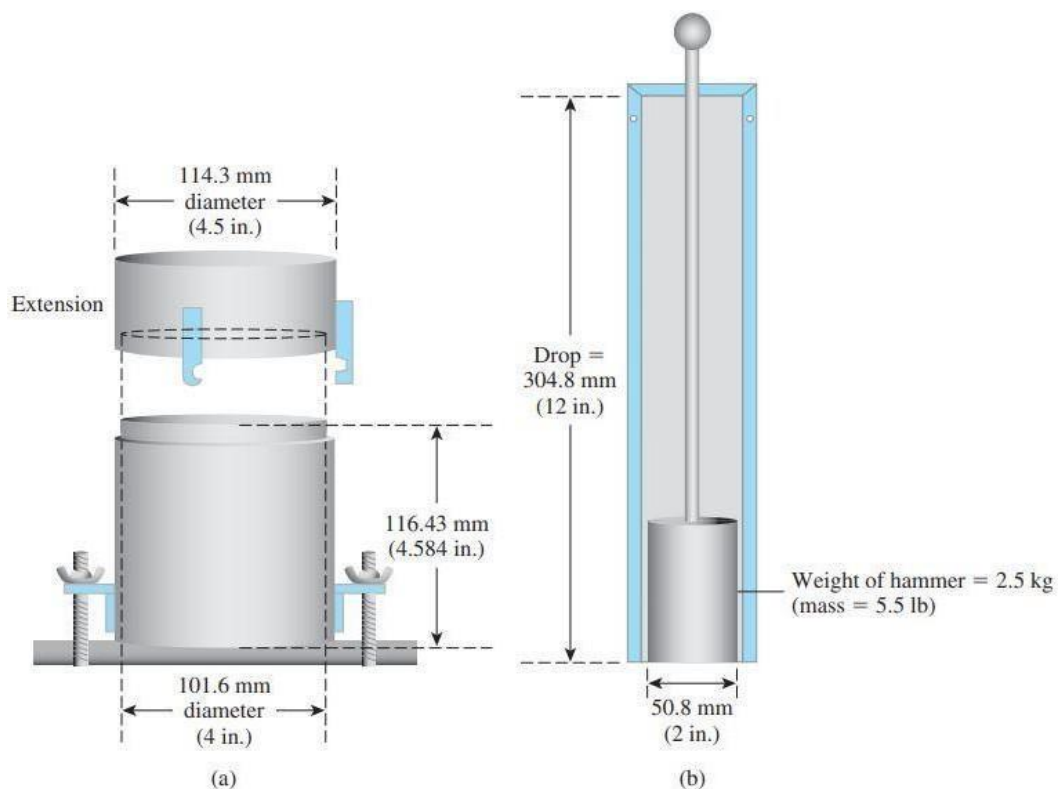


Figure 15. Standard Proctor test tool: (a) mold; (b) hammer. Source: [135].

101.6 mm (4 in.), As during laboratory experiment, the mold is connected to a bottom top plate and a top extension with the diameter of 114.3mm Figure 15 [127]. The ASTM standards offer guidance for administering the Standard Proctor Test to assure accuracy and consistency of findings. The equipment and techniques used in the test, including the Proctor mold, compaction effort, moisture content range, and calculation of maximum dry

density and optimal moisture content, are specified in these standards. Following these standards and guidelines will provide accurate and dependable results, guaranteeing the safe and efficient use of Hejaz soil in sustainable construction projects in Saudi Arabia.

3.4 Experimental Setup for Acoustic and Thermal Measurements

Following stabilization, the samples were sealed and cured for four weeks to stabilize their properties. For acoustic testing, the Acoustical Characteristics (AC) was measured using the BSWA SW series Impedance Tubes, specifically the SW422 model, complying with ISO 10534-2 standards. This setup involved using a 100mm width tube suitable for specific frequency ranges, with grease oil applied to the edges of soil samples to ensure a tight fit in the impedance tubes and prevent sound leakage [136], [137]. Each sample underwent a 90-second test, which was repeated three times to ensure consistency in the results. The amplitude measurements across frequencies were then analyzed, and custom colormaps were created to visually represent the soil's absorption properties based on AC categories. This acoustic testing procedure and the resultant data visualization are outlined in Figure 16. Simultaneously with acoustic testing, thermal conductivity measurements were initiated using the TLS-100 Thermal Conductivity Meter equipped with a 50 mm sensor, adhering to ASTM D5334 and IEEE 442-2017 standards [71]. These measurements were conducted on samples post-curing and following exposure to natural weathering conditions over periods of six, eight, and twelve weeks to track the temporal evolution of the soil's thermal properties. The methodology for these thermal tests, including the sequence of measurements and environmental conditions, is comprehensively detailed in Figure 17. The flowchart provided in Figure 16&17 offers a visual and systematic overview of the entire experimental protocol, from the initial soil sample collection through the

stabilization process, to the final stages of data analysis and heatmap generation for both acoustic and thermal properties.

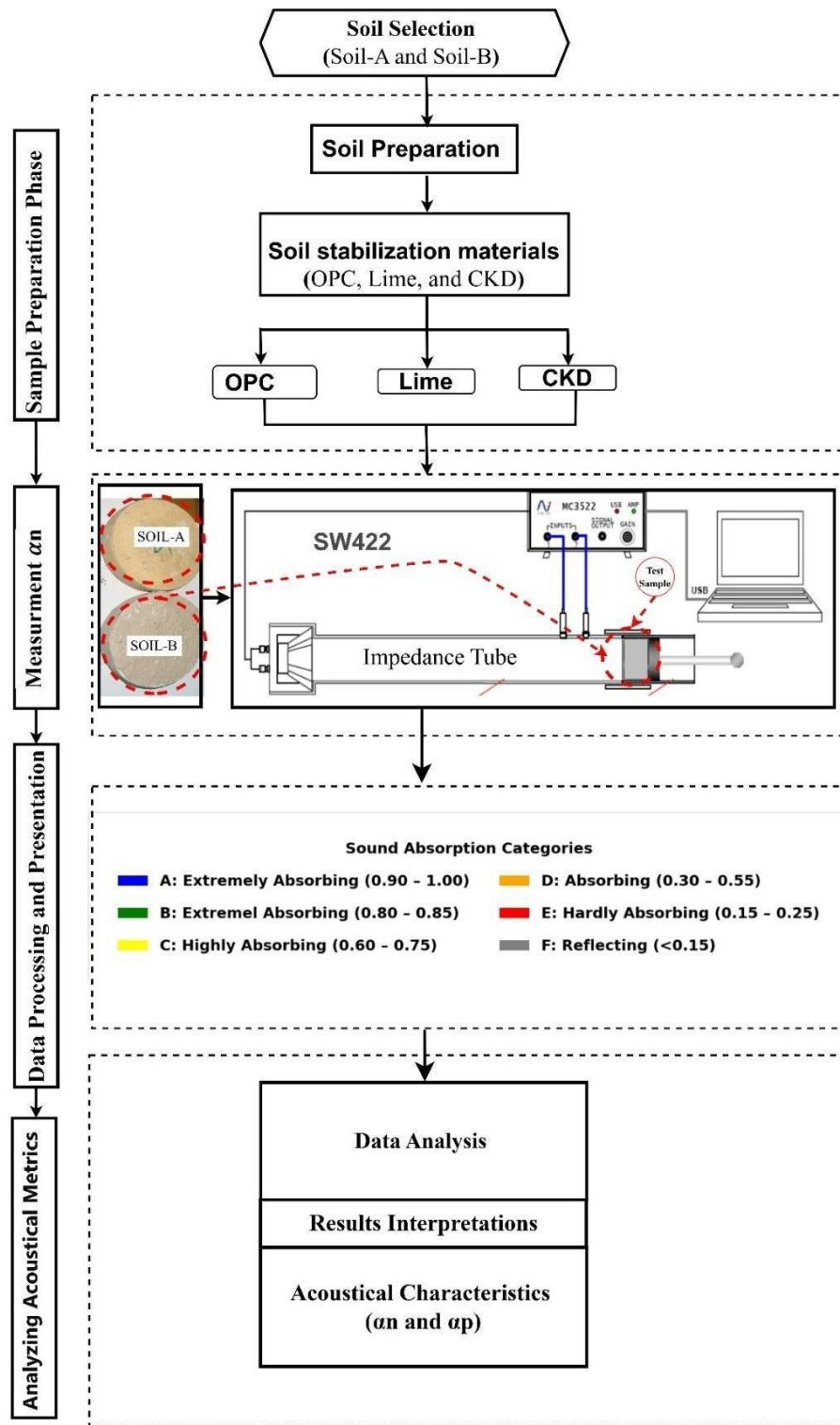


Figure 16. Acoustic Measurement Setup - Depicts the BSWA SW series Impedance Tube arrangement, including sample positioning, microphone spacings, and frequency ranges for acoustic testing of stabilized soils.

In previous studies, the box method was commonly used to measure the thermal conductivity of soil samples as shown in Figure 18 [11]. However, in this study, the TLS-100 Thermal Conductivity Meter was employed to provide more precise and reliable



measurements. The TLS-100 is a portable instrument for measuring the thermal conductivity and resistivity of materials such as polymers, rocks, soil, and concrete [138]. The TLS-100 is capable of measuring temperatures from different ranges [139]. Soil samples collected from the Hejaz region were prepared and tested using this machine (Figure 19). The TLS meter conforms to ASTM D5334 and IEEE 442-2017 standards [140]. It incorporates a needle with heating wire and temperature sensor, which are enclosed in a 50-mm steel tube. The sensor is fully embedded into the material being tested, as depicted in Figure 20. This figure demonstrates the precise positioning of both unstabilized and stabilized Hejaz soil samples in proximity to the TLS-100 device within a controlled experimental environment, ensuring accurate and reliable measurements.

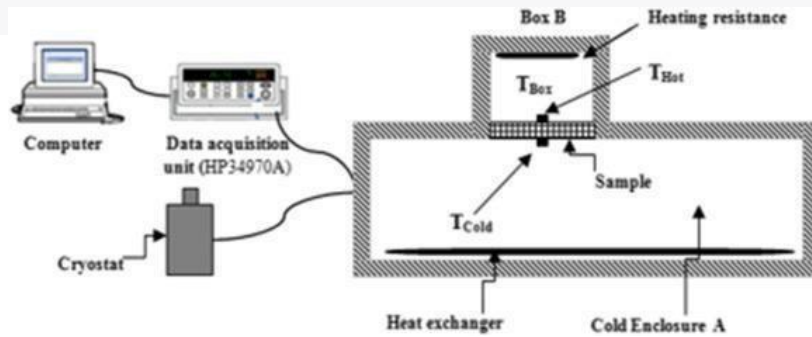


Figure 18. Traditional Box method setup for thermal conductivity measurement [11]



Figure 19. TLS-100 Machine. Source: [139]



Figure 20. illustrates the arrangement of both unstabilized and stabilized Hejaz soil samples next to the measurement equipment in a precisely controlled laboratory Environment for thermal conductivity.

The sensor is fully inserted into the sample for testing. Heat is applied to the sample using a constant current source (q), and the temperature increase is recorded over a specified period. The slope (a) from the plot of temperature rise versus the logarithm of time is utilized to calculate the thermal conductivity (k). Higher thermal conductivity in a sample results in a lower slope, whereas samples with low thermal conductivity exhibit a higher slope as illustrated in Figure 21 [141]. Therefore, The TLS-100 machine will provide accurate and reliable data on the thermal conductivity of the soil samples, which is an essential parameter for assessing the thermal performance of stabilized earth in Hejaz region.

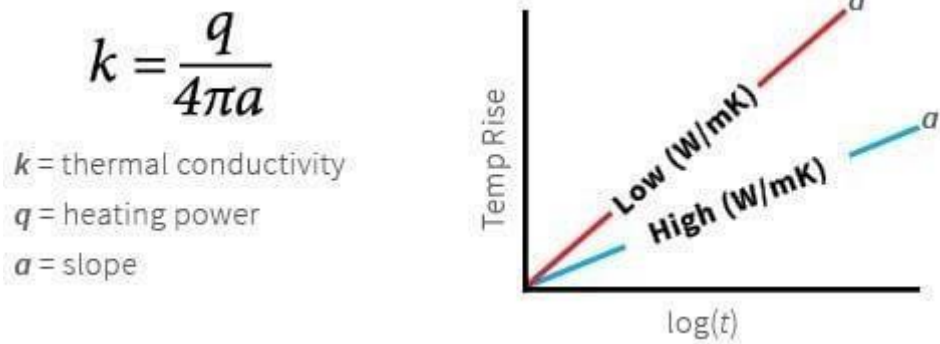


Figure 21. Calculation of Thermal Conductivity (k) Using the Slope (a) from Temperature Rise vs. Logarithm of Time Plot [141].

3.6 Sound Absorption Coefficient and Impedance Testing

The BSWA SW series Impedance Tubes, detailed in Table 3, play a critical role in this research by enabling the precise measurement of sound absorption coefficient and impedance of stabilized earth structures as per ISO and ASTM standards [142]. This equipment facilitates a robust evaluation of the acoustic performance of the materials used, crucial for assessing the effectiveness of sustainable construction practices in the Hejaz region. By employing this state-of-the-art apparatus, the study harnesses advanced techniques to derive significant trends and patterns through statistical analysis. This analysis helps to understand the correlation between various measured parameters and the acoustic efficiency of environmentally friendly stabilized earth materials, thereby contributing to the broader application of sustainable building technologies in the region.

Table 3 SPECIFICATION BSWA IMPEDANCE. Source:[103]

SPECIFICATION BSWA IMPEDANCE TUBE USED IN THIS STUDY	
Model	SW422
Value to be Measured	Sound Absorption Coefficient (α) and Transmission Loss (TL)
Standard	Sound Absorption Standard: GB/T-18696, 2-2002, ISO10534-2, 1998; ASTM E1050-08
Frequency Range (Hz)	63 ~ 1800 800 ~ 6300
Inner Diameter of Testing Tube	100 mm 30 mm
Loudspeaker	4 “in diameter, 20 Watts, 8 Ohm
OPTIONAL ITEMS	
1/4” Microphone	MPA416
Data Acquisition Card	MC3242
Power Amplifier	PA50
Software	VA-Lab4 Basic + VA-Lab4 IMP-AT

3.6.1 *Material Testing System BSWA Impedance Tube*

The BSWA VA-Lab software is equipped with the Impedance Tube Module (VALab IMP), which is used for measuring sound absorption (Figure 22) and sound insulation of BSWA SW series impedance tubes (Figure 24). Figure 23 depicts the unstabilized and stabilized Hejaz soil samples, methodically arranged alongside the BSWA Impedance Tube within a meticulously controlled experimental environment.

The software requires the use of BSWA MC3022, MC3522, MC3242, or MC3642 hardware for data acquisition and analysis [143]. The VA-Lab IMP supports two methods for determining the absorption coefficients of materials:

1. The Standing Wave Ratio Method (ISO10534-1)
2. The Transfer Function Method (ISO10534-2, ASTM E1050-08, and ASTM E2611-09)

Furthermore, measurements of sound transmission loss using the four-microphone technique are possible with the VA-Lab IMP.

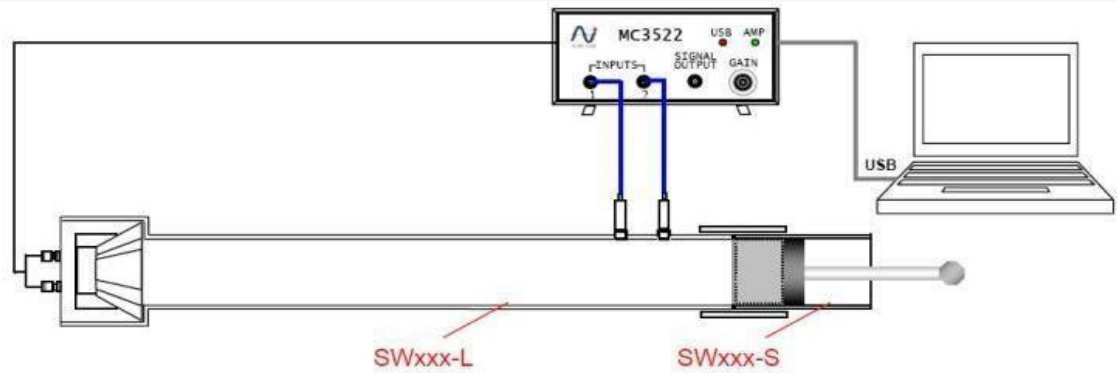


Figure 22. An Impedance Tube System for measuring sound absorption.

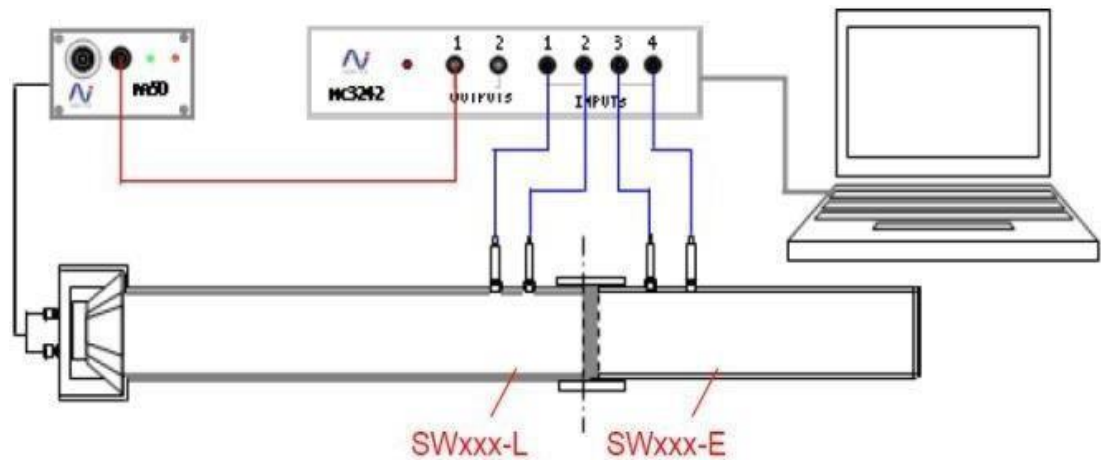


Figure 24. Impedance Tube System for Measuring Transmission Loss



Figure 23. unstabilized and stabilized Hejaz soil specimens alongside their corresponding measurement of BSWA Impedance

3.7 Data Analysis and Visualization

Data from the acoustic measurements were analyzed to determine the AC across different frequencies and visualized using Python's powerful libraries to create colormaps that represent the soil's absorption properties effectively. Similarly, thermal conductivity data were processed to evaluate the stabilization's effect over time. Both sets of data were illustrated in detailed flowcharts (Figure X for acoustic and Figure 4 for thermal), providing a visual and systematic overview of the methodologies from soil sample collection to final data analysis.

3.8 Acoustical Indicators of Sound Absorption

Acoustical indicators are essential metrics employed to assess the sound absorption properties of materials or structures. The fundamental indicator, the sound absorption coefficient (Alpha), quantifies the proportion of incident sound energy absorbed by a material rather than reflected. This coefficient ranges from 0 (no absorption) to 1.00 (total absorption) and is contingent upon frequency, angle of incidence, and various material characteristics.

Normal incident sound absorption (α_n) is a specific measure of sound absorption when the sound wave strikes a material perpendicularly. This metric is pivotal in determining a material's efficacy in absorbing sound when positioned directly opposite the sound source. Impedance tubes, adhering to standards such as ISO-10534-2:2023 [144] and ASTM-E1050 [145], are widely employed to measure α_n and acoustic impedance based on the two-microphone transfer-function method. Conversely, the random incidence sound absorption coefficient (α_r or **SAC**) quantifies sound absorption while accounting for sound waves incident at various angles. This measurement simulates more realistic conditions where sound originates from multiple directions. Consequently, α_r or **SAC** offers a more

practical understanding of a material's sound absorption capabilities in diverse situations. However, measuring α_r or **SAC** for construction materials is typically costly and necessitates the use of a standard reverberation (ASTM-C423, ISO-354 [146], [147]).

The weighted sound absorption coefficient (α_w) further simplifies α_r data by expressing it as a single numerical value obtained through comparison with a set of reference curves. Specifically, ISO-11654 outlines the procedure for determining α_w , which involves converting eighteen 1/3 octave values into six 1/1 octave values (250 - 4000 Hz) of practical sound absorption coefficient (α_p) and comparing them to the standard reference curves [148]. Deviations exceeding 0.25 between the measured curve and the reference curve are denoted by shape indicators L, M, or H, corresponding to specific frequency ranges. ISO 11654 is also utilized to classify sound absorption materials into categories or classes ranging from A (highest absorption) to E (lowest absorption) based on their measured absorption curves as shown in Table 4.

Table 4. Classification of materials by sound absorption coefficients and Noise Reduction Coefficient (NRC) values.

Sound Absorption Class	α_w	Absorption Class Interpretation	NRC, Equivalent
Class A	0.90 – 1.00	Extremely Absorbing	0.75 or more
Class B	0.80 – 0.85		
Class C	0.60 – 0.75	Highly Absorbing	0.50 – 0.70
Class D	0.30 – 0.55	Absorbing	
Class E	0.15 – 0.25	Hardly Absorbing	0.25 – 0.45
Not Classified	0.00 – 0.10	Reflecting	0.2 or less

While these acoustical indicators play a crucial role in assisting designers and engineers in optimizing the sound absorption properties of materials and structures, it is important to acknowledge that a single-number rating inherently oversimplifies the complex absorption behavior. Sound absorbers with vastly different absorption spectra can exhibit identical

single-number values, potentially leading to the selection of unsuitable materials for specific acoustic conditions. Therefore, a comprehensive understanding of a material's absorption characteristics across the entire frequency range is paramount for achieving optimal acoustic design. It is worth mentioning that in the current investigation, (α_w) values and classes were not determined because sound absorption measurements were limited to lower and mid frequencies. Therefore, the related classes shown in the above list were not applicable; however, measured (α_n) and (α_p) values were evaluated and described using similar terms, ranges, and interpretations (e.g., extremely-, highly-, hardly-absorbing, etc.).

3.9 Comparative Analysis of Cement, Lime, and CKD Stabilized Soils: Thermal and Acoustic Characteristics

3.9.1 Data Processing for Thermal Conductivity

The data processing involved collecting thermal conductivity measurements for Soil A and Soil B stabilized with varying percentages of OPC, Lime, and CKD (0%, 2.5%, 5%, 7.5%, 10%, 12.5%, and 15%) over four different weeks. These measurements were then averaged to obtain representative values for each stabilizer percentage, providing a clear indication of how thermal conductivity evolved with increased stabilizer content.

Specifically, the thermal conductivity values for each percentage of stabilizer were averaged over the four-week period to reflect overall performance trends rather than variations specific to any single week. This approach allowed for a more robust analysis of the thermal characteristics, ensuring that the data captured the general behavior of the soils when stabilized with different percentages of cement, lime, and CKD.

3.9.2 Data Processing for Acoustic Properties

For the acoustic properties, the study focused on the absorption coefficients at three key frequency ranges: 250 Hz, 500 Hz, and 1000 Hz. The raw acoustic data were collected at various frequencies within these ranges and then averaged to produce a single representative value per frequency band. Specifically, frequencies were grouped as follows: 200-315 Hz averaged 250 Hz, 400-630 Hz averaged 500 Hz, and 800-1250 Hz averaged as 1000 Hz. This averaging process ensured that the data captured the general acoustic behavior across each frequency range, facilitating a comprehensive comparison of the acoustic absorption properties for each soil and stabilizer combination. By averaging the absorption coefficients within each frequency range, the study was able to present a clear and consistent picture of the acoustic performance of the stabilized soils, allowing for meaningful comparisons between different stabilizer percentages and soil types.

CHAPTER 4

RESULTS AND DISCUSSION

The study offers a comprehensive soil characterization, detailing the significant differences between Soil A and Soil B in terms of their chemical compositions, particle size distributions, moisture retention capacities, and other physical properties. Soil A, identified as a silty clay (CL), has higher fine content and water retention capabilities, while Soil B, classified as a clayey silt (ML), exhibits different chemical reactivity. Additionally, the thermal and acoustic properties of these soils are examined to understand their behavior under various stabilization treatments. These distinctions are critical for optimizing soil stabilization methods for sustainable construction. This part sets the stage by offering a baseline understanding of each soil type's capacity for moisture content, maximum dry density, and plasticity, which are crucial for predicting their behavior under different environmental conditions. Following the characterization, the discussion transitions into the Chemical and Physical Properties in Soil Stabilization. In this examination, the effects of various stabilizers such as lime, cement, and cement kiln dust (CKD) on the soils are scrutinized. This section evaluates how each stabilizer alters the soil's chemical composition and physical properties, thereby influencing their suitability for different construction applications.

The Thermal Properties of Untreated Hejaz Soils section provides insights into the baseline thermal conductivity of the soils, crucial for understanding how they respond to environmental changes and their potential applications in thermal insulation. The subsequent parts, Impact of Stabilization on Soil Thermal Properties and Comparative Analysis of Stabilizer Agents' Thermal Effects, delve deeper into how different concentrations and types of soil stabilizers affect the thermal behaviors of Soil A and Soil B over time. These discussions are critical for determining the optimal soil treatments for increasing their thermal performance, particularly in arid environments like Hejaz.

The final sections of the study focus on the acoustic properties of the soils, exploring how untreated and treated soils perform in terms of sound absorption across a range of frequencies. This part is vital for applications where noise reduction is crucial, offering guidance on selecting the right soil and treatment method to meet specific acoustic needs.

4.1 Hejaz Soil Characterization for Sustainable Construction

This study investigates the thermal and acoustic properties of two distinct Hejaz soils, designated as Soil A and Soil B. Soil A. The study's results and discussions are organized into six sections: Soil Characterization Insights, Chemical and Physical Properties in Soil Stabilization. This approach allows us to elucidate the most effective soil stabilization techniques for optimal thermal and acoustic Characteristics in sustainable construction and environmental management within the Hejaz region.

4.1.1 Soil Characterization Insights

The Characterization Properties of Soils unveils significant contrasts between Soil A and Soil B as illustrated in Table 5. Soil A, with a fine content of 95.3% and a silty clay

composition (CL), suggests a denser structure with higher water retention but lower permeability, as opposed to Soil B's 92.5% fine content and clayey silt composition (ML), indicating a balance between moisture retention and drainage. The contrast extends to their moisture and density properties, where Soil A exhibits lower optimum moisture content (18.5%) and higher maximum dry density (20.69 KN/m³) compared to Soil B's 23% and 15.89 KN/m³, respectively, impacting soil compaction and strength. Moreover, the plasticity properties, with both soils sharing the same liquid limit (41%) but differing in plastic limit and plasticity index, highlight Soil A's higher shrink-swell potential and Soil B's relative stability.

Table 5. Comprehensive Characterization Properties of Soils

Property	Soil B	Soil A
Fine Content (%)	92.5	95.3
Sand Content (%)	7.4	4.9
Unified Soil Classification	ML (Clayey silt)	CL (Silty clay)
Optimum Moisture Content (%)	23	18.5
Maximum Dry Density (KN/m ³)	15.89	20.69
Liquid Limit (%)	41	41
Plastic Limit (%)	26	18
Plasticity Index (%)	17	23
pH (With Water)	8.66	7.59
pH (With Calcium)	8.13	4.57
Conductivity (mS/cm)	7.911	16.96

pH variations further delineate these soils; Soil A shows significant reactivity to acidic conditions, dropping from a pH of 7.59 (with water) to 4.57 (with calcium), while Soil B maintains a more stable alkaline nature (8.66 with water, 8.13 with calcium). These pH changes are vital for nutrient availability and soil fertility. Additionally, Soil A's higher conductivity (16.96 mS/cm) indicates a greater salt concentration, potentially impacting plant growth and soil health, compared to Soil B's lower conductivity (7.911 mS/cm).

While this study primarily focuses on thermal characteristics in soil stabilization,

understanding these soil properties is indispensable for generalizing the findings to broader construction practices. The distinctions between Soil A and B in terms of physical composition, moisture content, density, plasticity, pH response, and conductivity offer valuable insights. Soil A, suited for scenarios requiring higher water retention, demands careful management due to its acidification potential and higher plasticity. In contrast, Soil B, with its higher sand content and stable pH, emerges as a more favorable candidate for construction and less intensive agricultural applications.

4.1.2 Chemical and Physical Properties in Soil Stabilization

Chemical Composition: The chemical analysis reveals distinct characteristics for each stabilizer. Lime is exceptionally high in Calcium (Ca) content at 98.09%, significantly higher than Cement and CKD, suggesting its strong potential for altering soil pH and enhancing binding properties. In contrast, Cement, with a Si content of 10.52% and Fe content of 5.45%, indicates a likelihood of improved strength and durability in stabilized soils. CKD, with a balanced composition of 79.33% Ca, 3.53% Si, and 3.86% Fe, presents as a versatile stabilizer, potentially imparting both strength and binding properties to the soils as shown Table 6.

Table 6. Chemical Composition of CKD, Cement, and Lime

Material	Ca (%)	Si (%)	Al (%)	Mg (%)	S (%)	Fe (%)
CKD	79.33	3.53	1.78	0.4	2.05	3.86
Cement	75.93	10.52	2.79	0.57	2.67	5.45
Lime	98.09	0.33	0.41	0.23	0.16	0.25

4.1.3 Physical Properties:

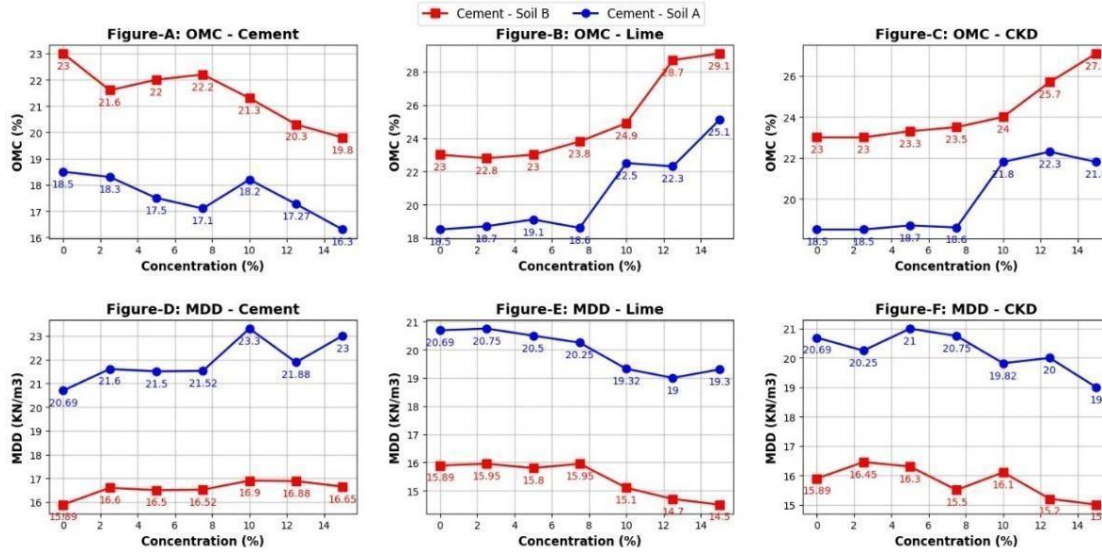


Figure 25. Impact of Stabilizers on Geotechnical Properties of Soil-A and Soil-B, Detailed in OMC and MDD Metrics

Analyzing the physical properties, as presented in (Figures 25) A, B, and C for Optimum Moisture Content (OMC), and Figures 16 D, E, and F for Maximum Dry Density (MDD).

For OMC, there is a general decrease with increasing stabilizer concentration in Soil-A for both Cement and CKD, as seen in Figures 14 A and C. This reduction suggests a denser soil structure with less water-holding capacity. Conversely, Lime leads to an increase in OMC in both soils (Figure 25), indicative of enhanced moisture retention. MDD trends, as illustrated in Figure 25 D, E, and F, show that Cement and CKD contribute to increased soil density, with Soil-A reaching a peak MDD of 23 KN/m³ at 15% Cement concentration. However, Lime displays a decreasing trend in MDD with increasing concentration in Soil-A, hinting at a potential weakening effect at higher concentrations.

The study highlights the critical role of stabilizers' chemical composition in influencing their interaction with soils. While CKD and Cement generally enhance soil density and reduce moisture content, Lime shows an increase in moisture retention, affecting soil compaction differently. Selecting the appropriate stabilizer and concentration is crucial,

depending on the desired soil property modifications for specific sustainable construction applications. The study highlights the critical role of stabilizers' chemical composition in influencing their interaction with soils. While CKD and Cement generally enhance soil density and reduce moisture content, Lime shows an increase in moisture retention, affecting soil compaction differently. Selecting the appropriate stabilizer and concentration is crucial, depending on the desired soil property modifications for specific sustainable construction applications.

4.2 Thermal Properties of Untreated Hejaz Soils

In the study of Hejaz soils, Soil A and Soil B were evaluated to determine their baseline thermal conductivity. Initially, in airtight conditions at week four, Soil A's thermal conductivity was 0.251 W/m·K, and Soil B's was slightly higher at 0.271 W/m·K. This initial data, critical for benchmarking subsequent changes, was recorded in Table 7.

Table 7. Baseline Thermal Properties of Untreated Hejaz Soils

Soil Type	Condition	Week	Thermal Conductivity (K) [W/m·K]
Soil A	Airtight Container	Week 4	0.251
	Sun Exposure	Week 6	0.198
		Week 8	0.175
		Week 12	0.154
Soil B	Airtight Container	Week 4	0.271
	Sun Exposure	Week 6	0.231
		Week 8	0.198
		Week 12	0.175

As the study progressed, the soil was exposed to sun, and notable changes in their thermal conductivity were observed. By the six-week mark, Soil A's conductivity decreased by 21.1% to 0.198 W/m·K, and further decreased by 30.3% to 0.175 W/m·K at eight weeks, and eventually by 38.6% to 0.154 W/m·K at twelve weeks. In a similar pattern, Soil B's thermal conductivity reduced by 14.8% to 0.231 W/m·K at six weeks, by 27% to 0.198 W/m·K at eight weeks, and finally by 35.4% to 0.175 W/m·K at twelve weeks. This consistent decrease in thermal conductivity over time for both soil types suggest a reduction in their heat conduction capability, likely due to structural alterations from sustained sun exposure. These findings, as illustrated in Figure 26, underscore the dynamic nature of soil properties in response to environmental factors. The decision to conclude this measurement by the end of week 12 was taken balancing the need to observe significant changes in thermal properties against the practicalities of maintaining a controlled study environment.

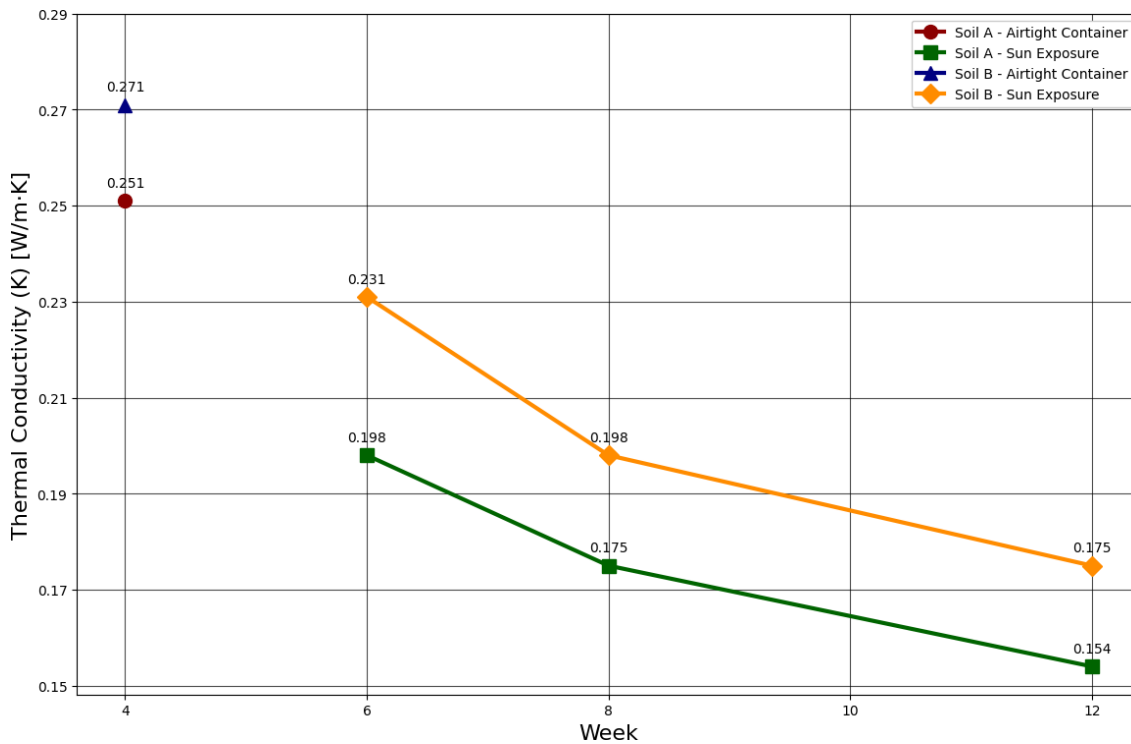


Figure 26. Initial Thermal Conductivity Benchmarks for Hejaz Soils

It is balanced that was adequate to capture the impact of environmental exposure on the soil's thermal conductivity while minimizing the introduction of external variables.

The findings from this time-bound study provide a solid foundation for future research into soil stabilization and its impact on thermal properties. Furthermore, these results underscore the potential of Hejaz soils as sustainable building materials. The observed reduction in thermal conductivity, particularly under sun exposure, points to their applicability in roles that benefit from low heat transfer, such as thermal insulation. With proper treatment and stabilization, these soils could be optimized for specific construction needs, enhancing their suitability as sustainable building materials in arid regions like the Hejaz.

4.3 Impact of Stabilization on Soil Thermal Properties

In this section, focuses on the thermal effects of different stabilizers on Hejaz soils, as detailed in Table 8. The analysis encompasses the impact of cement, lime, and cement kiln dust (CKD) on the thermal properties of two distinct soil types, Soil-A and Soil-B. The study specifically discuss the following aspects: Cement's Effect on Hejaz Soil from a Thermal Perspective for both Soil-A and Soil-B, Lime's Influence on the Thermal Properties of Hejaz Soil, and the CKD Effect on the Thermal Conductivity of Soil-A and soil-B. Additionally, a Comparative Analysis of Stabilizer Agents' Thermal Effects on Hejaz Soils is presented, providing a comprehensive understanding of how each stabilizer modifies the soil's thermal behavior, crucial for sustainable building practices in arid environments.

Table 8. Cement, Lime, and CKD Influence on Thermal Conductivity at Different Time Intervals of Stabilized soil

Week	% of Added Stabilizers	Thermal Conductivity (K)					
		Soil-A Cement	Soil-B Cement	Soil-A Lime	Soil-B Lime	Soil-A CKD	Soil-B CKD
Plastic Wrap	Week-4	0%	0.251	0.271	0.251	0.271	0.251
		2.50%	0.528	0.552	0.555	0.463	0.427
		5%	0.596	0.467	0.543	0.466	0.468
		7.5%	0.506	0.452	0.52	0.459	0.507
		10%	0.435	0.432	0.512	0.416	0.517
		12.5%	0.664	0.42	0.511	0.431	0.553
		15%	0.447	0.404	0.53	0.441	0.788
Sun Exposed	Week-6	0%	0.198	0.231	0.198	0.231	0.198
		2.50%	0.443	0.334	0.525	0.306	0.257
		5%	0.413	0.31	0.485	0.241	0.358
		7.5%	0.305	0.228	0.457	0.311	0.377
		10%	0.29	0.308	0.431	0.221	0.382
		12.5%	0.361	0.332	0.416	0.333	0.364
		15%	0.318	0.309	0.386	0.288	0.425
	Week-8	0%	0.175	0.198	0.175	0.198	0.175
		2.50%	0.43	0.327	0.52	0.312	0.253
		5%	0.415	0.322	0.488	0.23	0.368
		7.5%	0.274	0.234	0.434	0.296	0.353
		10%	0.302	0.299	0.466	0.193	0.372
		12.5%	0.364	0.304	0.353	0.307	0.41
		15%	0.262	0.3	0.397	0.307	0.363
	Week-12	0%	0.154	0.175	0.154	0.175	0.154
		2.50%	0.49	0.342	0.52	0.307	0.243
		5%	0.396	0.309	0.465	0.219	0.343
		7.5%	0.267	0.227	0.464	0.225	0.362
		10%	0.291	0.319	0.446	0.214	0.376
		12.5%	0.361	0.302	0.413	0.309	0.419
		15%	0.33	0.308	0.379	0.271	0.356

4.4 Cement's Effect on Hejaz Soil: A Thermal Perspective

In evaluating the thermal conductivity properties of Hejaz soil modified with varying percentages of cement, an in-depth examination of the data from weeks 4 to 12, as depicted in Figure 27A to 6D, and Table 8, offers significant insights.

Initially, in week 4 (Figure 27), under airtight conditions, the untreated Hejaz soil exhibited a baseline thermal conductivity (K) of $0.251 \text{ W/(m}\cdot\text{K)}$. The introduction of cement notably increases this thermal conductivity. For instance, a 2.5% addition of cement resulted in a 110.36% increase in K , elevating it to $0.528 \text{ W/(m}\cdot\text{K)}$. This increase can be attributed to the cement hydration process, which over time leads to a more compact cement paste cohesion structure [149], thereby increasing thermal conductivity. Furthermore, the calcium-silicate-hydrates (C–S–H) formed in the hydrated Portland cement contribute to this behavior, exhibiting a dynamic mechanical behavior [150], that may enhance soil's thermal properties. Further analysis reveals that the influence of sunlight exposure on the soil's thermal conductivity is significant. In week 6 (Figure 27B), soils with cement content, particularly at lower concentrations such as 2.5% and 5%, experienced a decrease in K from their peak values in week 5. The 2.5% cement sample saw a 16.1% reduction in K , emphasizing the vulnerability of thermal conductivity to environmental conditions. This decrease under sunlight exposure can be attributed to processes such as elastic mismatch, particle-particle friction, and micro-cracking, which are likely to occur in the soil [151], leading to a reduction in thermal conductivity.

By week 12, the thermal conductivity of the soil with a 15% cement concentration was reduced by 26.18%, a lesser decrease compared to the untreated soil, which experienced a 38.65% reduction in K . This lesser decrease in thermal conductivity in cement-treated soil over time can be attributed to the thermal degradation of hydration products like C–S–H and calcium hydroxide (CH) in the cement paste. Such degradation can induce micro-cracking and pore-coarsening, yet it imparts a degree of resilience to the soil structure, maintaining its integrity against environmental stresses [152].

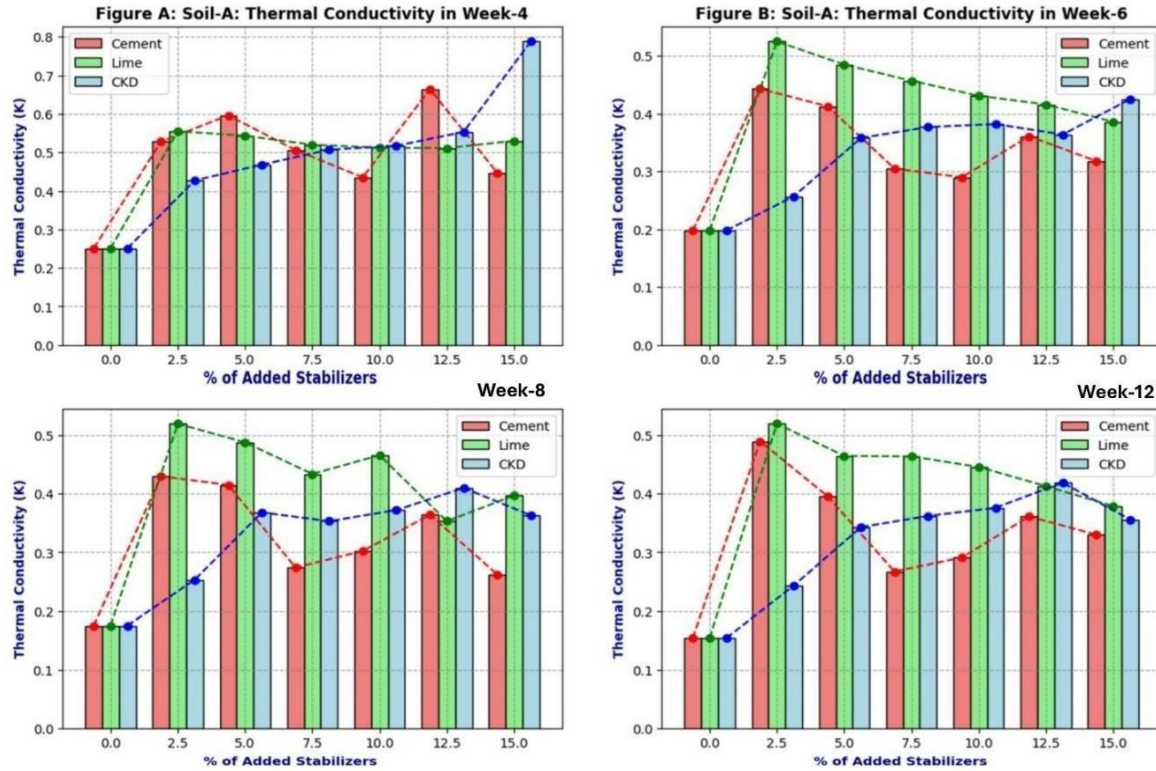


Figure 27. Week-wise Thermal Conductivity Trends in Soil-As Cement, Lime, and CKD Stabilized Soils.

The data collectively indicate that the addition of cement to Hejaz soil significantly enhances its thermal conductivity, particularly at higher concentrations. However, this enhancement is subject to environmental factors, such as sunlight exposure, which can inversely affect the thermal conductivity over time. The results suggest that while cement stabilization can improve the thermal performance of Hejaz soil, the long-term stability of these improvements under varying environmental conditions remains a critical consideration. These findings have significant implications for the application of cement-stabilized Hejaz soil in construction and thermal management systems, particularly in contexts where environmental exposure is a critical factor.

4.5 lime's Effect on Hejaz Soil-A Thermal

The experimental investigation into the thermal conductivity (K) of Hejaz soil, modified with varying concentrations of lime and subjected to environmental conditions over a 12-week period, presents intriguing insights into the material's thermal behavior. This study's comprehensive data, depicted in Table 8 and Figure 27A-D, not only demonstrates the immediate impacts of lime addition but also reveals the longer-term thermal dynamics under sun exposure.

Initially, in Week 4 (Figure 27A), the introduction of lime into the soil exhibited a marked influence on its thermal properties. The baseline K for untreated soil stood at 0.251 W/(m·K). The addition of 2.5% lime elevated K significantly to 0.555 W/(m·K), registering a substantial increase of 121.12%. This pronounced increase can be attributed to the changes in the microstructure and water retention properties of the soil [153], as lime treatment leads to a denser soil matrix with reduced porosity, thereby improving thermal conductivity. Incremental increases in lime content to 5% and 7.5% resulted in K values of 0.543 and 0.52 W/(m·K), respectively. These figures, while still representing considerable improvements from the baseline, suggest a diminishing return with higher lime concentrations. Further increases to 10%, 12.5%, and 15% lime yielded K values of 0.512, 0.511, and 0.53 W/(m·K), respectively, indicating a leveling off in the effectiveness of lime as a thermal conductivity enhancer at these higher concentrations.

The dynamics shifted notably in Week 6 (Figure 27B) under sun exposure. The non-stabilized soil's K decreased to 0.198 W/(m·K), a 21.12% reduction from the baseline. In contrast, lime-treated soils demonstrated varying degrees of resilience. The 2.5% lime mixture maintained a high K of 0.525 W/(m·K), a 109.16% increase from the baseline, affirming the stabilizing effect of lime at this concentration. However, as lime content rose,

the rate of K reduction became more pronounced. This trend suggested that while lime is effective in increasing soil's thermal conductivity, its protective capacity against environmental degradation is not absolute and varies with concentration. The durability of lime-stabilized soils and the pozzolanic reaction's impact on soil properties play a crucial role in these observations [154].

By Week 8 (Figure 27C), the untreated soil experienced a further decrease in K to $0.175 \text{ W/(m}\cdot\text{K)}$, a 30.28% reduction from the initial baseline. Lime-stabilized soils, particularly at higher concentrations, continued to display a decrease in K but remained notably above the untreated baseline. This trend is consistent with the geotechnical behavior and physico-chemical changes observed in lime-treated soils [155], where the addition of lime alters the soil's properties in a way that can affect its thermal conductivity. The final observations at Week 12 (Figure 27D) solidified these findings, with lime-stabilized soils exhibiting consistently higher K values, highlighting the nuanced and concentration-dependent effectiveness of lime in improving and sustaining K under prolonged sun exposure.

These observations indicate that the addition of lime to Hejaz soil significantly increases its thermal conductivity, particularly at lower concentrations like 2.5%, which maintained the most considerable improvements throughout the study. However, the effectiveness of lime in improving and sustaining K under prolonged sun exposure is nuanced and concentration-dependent, highlighting the need for a balanced approach in the application of lime for soil stabilization in thermally challenging environments.

4.6 CKD Effect on Hejaz Soil-A Thermal

The experimental investigation into the thermal conductivity of Hejaz soil amended with varying concentrations of Cement Kiln Dust (CKD) yielded significant insights, as detailed in the data and corresponding figures. In the initial phase of the study (Week 4, Figure 27A), the introduction of CKD to the soil exhibited a pronounced effect on its thermal properties. For instance, a mere 2.5% addition of CKD elevated the thermal conductivity (K) value from 0.251 to 0.427 W/(m·K), representing a substantial increase of 70.12%. This increase in thermal conductivity is attributed to the pozzolanic reaction of CKD in the soil, which leads to increased density and improved soil structure, as evidenced by the significant increase in density, CBR, and UCS observed in CKD-stabilized soils [156]. This pozzolanic reaction, crucial for soil stabilization, results in the bonding of dispersed soil particles, increasing the soil's thermal properties [157].

As the CKD content increased to higher percentages, the K values continued to rise, reaching a peak at 15% CKD with a 213.55% increase. This exponential growth in thermal conductivity is consistent with the findings on the strength improvement of CKD-stabilized expansive clayey soil, highlighting CKD's role in increasing soil stabilization [158]. The study on analytical tests evaluating pozzolanic reactions in lime-stabilized soils, although focused on lime, provides further insights into the quantification of pozzolanic products [159], which are relevant for understanding CKD's effects in soil [4].

Under sun exposure in Week 6 (Figure 27B), all samples, including those treated with CKD, experienced a decrease in thermal conductivity. However, the CKD-treated soils still demonstrated superior performance compared to untreated soil, indicating CKD's effectiveness in increasing and maintaining thermal conductivity under varying environmental stressors. This sustained performance, despite environmental challenges,

aligns with the findings from the study on the sustainable utilization of CKD for improving collapsible soil [160], which sheds light on the mechanisms by which CKD increases soil properties.

These findings imply that adding CKD to Hejaz soil greatly increases its thermal conductivity, with the most significant improvements correlated with higher CKD percentages. Additionally, CKD-treated soils exhibit a degree of thermal resilience against external variables, especially under prolonged sun exposure. The study underscores CKD's potential as a long-term soil stabilizer that can increase thermal characteristics and provide a reliable solution for engineering applications sensitive to environmental conditions.

4.7 Cement's Effect on Hejaz Soil-B Thermal

The experimental investigation into the thermal conductivity of Hejaz Soil-B, stabilized with varying percentages of cement, reveals significant insights into soil-cement interactions. Initially, at week 4 (Figure 28), the addition of 2.5% cement resulted in a dramatic increase in thermal conductivity, registering a 103.7% surge to 0.552 W/m·K. This marked elevation indicates an increased thermal pathway formation, likely due to the filler effect of cement particles within the soil matrix. Research on the thermal conductivity of cement paste containing various fillers, such as waste glass powder, metakaolin, and

limestone [161], provides insights into how the filler effect of cement influences thermal properties, supporting the observations.

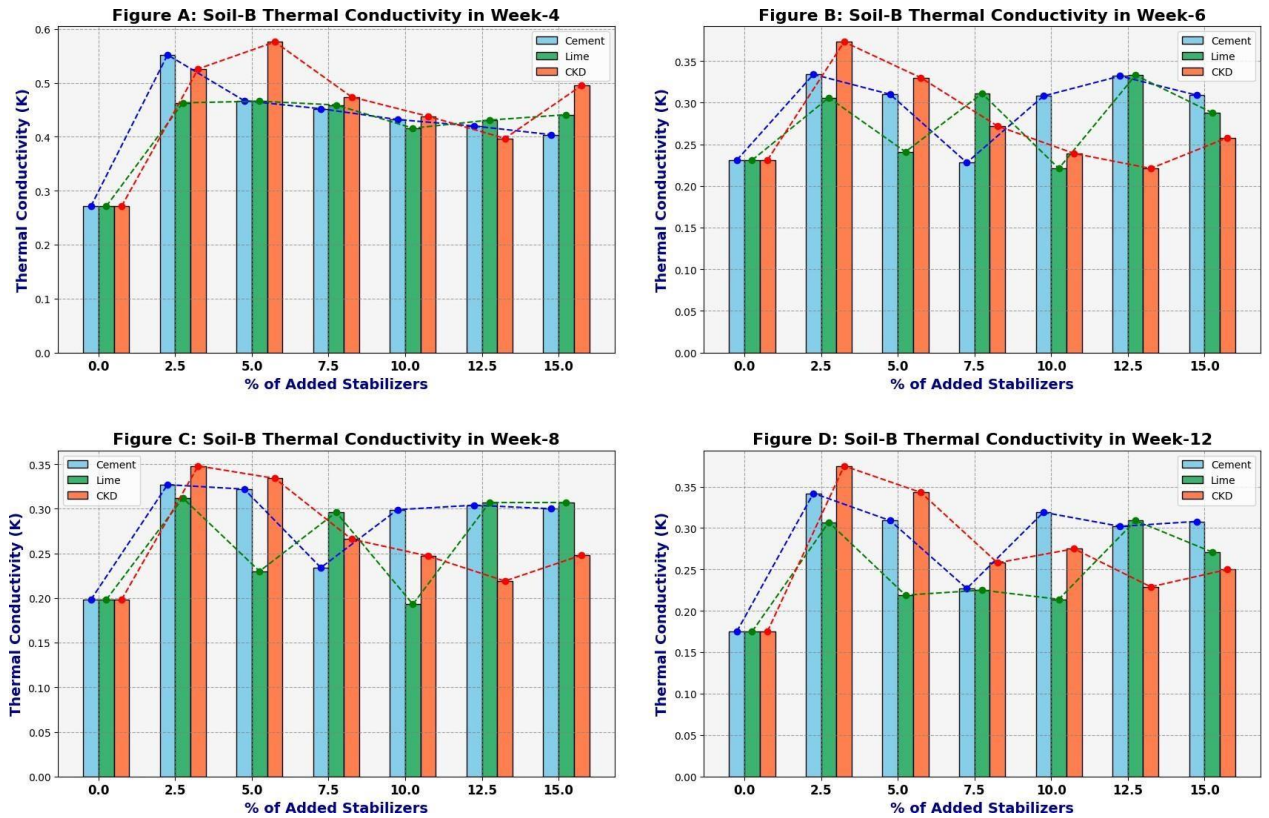


Figure 28. Progressive Changes in Thermal Conductivity of Soil-A with Cement, Lime, and CKD Stabilization Across Weeks.

Further cement incorporation to 5% continues this upward trend, albeit at a reduced rate, with a 72.3% increase in conductivity to 0.467 W/m·K. However, as the cement content escalates to 7.5% and beyond, the incremental gains in thermal conductivity diminish. For instance, at 10% cement, the conductivity peaks at 0.432 W/m·K, followed by a gradual decline to 0.404 W/m·K at 15% cement content. This pattern suggests a saturation point beyond which additional cement does not proportionally increase the soil's thermal transfer capabilities.

The study's progression into weeks 6 and 8, under sun exposure conditions, introduces another layer of complexity (Figure 28B and C). In week 6, the control soil (0% cement)

exhibited a decrease in thermal conductivity by 14.8% to 0.231 W/m·K, highlighting the soil's inherent vulnerability to external thermal influences. Conversely, soil samples with a 5% cement admixture displayed a notable increase in thermal conductivity by 32.5% compared to the baseline, indicating a bolstered thermal resilience attributable to cement addition. Studies on the thermal conductivity of thermal insulation cement in geothermal wells offer relevant information on how cement's properties [162], including its role affecting thermal conductivity, further elucidating the resilience observed in the cement-treated samples.

By week 8, while overall thermal conductivity decreases under sustained sun exposure, soils with higher cement content (e.g., 10% and above) show a relatively smaller decrement in conductivity. This observation suggests that while cement increases initial thermal conductivity, its long-term effectiveness in maintaining these properties under continuous thermal stress varies depending on the concentration.

By week 12 (Figure 28D), a clear trend emerges, with a consistent decrease in thermal conductivity across all cement percentages from their respective peaks in earlier weeks. For instance, at 7.5% cement, conductivity reduces to 0.227 W/m·K, further decreasing to 0.308 W/m·K at 15% cement. This trend indicates a dynamic interplay between cement content, soil composition, and thermal properties over time. The data, as systematically presented in Table 8, suggest an optimal range of cement content that maximizes thermal conductivity. This finding is crucial for determining the most effective cement content for soil stabilization in terms of thermal management.

This finding is pivotal for applications where temperature control is essential. The study underscores the necessity for a nuanced approach in soil-cement mixture design,

taking into consideration the long-term thermal behavior and environmental impacts to achieve sustainable and efficient construction materials.

4.8 lime's Effect on Hejaz Soil-B Thermal

In the realm of soil stabilization, the addition of lime to Hejaz soil-B presents a complex interaction between the stabilizer concentration and the soil's thermal properties. The initial phase of this study, as depicted in Figure 28A, focuses on the increasement of thermal conductivity (K) with varying lime concentrations. At Week 4, the addition of lime resulted in a significant increase in K across all concentrations. Notably, a 5% lime addition resulted in a high thermal conductivity increase of 71.96% increase in K. This significant increase in thermal conductivity can be attributed to the clay-lime physicochemical reactions, which lead to a denser soil structure and reduced porosity, enhancing heat transfer. These reactions, crucial for understanding the increase in thermal conductivity due to lime addition, have been examined in studies focusing on the geotechnical improvement of clay soils using lime [163].

Moving into the exposure phase, it was observed that the thermal conductivity trend reverses with sun exposure in Figure 28B (Week 6) and 7C (Week 8). In Week 6, the K value of the control sample (0% lime) decreased by 14.76%, whereas the K values of the lime-treated samples decreased at all concentrations. For example, K dropped by 48.28% at 5% lime and by 46.88% and 34.69% at 10% and 15% lime, respectively. This phenomenon suggests that the initial positive effects of lime stabilization may be diminished with prolonged exposure to solar radiation. Research on the short- and long-term effects of lime and gypsum applications on acid soils in a water-limited environment has shown that lime with gypsum can reduce soil Al more deeply than lime alone over

extended periods [164]. This reduction in Al levels, indicative of changes in soil chemical properties, could be linked to the observed decrease in thermal conductivity under sun exposure. By week 12 (Figure 28D), a clear trend emerges, with a consistent decrease in thermal conductivity across all lime percentages from their respective peaks in earlier weeks. For instance, at 7.5% lime, conductivity reduces to 0.227 W/m·K, further decreasing to 0.308 W/m·K at 15% lime. This phase of the study illustrates the temporal variability and the influence of environmental conditions on the thermal properties of lime-treated soil. It emphasizes the need for a meticulous balance between lime concentration and environmental exposure to harness the full potential of lime as a sustainable stabilizing agent in soil engineering. This study, through its comprehensive analysis of lime-soil interactions over time, provides a foundational understanding for optimizing lime stabilization methods for desired thermal performance in geotechnical applications.

4.9 CKD's Effect on Hejaz Soil-B Thermal

The exploration into the thermal properties of Soil-B modified with varying percentages of Cement Kiln Dust (CKD) provides a comprehensive understanding of the material's thermal conductivity behavior under different conditions. Analyzing the data from Table 11 and correlating it with the observations from Figure 28A-D, a nuanced picture emerges, highlighting the significant role of CKD concentration in altering the thermal dynamics of the soil.

Initially, Figure 28A (Week-4) establishes a baseline for the thermal conductivity of Soil-B without any CKD, at 0.271 W/m·K. The introduction of 2.5% CKD leads to a notable increase in thermal conductivity to 0.526 W/m·K, illustrating an approximately 94% increase. This trend continues with 5% CKD, where conductivity reaches 0.576

W/m·K, a 112.5% increase from the baseline. However, at higher CKD concentrations, the rate of increase in thermal conductivity begins to decline; with 7.5% CKD, conductivity is 0.474 W/m·K (a 74.9% increase), and with 10% and 12.5% CKD, it is 0.438 W/m·K and 0.397 W/m·K, reflecting increases of 61.6% and 46.5%, respectively. Remarkably, at 15% CKD, a reversal of this trend is observed, with conductivity increasing to 0.495 W/m·K, indicating an 82.7% increase from the baseline. This increase in thermal conductivity can be related to the effects of CKD, a pozzolanic material similar to fly ash, as explored in studies on the thermal conductivity of soil mixtures with fly ash. These materials, due to their pozzolanic nature, likely reduce soil porosity and enhance particle packing, leading to improved heat transfer [165].

The introduction of solar exposure leads to a shift in this behavior. Figure 28B (Week-6) presents a marked decrease in thermal conductivity across all CKD percentages. For instance, at 15% CKD, conductivity falls to 0.258 W/m·K, a 47.9% reduction from the Week-4 value. This decreasing trend in conductivity with increased solar exposure continues through Weeks 8 and 12, as evidenced in Figure 28C and D. By Week-12, for the 15% CKD mix, conductivity is reduced to 0.25 W/m·K, nearly halving from its initial Week-4 value. This trend is indicative of potential progressive alterations in the soil-CKD matrix under sustained solar influence, potentially due to structural or compositional changes that adversely affect thermal properties.

In synthesizing these observations, it becomes evident that the integration of CKD into Soil-B significantly modifies its thermal conductivity. This alteration is initially positive, with an increase in conductivity observed up to a certain CKD concentration. Beyond this concentration, the rate of enhancement diminishes, and with prolonged solar exposure, a

consistent decrease in thermal conductivity is observed across all CKD percentages. These findings underscore the dynamic nature of the thermal properties of soil-CKD composites and suggest potential implications for their use in applications where environmental exposure and material longevity are critical considerations. The observed trends provide a foundation for further research into the sustainability and practicality of using CKD in soil modification for engineering applications.

4.10 Comparative Analysis of Stabilizer agents Thermal Effects on Hejaz Soils

3.1.1 Cement Integration: Thermal Impacts on Hejaz Soils (A and B)

Comparing the thermal conductivity of Hejaz soils, A and B with incremental cement additions reveals intricate patterns in their thermal response. For Soil A, at week 4 under plastic wrap conditions, the baseline thermal conductivity with 0% added cement was 0.251 K. When 2.5% cement was introduced, there was a significant jump in conductivity to 0.528 K, marking a 110% increase. This trend of increasing conductivity with higher cement content continued, with 5% cement leading to 0.596 K (a 137.45% increase), 7.5% to 0.506 K (101.59% increase), and 10% to 0.435 K (73.31% increase). Notably, at 12.5% cement, Soil A reached its peak conductivity of 0.664 K, a striking 164.54% increase from the baseline. However, further addition of cement to 15% caused a reduction in conductivity to 0.447 K, still a 78.09% increase from the baseline but indicating an optimal cement content threshold. In contrast, Soil B showed a different thermal behavior. Starting from a baseline conductivity of 0.271 K at 0% cement, the addition of 2.5% cement resulted in a conductivity of 0.552 K (a 103.7% increase). However, unlike Soil A, Soil B's conductivity decreased progressively with more cement: 0.467 K at 5% (72.32% increase),

0.452 K at 7.5% (66.79% increase), and 0.432 K at 10% (59.41% increase), culminating in 0.404 K at 15% cement (49.08% increase).

The effect of sun exposure over a 12-week period on these soils' thermal conductivities further demonstrates their varied response to environmental factors. For Soil A, under sun exposure, the conductivity at 2.5% cement decreased to 0.443 K at week 6 (a 76.49% increase from the baseline), 0.43 K at week 8 (71.31% increase), and further down to 0.49 K at week 12 (95.22% increase). At the optimal 12.5% cement content, conductivity reduced from 0.664 K at week 4 to 0.361 K at week 12, marking a 45.6% decrease from its peak but still a 43.82% increase from the baseline. Soil B, under similar sun-exposed conditions, showed a consistent decrease in conductivity with increased cement content over time: from 0.552 K at 2.5% cement (week 4) to 0.342 K at week 12 (26.20% increase from the baseline), and from 0.42 K at 12.5% cement (week 4) to 0.302 K at week 12 (11.44% increase from the baseline). These observations underscore the dynamic interaction between cement content, soil type, and environmental exposure in determining thermal conductivity, crucial for optimizing the use of these soils in sustainable construction.

3.1.2 Lime Integration: Thermal Impacts on Hejaz Soils (A and B)

In a detailed analysis of the thermal conductivity of Hejaz Soil-A and Soil-B with varying lime additions, distinct patterns emerge when compared to their baseline values at 0% lime addition in week 4. Initially, Soil-A and Soil-B presented thermal conductivities of 0.251 W/(m·K) and 0.271 W/(m·K) respectively under plastic wrap. With a 2.5% lime addition, Soil-A's thermal conductivity increased significantly to 0.555 W/(m·K), marking a 121.12% increase, while Soil-B recorded a 70.85% increase, reaching 0.463

W/(m·K). This upward trend in conductivity with increased lime percentages was consistent across both soils. For instance, at 5% lime, Soil-A and Soil-B achieved conductivity values of 0.543 W/(m·K) and 0.466 W/(m·K), representing 116.33% and 72.14% increases over their respective baselines. The peak conductivity for Soil-A was observed at 15% lime (0.53 W/(m·K), a 111.16% increase), whereas Soil-B peaked at 7.5% lime (0.459 W/(m·K), a 69.37% increase).

Under sun exposure, the thermal conductivities of both soils exhibited reductions from their peak values. By week 12, Soil-A with 2.5% lime maintained a conductivity of 0.52 W/(m·K), representing a 6.31% decrease from its peak under plastic wrap but still a 107.17% increase from its week-4 baseline. Soil-B, at the same lime concentration and time frame, showed a thermal conductivity of 0.307 W/(m·K), a 53.00% reduction from its peak and a 13.28% increase over its baseline. The differential response of the soils to sunlight exposure was evident across all percentages of lime. For example, at 15% lime, Soil-A's conductivity decreased to 0.379 W/(m·K) by week 12, a 28.49% decrease from its peak but still a 51.00% increase from the baseline. In contrast, Soil-B at the same lime percentage and time frame saw its conductivity decrease to 0.271 W/(m·K), a 38.32% reduction from its peak and a mere 0.00% increase from its baseline. This analysis highlights the significant impact of lime stabilization on the thermal conductivity of soils and the varying degrees of resilience to environmental conditions, underscoring the importance of tailored soil treatment strategies.

3.1.3 CKD Integration: Thermal Impacts on Hejaz Soils (A and B)

The detailed analysis of the thermal conductivity of Hejaz Soils A and B, amended with varying concentrations of Cement Kiln Dust (CKD), reveals significant insights into the

interaction between soil properties and CKD under different environmental conditions. In Figure 27-A, corresponding to Week 4 under plastic wrap, Soil-A demonstrates a remarkable increase in thermal conductivity with the addition of CKD. At a baseline conductivity of $0.251 \text{ W/(m}\cdot\text{K)}$ with 0% CKD, the addition of 2.5% CKD elevates conductivity to $0.427 \text{ W/(m}\cdot\text{K)}$, marking a 70.12% increase. This upward trend continues with increasing CKD concentrations, culminating in a dramatic 213.55% increase to $0.788 \text{ W/(m}\cdot\text{K)}$ at 15% CKD. Soil-B, starting from a baseline of $0.271 \text{ W/(m}\cdot\text{K)}$, also shows an increase in thermal conductivity, reaching a peak of 112.5% ($0.576 \text{ W/(m}\cdot\text{K)}$) at 5% CKD. However, unlike Soil-A, Soil-B's conductivity gains diminish at higher CKD concentrations, indicating a less linear response to CKD addition.

Upon transitioning to sun-exposed conditions, as detailed in Figure 27B-D, a notable decline in thermal conductivity is observed for both soils. For Soil-A, the thermal conductivity at 15% CKD decreases from its peak of $0.788 \text{ W/(m}\cdot\text{K)}$ at Week 4 to $0.356 \text{ W/(m}\cdot\text{K)}$ by Week 12 (Figure 27D), representing a significant drop of 54.85% from its peak performance under plastic wrap. This reduction, however, still reflects a 41.83% increase from its baseline of $0.251 \text{ W/(m}\cdot\text{K)}$ with 0% CKD, underscoring a certain level of resilience in CKD-treated Soil-A. In contrast, Soil-B experiences a more drastic decrease. The 15% CKD mixture in Soil-B, which initially peaked at $0.576 \text{ W/(m}\cdot\text{K)}$ under plastic wrap conditions, plummets to $0.25 \text{ W/(m}\cdot\text{K)}$ by Week 12 (Figure 28D), a reduction of 56.59% from its peak and slightly below its original baseline, indicating a 7.75% decrease from the initial $0.271 \text{ W/(m}\cdot\text{K)}$. These observations highlight the differential impact of environmental exposure on CKD-amended soils, with Soil-A displaying a degree of thermal conductivity retention under solar influence, while Soil-B demonstrates a marked

vulnerability. The results emphasize the importance of considering both soil type and environmental factors in assessing the long-term efficacy of CKD as a soil amendment for thermal conductivity increase.

4.11 Acoustic Performance of Untreated Soils

The study analysis explores the acoustic properties of untreated soils, Soil-A and Soil-B, using 1/3 octave-band and 1/1 octave-band frequencies. The 1/3 octave-band analysis reveals distinct peaks in sound absorption at specific frequencies: Soil-A demonstrates notable absorption at a middle frequency of 500 Hz in Figure 29A, while Soil-B shows its peak at 630 Hz. This level of detail in frequency bands allows for a nuanced understanding of how these soils interact with sound waves across a broader spectrum. The 1/1 octave-band frequency analysis, as shown in Figure 29B, further categorizes the acoustic performance of these soils into six classes ranging from Extremely Absorbing to Reflecting. Soil-A and Soil-B both display varied acoustic behaviors depending on the frequency. For instance, at 500 Hz, Soil-A is classified as Extremely Absorbing, indicative of its high potential for sound insulation. In contrast, at other frequencies such as 250 Hz and 1250 Hz, it falls into the Hardly Absorbing and Reflecting categories, respectively, showing less efficacy in sound absorption. For a detailed visualization of the 1/3 octave-band frequency analysis, as shown in Figure 30, which features a color-coded heatmap representing the varying degrees of sound absorption across different frequencies for both soils. This comprehensive analysis underscores the complex intersection of soil properties with acoustic performance. The peak absorption frequencies—500 Hz for Soil-A and 630 Hz for Soil-B—highlight their potential in specific sound insulation applications within sustainable construction. Such detailed insights into the acoustic characteristics of

untreated soils are crucial for optimizing material selection to balance environmental benefits with performance requirements.

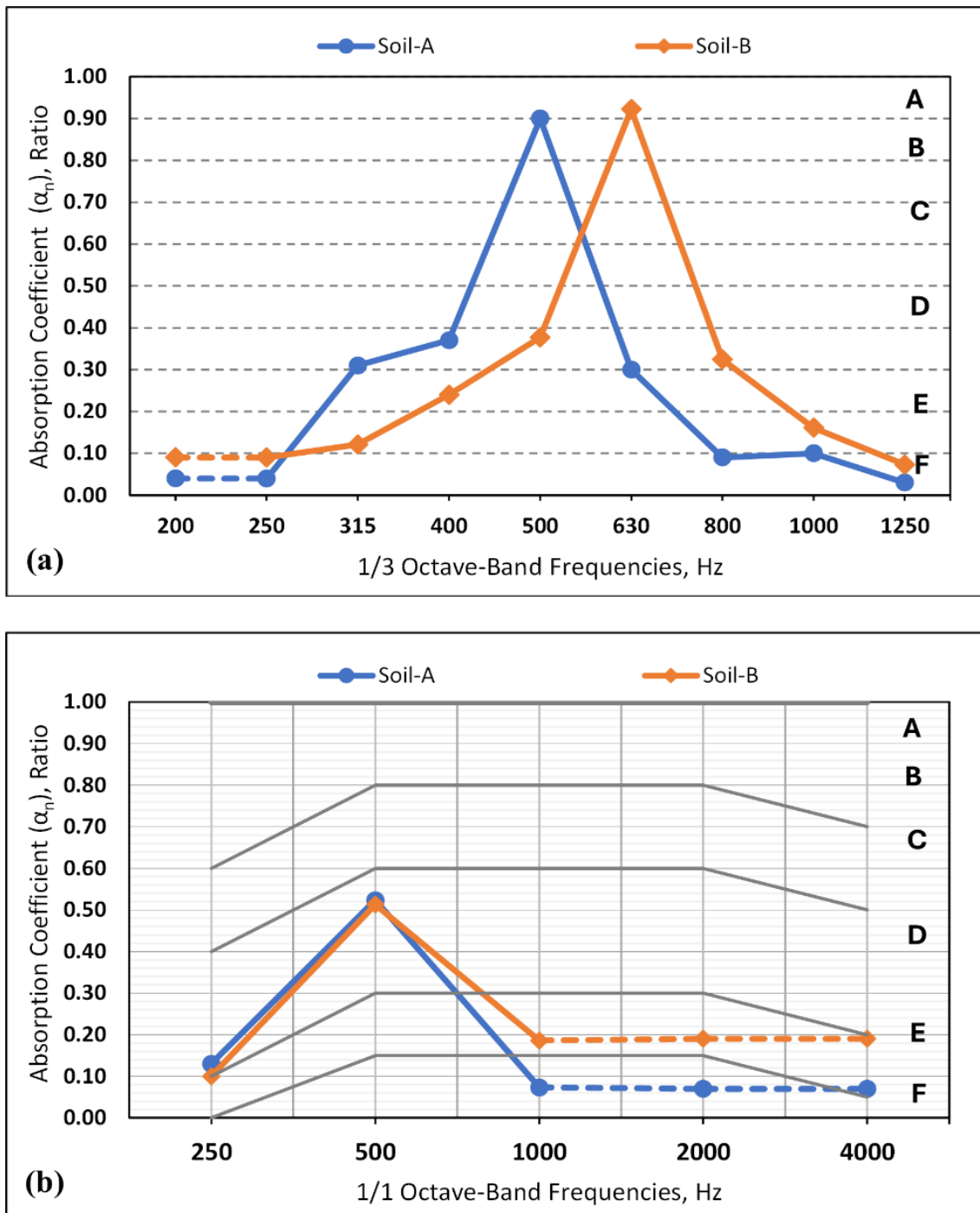


Figure 29. Acoustic absorption characteristics across 1/3 octave-band frequencies for Soil-A and Soil-B. (b): Classification of average sound absorption for Soil-A and Soil-B at 1/1 octave-band frequencies.

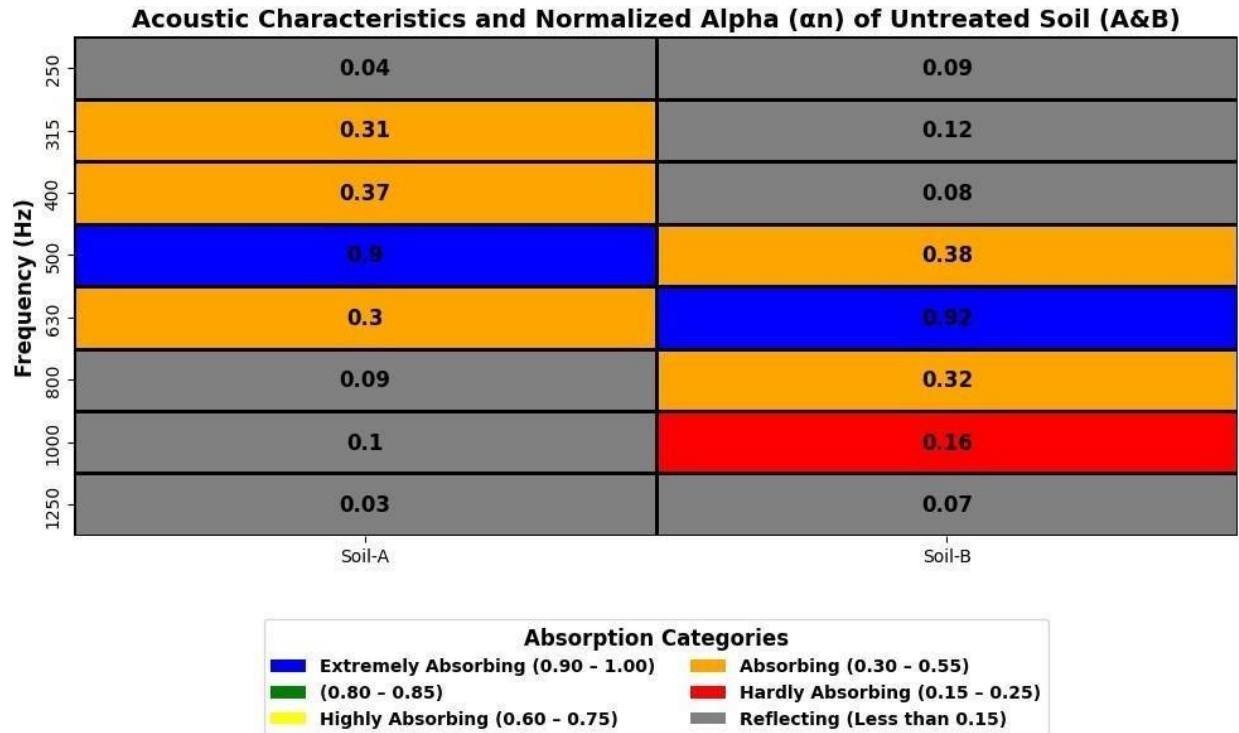


Figure 30. Acoustical characteristics of Untreated Soils: Soil-A vs. Soil-B 1/3 octave band frequency (200-1250Hz)

4.12 Impact of OPC Stabilizing Acoustical Characteristics on Soils A&B

The integration of materials science and acoustic engineering in sustainable construction provides insights into the behavior of Hejaz soils A and B when stabilized with cement. This research examines how varying percentages of cement influence the acoustical characteristics of these soils. The study focuses on changes in Acoustical Characteristics across frequencies ranging from low to middle frequency bands. At a lower frequency of 250 Hz, both soils demonstrate decreased sound absorption with increased OPC content. Soil A shows a notable reduction in absorption capability, decreasing from minor absorption at no cement to even less absorption with a 5% cement addition. Similarly, Soil B begins with moderate absorption and follows a decreasing trend in absorption as OPC content increases. Significantly, at 500 Hz, both soils behave differently. Soil A exhibits

reduced sound absorption as OPC content increases, transitioning from highly absorptive to less absorptive characteristics. Conversely, Soil B initially increases in sound absorption at a 2.5% OPC content, making it highly absorptive, but this absorption capability reduces substantially as more cement is added. A key observation occurs at 630 Hz for Soil B, where it exhibits its highest sound absorption with no OPC addition, falling into the category of being extremely absorptive. However, introducing even a small amount of OPC (2.5%) causes a significant reduction in its sound absorption properties. The behavior of Soil B at a middle frequency of 400 Hz with a 7.5% cement addition shows a substantial increase in sound absorption, illustrating OPC's potential to increase sound insulation under certain conditions. However, this trend does not hold consistently across higher frequencies. At 1250 Hz, increasing the OPC content to between 12.5% and 15% results in a marginal increase in Acoustical Characteristics, indicating a beneficial use of OPC in potentially noise-sensitive applications. Table 9A and 9B illustrate these findings. Table 9A displays the 1/3 octave-band frequencies' characteristics α_n (normal), highlighting the effects of OPC content at specific frequencies for Soils A and B. In Figure 31A&B, the processed data averaged into 1/1 octave-band frequencies show how both soil acoustical properties vary with different OPC contents. These acoustical characteristics, α_p (practical), suggest varying levels of sound absorption from extremely absorbing to reflecting, based on the cement content as shown in Figure 31A and B. These variations underline the need for precise application of OPC in soil stabilization, tailored to the specific acoustical requirements of sustainable construction projects. The color-coded heatmap of 1/3 octave-band frequencies, characteristics α_n (normal) indicating levels of Acoustical Characteristics from extremely absorbing to reflecting, can be found in

Figure 32. Additionally, Appendix A, Figure A and B, show further details of these characteristics, with 1/3 octave-band frequencies and characteristics alpha (normal) α_n , indicating trends of Acoustical Characteristics from various materials tested. This study confirms that while cement can enhance sound insulation properties at certain frequencies, its impact can vary significantly, necessitating a balanced approach in its use. This insight into the acoustical characteristics of stabilized soils underlines the importance of targeted application to meet both construction and environmental objectives.

Table 9. Impact of OPC content on sound absorption for Soils A and B at 1/3 octave-band frequencies.

OPC	1/3-Octave-Linear-interpolation						
%	0%	2.5%	5%	7.5%	10%	12.5%	15%
Frequency	Soil-A	Soil-A	Soil-A	Soil-A	Soil-A	Soil-A	Soil-A
250.00	0.04	0.03	0.01	0.04	0.10	0.09	0.03
315.00	0.31	0.07	0.04	0.04	0.32	0.24	0.06
400.00	0.37	0.02	0.15	0.05	0.29	0.37	0.07
500.00	0.9	0.37	0.28	0.06	0.25	0.18	0.58
630.00	0.3	0.36	0.58	0.05	0.03	0.15	0.20
800.00	0.09	0.33	0.14	0.10	0.03	0.02	0.16
1000.00	0.1	0.30	0.17	0.15	0.03	0.08	0.03
1250.00	0.03	0.26	0.12	0.21	0.03	0.15	0.01
(A)							
%	0%	2.5%	5%	7.5%	10%	12.5%	15%
Frequency	Soil-B	Soil-B	Soil-B	Soil-B	Soil-B	Soil-B	Soil-B
250.00	0.09	0.04	0.04	0.05	0.05	0.02	0.04
315.00	0.12	0.09	0.11	0.26	0.16	0.14	0.03
400.00	0.08	0.20	0.15	0.78	0.41	0.34	0.02
500.00	0.38	0.92	0.39	0.33	0.62	0.03	0.21
630.00	0.92	0.14	0.87	0.19	0.15	0.04	0.64
800.00	0.32	0.01	0.24	0.16	0.09	0.06	0.35
1000.00	0.16	0.09	0.12	0.10	0.01	0.08	0.07
1250.00	0.07	0.04	0.01	0.03	0.01	0.11	0.01
(B)							

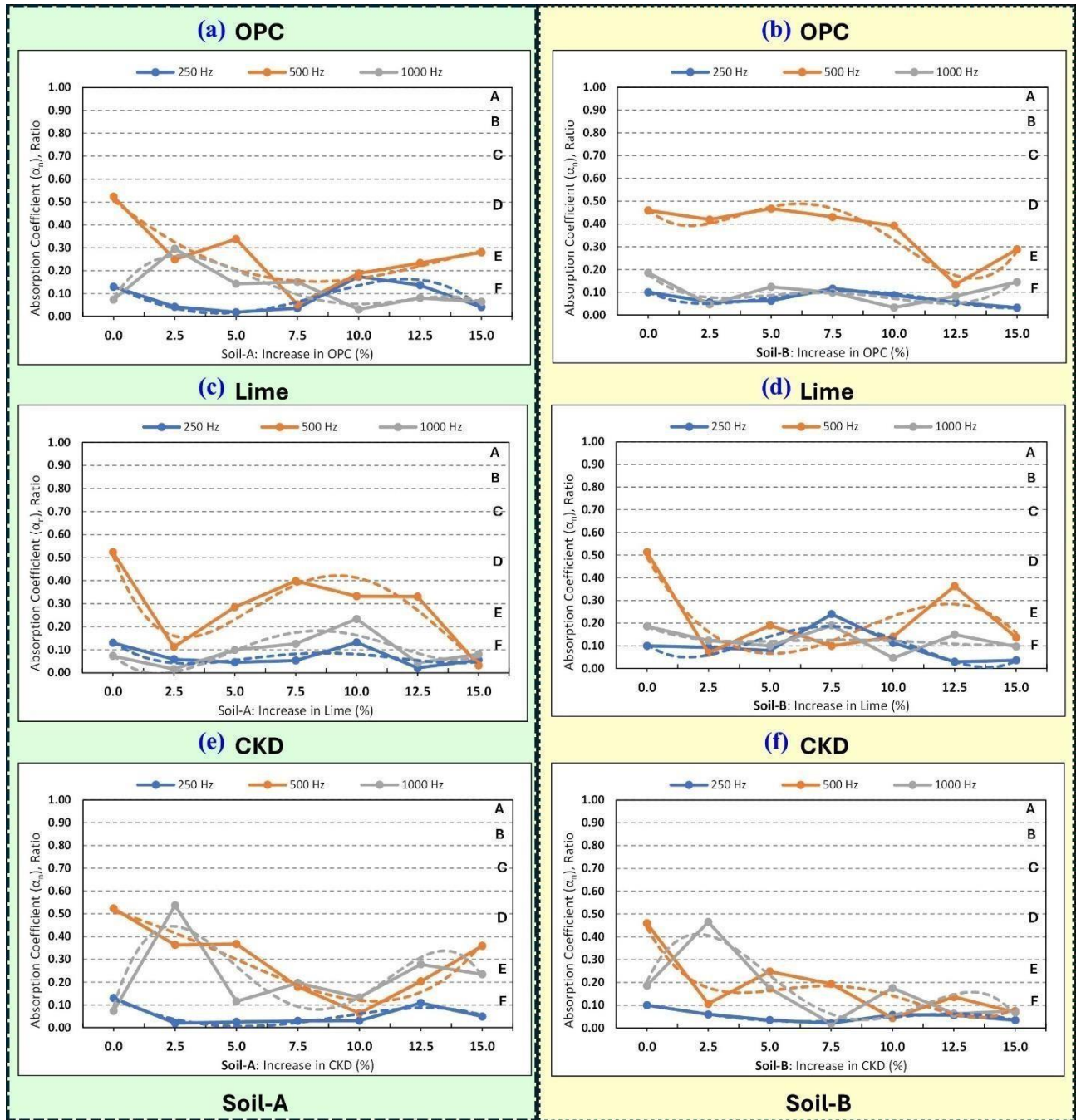


Figure 31. Averaged acoustical properties at 1/1 octave-band frequencies for varying cement contents.

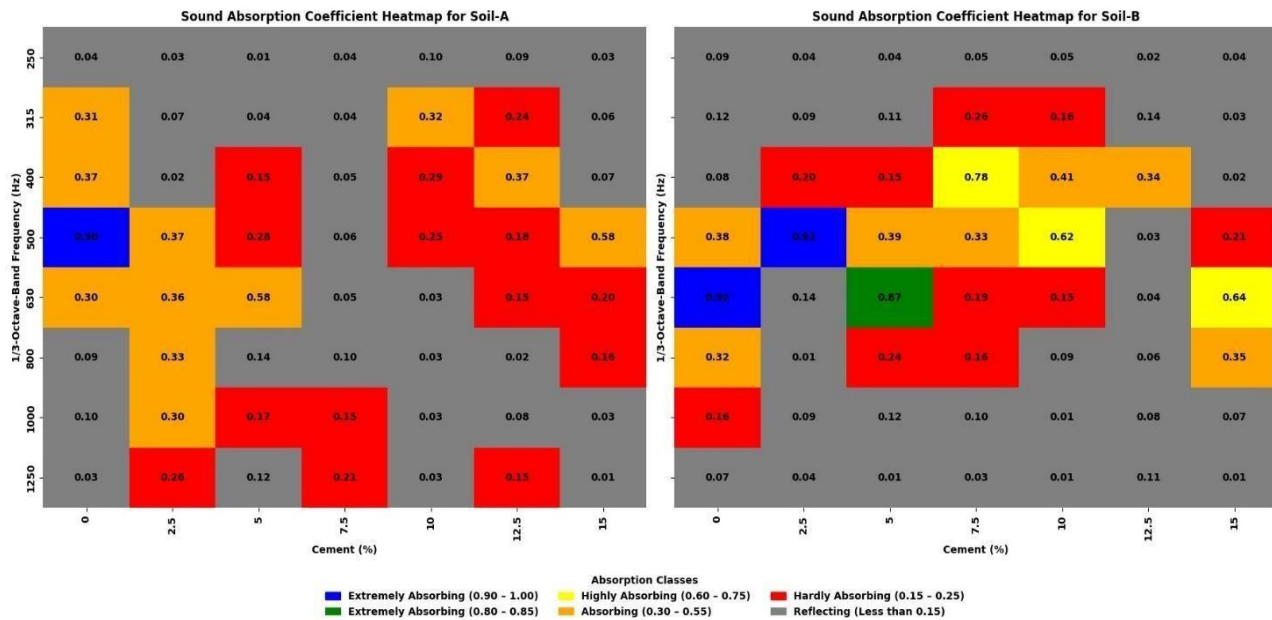


Figure 32. Sound absorption characteristics at 1/3 octave-band frequencies in response to varying Cement levels in Soils A and B

4.13 Impact of Lime Stabilizing Acoustical Characteristics on Soils A&B

The exploration of soil-lime mixtures delves into their acoustic properties, revealing how material composition influences acoustical characteristics. This study examines the effects of varying lime content on Soils A and B, assessing their acoustical characteristics across a spectrum of low and middle frequencies. The 1/3 octave-band linear interpolation provides a detailed analysis of Soil A and Soil B at low frequencies (250 Hz to 500 Hz) shows that the addition of lime tends to decrease sound absorption. As detailed in Table 10, both soils initially demonstrate higher absorption capabilities without lime. With an increase in lime content, it shows reduction in their ability to absorb sound, indicating a shift toward less absorptive properties. For example, As detailed in Table 10A, Soil A at 500 Hz significantly reduces its sound absorption from being highly absorptive with no lime to considerably less so with an addition of 2.5% lime. At middle frequencies (630 Hz to 1250 Hz), the behavior of the lime-soil mixtures varies more significantly. As shown in

Table 10B, at 630 Hz, Soil B experiences a considerable decrease in sound absorption with a small lime addition, moving from a highly absorptive to reflective. However, at 800 Hz, an increase in lime content in Soil A enhances sound absorption, showcasing a frequency where lime addition can be beneficial. The trend continues at higher middle frequencies, where lime additions selectively improve acoustical characteristics, suggesting potential applications in noise-sensitive environments.

Table 10. Impact of Lime content on sound absorption for Soils A and B at 1/3 octave-band frequencies

1/3-Octave-Linear-interpolation							
Lime	0%	2.5%	5%	0.08	10%	13%	15%
Frequency	Soil-A	Soil-A	Soil-A	Soil-A	Soil-A	Soil-A	Soil-A
250.00	0.04	0.03	0.03	0.04	0.04	0.02	0.02
315.00	0.31	0.12	0.07	0.09	0.32	0.03	0.12
400.00	0.37	0.23	0.12	0.44	0.12	0.13	0.00
500.00	0.9	0.07	0.38	0.55	0.56	0.12	0.08
630.00	0.3	0.04	0.35	0.21	0.32	0.75	0.02
800.00	0.09	0.03	0.25	0.03	0.49	0.11	0.06
1000.00	0.1	0.02	0.05	0.18	0.13	0.01	0.11
1250.00	0.03	0.00	0.00	0.17	0.08	0.01	0.07
(A)							
Lime	0%	2.5%	5%	0.08	10%	13%	15%
Frequency	Soil-B	Soil-B	Soil-B	Soil-B	Soil-B	Soil-B	Soil-B
250.00	0.09	0.1	0.1	0.1	0.09	0.03	0.05
315.00	0.12	0.08	0.04	0.52	0.16	0.03	0.01
400.00	0.08	0.05	0.09	0.18	0.34	0.11	0.05
500.00	0.38	0.07	0.26	0.05	0.02	0.4	0.13
630.00	0.92	0.09	0.22	0.07	0.06	0.58	0.23
800.00	0.32	0.12	0.17	0.29	0.14	0.18	0.22
1000.00	0.16	0.16	0.1	0.16	0	0.09	0.05
1250.00	0.07	0.09	0.03	0.12	0	0.18	0.02
(b)							

The 1/1 octave-band frequencies, represented by the acoustical characteristics alpha (practical) α_p , average the effects across broader frequency ranges and provide insights into the overall behavior of soil-lime mixtures. This aggregated data, as depicted in Figure

31C and 5D, offer a comprehensive perspective on the acoustic impact of lime, highlighting specific frequencies at which the addition of lime either enhances or diminishes sound absorption. Both the 1/3 and 1/1 octave-band analyses underscore the complex relationship between lime content, soil type, and acoustic performance. They emphasize the need for careful selection and application of lime in soil stabilization processes, ensuring that the benefits of enhanced structural integrity do not compromise the acoustical qualities required for specific construction scenarios. The color-coded heatmap of 1/3 octave-band frequencies, representing the acoustical characteristics alpha (Normal) α_n and indicating levels of sound absorption from extremely absorbing to reflecting, is shown in Figure 33 further illustrate these characteristics by showing the trends of acoustical characteristics across various frequencies. Moreover, Appendix A, Figures C and D, provide additional insights into these characteristics, displaying 1/3 octave-band frequencies and characteristics alpha (normal) α_n , which reveal trends in Acoustical Characteristics from different tested materials.

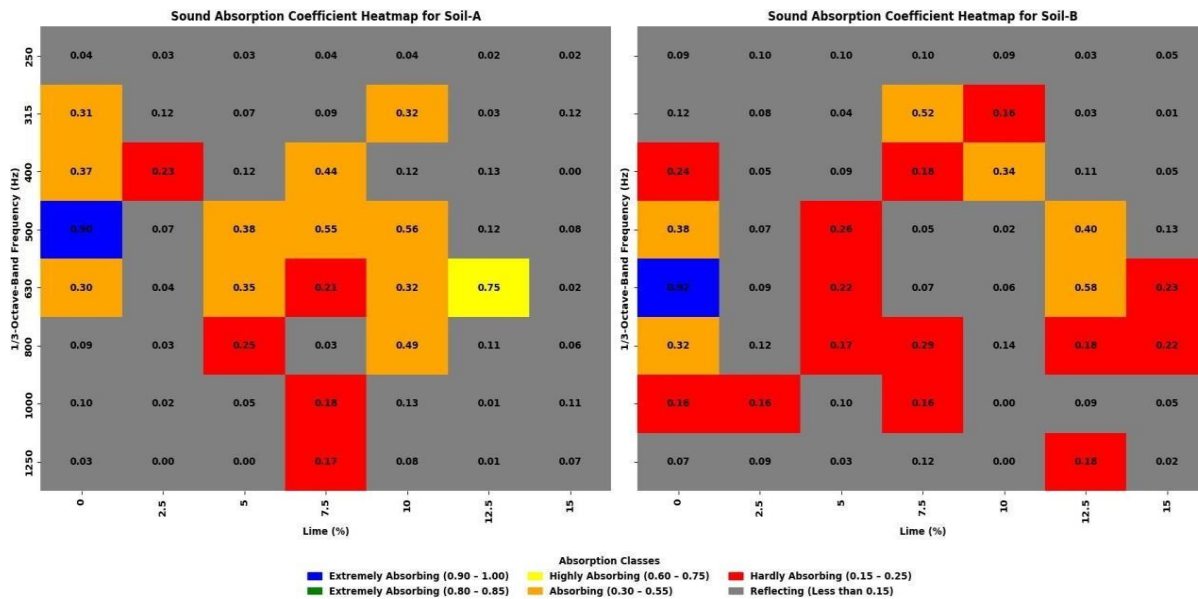


Figure 33. Sound absorption characteristics at 1/3 octave-band frequencies in response to varying Lime levels in Soils A and B

4.14 Impact of CKD Stabilizing Acoustical Characteristics on Soils A&B

Exploring the influence of Cement Kiln Dust (CKD) on soil stabilization offers valuable insights into the acoustical properties of construction materials. This study investigates how different percentages of CKD affect the sound absorption capabilities of Soils A and B. Significant variations in acoustical characteristics are observed as CKD content is altered. This study demonstrates the effect of CKD on sound absorption at low to middle frequencies. As detailed in Table 11A, For Soil-A, the addition of CKD at 500 Hz results in notable changes in sound absorption, highlighting CKD's capacity to modify soil's acoustical characteristics effectively. Similarly, Table 11B Soil-B demonstrates a significant shift in sound absorption at 630 Hz with varying CKD levels, reflecting the material's potential to enhance acoustical properties at mid-range frequencies. This study reveals that the effectiveness of CKD in improving acoustical characteristics is frequency dependent. Some frequencies show enhanced absorption with specific CKD concentrations, while at others, there may be a decrease in acoustical performance. The data shows that at 1000 Hz, Soil-A exhibits an increase in acoustical characteristics with the introduction of CKD, emphasizing the material's utility at this frequency. However, at 250 Hz, both soils generally remain less absorptive, with limited increases in sound absorption despite the addition of CKD. The study shows the complex relationship between CKD stabilization, soil type, frequency, and sound absorption. It emphasizes the importance of customized application of stabilization techniques to achieve optimal construction and acoustical outcomes.

Table 11. Impact of CKD content on sound absorption for Soils A and B at 1/3 octave-band frequencies.

1/3-Octave-Linear-interpolation							
CKD	0%	2.5%	5%	0.08	10%	13%	15%
Frequency	Soil-A	Soil-A	Soil-A	Soil-A	Soil-A	Soil-A	Soil-A
250.00	0.04	0.02	0.02	0.04	0.03	0.07	0.06
315.00	0.31	0.02	0.03	0.01	0.03	0.19	0.04
400.00	0.37	0.10	0.05	0.23	0.02	0.33	0.13
500.00	0.9	0.63	0.20	0.07	0.09	0.12	0.51
630.00	0.3	0.36	0.85	0.24	0.09	0.16	0.44
800.00	0.09	0.44	0.20	0.22	0.18	0.21	0.35
1000.00	0.1	0.53	0.08	0.20	0.14	0.27	0.24
1250.00	0.03	0.64	0.07	0.17	0.08	0.35	0.11
(A)							
CKD	0%	2.5%	5%	0.08	10%	13%	15%
Frequency	Soil-B	Soil-B	Soil-B	Soil-B	Soil-B	Soil-B	Soil-B
250.00	0.09	0.05	0.03	0.03	0.06	0.04	0.01
315.00	0.12	0.09	0.04	0.00	0.056	0.096	0.08
400.00	0.08	0.02	0.03	0.15	0.05	0.17	0.075
500.00	0.38	0.05	0.12	0.16	0.046	0.24	0.07
630.00	0.92	0.25	0.60	0.28	0.04	0.00	0.061
800.00	0.32	0.71	0.32	0.02	0.20	0.03	0.05
1000.00	0.16	0.41	0.18	0.02	0.18	0.13	0.02
1250.00	0.07	0.27	0.02	0.02	0.155	0.02	0.16
(B)							

The 1/3 octave-band frequencies represented by the acoustical characteristics α_p (practical) α_p , data offers a detailed examination of how specific frequencies respond to CKD stabilization in Soils A and B. The 1/3 octave linear interpolation reveals that the addition of CKD can both enhance and diminish the soils' sound absorption capabilities, depending on the frequency and percentage of CKD used. The 1/1 octave-band frequencies, represented by the acoustical characteristics α_p (normal) α_p , provide a broader view of the overall acoustical impact of CKD across a wider range of frequencies. This aggregate data, illustrated in Figure 31E&F, provides a comprehensive overview of the soils' acoustical properties under different CKD concentrations, from extremely

absorbing to reflecting. This helps in understanding the broader implications of CKD use in soil stabilization. Both the 1/3 and 1/1 octave analyses highlight the nuanced and frequency-dependent nature of CKD's impact on soil acoustics. By wise selecting materials and CKD concentrations, practitioners can enhance the sustainability and acoustic insulation of construction projects. These findings facilitate a more informed approach to material selection and application in sustainable construction, ensuring that environmental and acoustical performance are harmonized. A color-coded heatmap of 1/3 octave-band frequencies, detailing levels of sound absorption, is available in Figure 34. Additionally, Appendix A, Figures E and F illustrate the characteristics of these 1/3 octave-band frequencies. These figures provide alpha (normal) α_n values, indicating trends in the Acoustical Characteristics, further enriching the understanding of sound absorption trends.

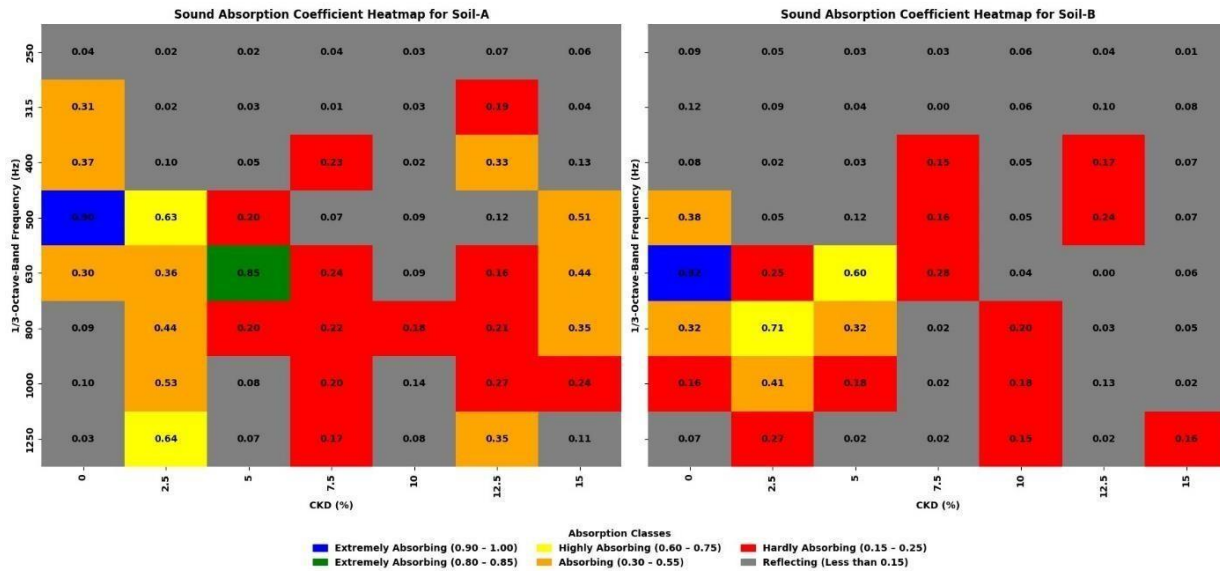


Figure 33. Comparative sound absorption at 1/3 octave-band frequencies for Soils A and B with different CKD contents.

4.15 Comparative Analysis of Stabilized Soils: Thermal and Acoustic Characteristics

This comparative analysis investigates the thermal conductivity and acoustic absorption characteristics of soils stabilized with three different stabilizers: Ordinary Portland Cement (OPC), Lime, and Cement Kiln Dust (CKD). By examining Soil A and Soil B across varying stabilizer percentages, this study aims to provide a comprehensive understanding of how each stabilizer influences the overall performance of the soils in terms of thermal and acoustic characteristics, thereby guiding optimal stabilization strategies for sustainable construction applications.

4.15.1 Comparative Analysis of Cement Stabilized Soils: Thermal and Acoustic Characteristics

The comparative analysis of the thermal and acoustic characteristics of cement-stabilized soils for both Soil A and Soil B reveals distinct trends and performance metrics across

different stabilizer percentages. As illustrated in Table 12 and Figure 34, the thermal conductivity for Soil A shows an initial increase with the addition of cement, peaking at a 2.5% stabilizer percentage (0.448 W/m·K) before gradually decreasing with higher cement content. This trend suggests that a moderate addition of cement optimizes the thermal performance of Soil A. Similarly, Soil B exhibits a comparable pattern, where the thermal conductivity reaches its maximum (0.388 W/m·K) at a 2.5% cement addition, indicating that both soil types benefit from low to moderate cement stabilization for enhanced thermal properties. Concurrently, the acoustic absorption at lower frequencies (250 Hz) is relatively higher for Soil A at 10% cement (0.141 α), whereas for Soil B, the highest absorption at 250 Hz occurs at 7.5% cement (0.101 α). These observations highlight that while thermal conductivity benefits from moderate cement stabilization, optimal acoustic absorption can require different percentages depending on the soil type.

Table 12. Comparative Data of Thermal Conductivity and Acoustic Absorption for Cement-Stabilized

Stabilizer Percentage	Thermal	Thermal	250 Hz	250 Hz	500 Hz	500 Hz	1000 Hz	1000 Hz
	Soil A	Soil B	Soil A	Soil B	Soil A	Soil B	Soil A	Soil B
0%	0.19	0.21	0.11	0.07	0.52	0.46	0.07	0.19
2.5%	0.44	0.38	0.03	0.042	0.25	0.42	0.3	0.05
5%	0.45	0.35	0.016	0.049	0.34	0.47	0.14	0.12
7.5%	0.38	0.28	0.025	0.101	0.05	0.43	0.15	0.1
10%	0.36	0.33	0.141	0.069	0.19	0.39	0.03	0.03
12.5%	0.43	0.33	0.108	0.05	0.23	0.13	0.08	0.08
15%	0.33	0.33	0.031	0.02	0.28	0.29	0.06	0.15

Furthermore, the analysis of mid-range frequencies (500 Hz) demonstrates that Soil A achieves its highest acoustic absorption (0.52 α) without any cement stabilization, which

decreases significantly with increasing cement content. In contrast, Soil B reaches its peak absorption at 7.5% cement (0.43α), suggesting a more complex relationship between cement content and acoustic properties for different frequencies. This divergence in behavior shows the need to balance thermal and acoustic enhancements through careful selection of cement percentages. The comparative data shows the necessity for a wise approach to soil stabilization, where both thermal and acoustic requirements are simultaneously optimized. Furthermore, the mid-frequency acoustic absorption (1000 Hz) indicates a significant variation between Soil A and Soil B. For Soil A, the maximum absorption (0.30α) occurs at 2.5% cement, while Soil B shows a peak absorption at 5% cement (0.12α). These results, depicted in Figure 34, imply that higher frequencies respond differently to cement stabilization compared to lower frequencies. Additionally, the overall comparative analysis suggests that while both soil types show an increase in thermal conductivity with initial cement addition, they exhibit distinct peak points and trends in acoustic absorption across frequencies. Therefore, the application of cement stabilization for soil improvement must consider the specific performance needs, ensuring that the chosen stabilizer percentage provides a balanced enhancement of both thermal and acoustic characteristics.

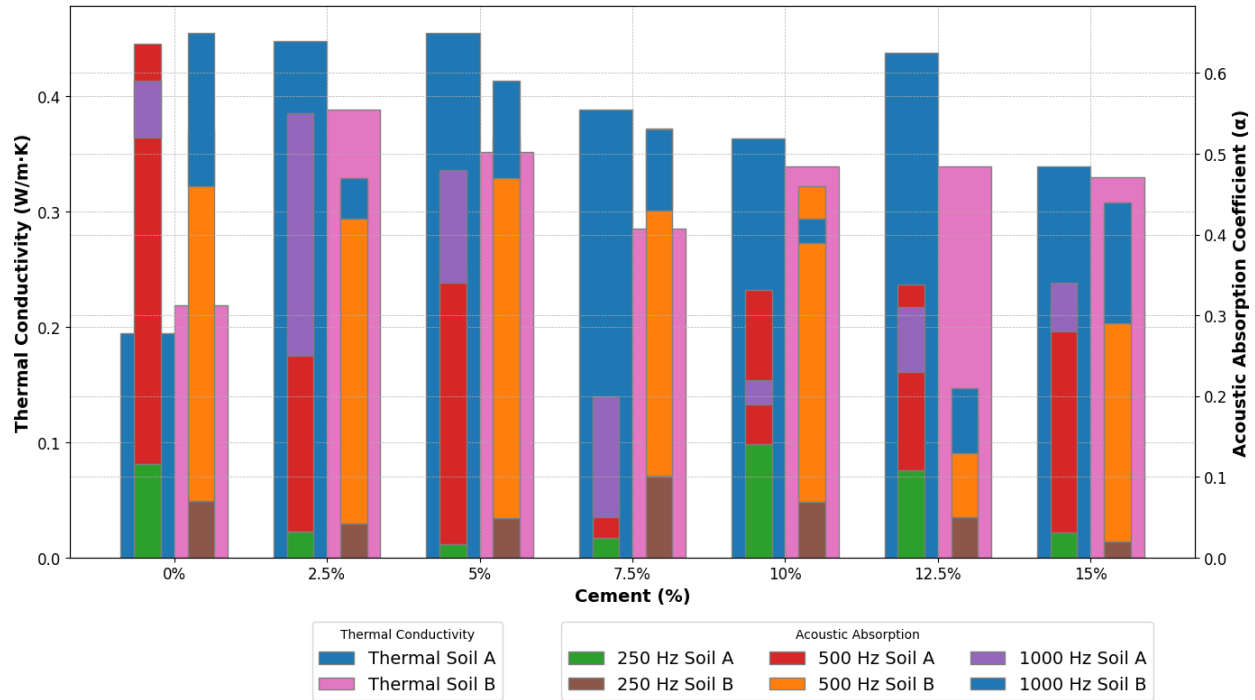


Figure 34. Thermal and Acoustic Performance of Cement-Stabilized Soils

4.15.2 Comparative Analysis of Lime Stabilized Soils: Thermal and Acoustic Characteristics

Examining the thermal and acoustic properties of lime-stabilized soils reveals intricate patterns and insights for both Soil A and Soil B. In Table 13 and Figure 35, it observes that the thermal conductivity of Soil A rises notably with lime stabilization, peaking at 2.5% lime addition (0.530 W/m·K). This suggests that even a small percentage of lime significantly increases thermal conductivity. In contrast, Soil B's thermal conductivity shows a more modest increase, achieving its highest value (0.347 W/m·K) at the same 2.5% lime level. These findings highlight that while both soil types benefit from lime stabilization, Soil A experiences a more pronounced improvement in thermal conductivity with the initial lime addition. Concurrently, the acoustic absorption characteristics at 250 Hz for Soil A reach a maximum (0.119 α) at 10% lime, whereas Soil B shows its absorption at the same lime percentage but with a lower value (0.083 α).

Table 13. Thermal Conductivity and Acoustic Absorption Coefficients of Lime-Stabilized Soils A and B at Various Stabilizer Percentages.

Stabilizer Percentage	Thermal Conductivity	Thermal Conductivity	250 Hz	250 Hz	500 Hz	500 Hz	1000 Hz	1000 Hz
	Soil A	Soil B	Soil A	Soil B	Soil A	Soil B	Soil A	Soil B
0%	0.25	0.27	0.116	0.07	0.52	0.46	0.07	0.19
2.5%	0.53	0.34	0.049	0.06	0.11	0.07	0.02	0.12
5%	0.49	0.28	0.034	0.046	0.29	0.19	0.1	0.1
7.5%	0.46	0.32	0.041	0.20	0.4	0.1	0.13	0.19
10%	0.46	0.26	0.119	0.08	0.33	0.14	0.23	0.05
12.5%	0.42	0.34	0.015	0.02	0.33	0.36	0.04	0.15
15%	0.423	0.32	0.047	0.02	0.03	0.14	0.08	0.1

In mid-range frequencies (500 Hz), Soil A's acoustic absorption reaches its highest value (0.52 α) without any lime addition, and this value diminishes with increasing lime content. For Soil B, however, the peak absorption at 500 Hz occurs at 12.5% lime (0.36 α). This contrasting behavior between Soil A and Soil B suggests that lime stabilization impacts acoustic properties differently depending on the soil type and frequency range. The thermal conductivity of Soil B demonstrates a consistent increase with higher lime content, stabilizing around 10% lime addition. This indicates that beyond a certain lime percentage, the thermal benefits plateau. In contrast, Soil A's thermal conductivity shows a steady decline after reaching its peak at 2.5% lime, suggesting diminishing returns with excessive lime stabilization. The data underscores the need to optimize lime content carefully to balance both thermal and acoustic properties effectively. At mid frequencies (1000 Hz), the acoustic absorption properties diverge further between Soil A and Soil B. Soil A achieves its maximum absorption (0.23 α) at 10% lime, while Soil B reaches its peak (0.15 α) at 12.5% lime. These observations, depicted in Figure 35, reveal that higher frequencies

are less responsive to lime stabilization compared to lower and mid-range frequencies. Additionally, Soil A generally exhibits higher acoustic absorption across all lime percentages compared to Soil B, suggesting that Soil A might be more suitable for applications requiring enhanced acoustic properties. Therefore, the analysis indicates that while lime stabilization significantly improves thermal conductivity for both soils, the optimal percentage varies, and its impact on acoustic properties requires a wise approach.

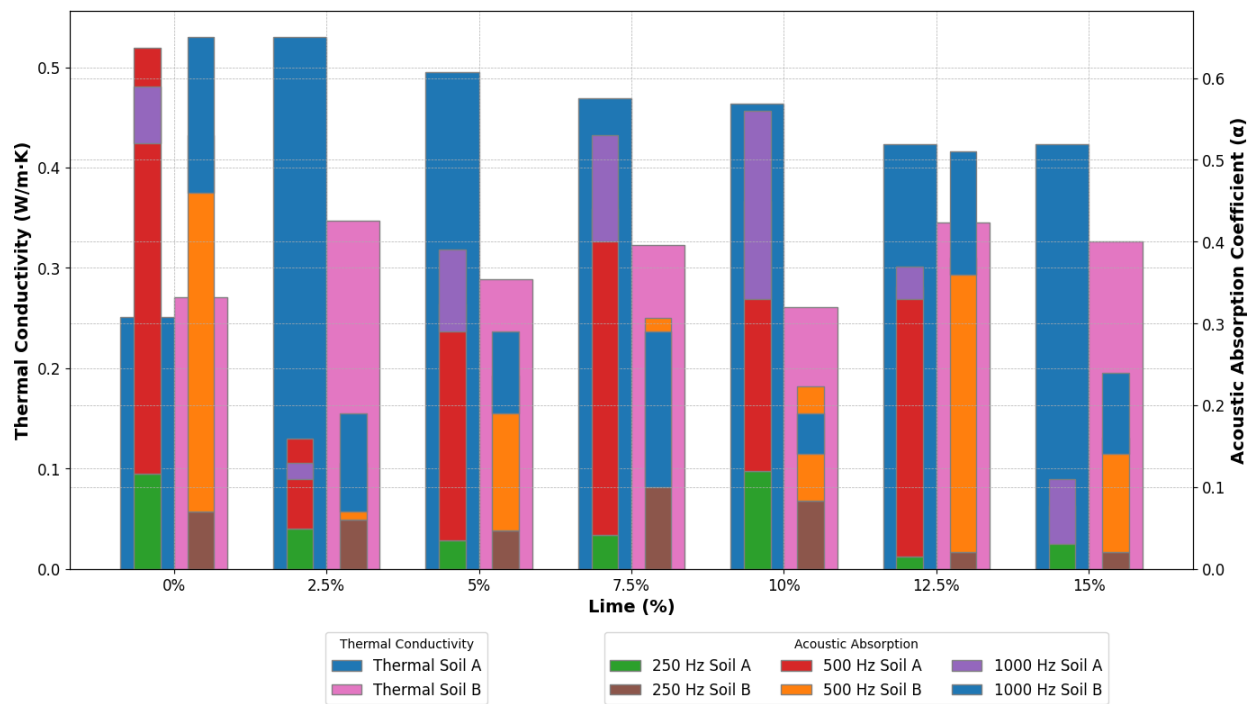


Figure 35. Comparative Analysis of Thermal and Acoustic Properties of Lime-Stabilized Soils A and B Across Different Stabilizer Percentages.

4.15.3 Comparative Analysis of CKD Stabilized Soils: Thermal and Acoustic Characteristics

The evaluation of CKD-stabilized soils unveils unique insights into the thermal and acoustic performance of Soil A and Soil B, as presented in Table 14 and Figure 36. For thermal conductivity, Soil A demonstrates a steady increase with CKD addition, reaching a peak value of 0.483 W/m·K at 15% CKD. This indicates that higher percentages of CKD

significantly enhance the thermal properties of Soil A. Conversely, Soil B's thermal conductivity also increases with CKD stabilization, though it achieves its highest value (0.395 W/m·K) at 5% CKD, after which the improvements stabilize. This suggests a different optimal stabilization point for Soil B compared to Soil A. Simultaneously, the acoustic absorption at lower frequencies (250 Hz) for Soil A shows its highest absorption (0.117 α) with no CKD, decreasing as more CKD is added. For Soil B, the peak absorption at 250 Hz (0.070 α) occurs at 0% CKD, indicating that CKD addition does not favor low-frequency acoustic absorption for either soil type. Exploring mid-range frequencies (500 Hz), the acoustic absorption behavior differs markedly. Soil A's highest absorption (0.52 α) is observed without CKD, which significantly drops as CKD content increases. On the other hand, Soil B achieves its maximum absorption (0.25 α) at 5% CKD, suggesting that CKD can enhance mid-range acoustic absorption to a certain extent before diminishing returns set in. These trends are critical for applications where mid-range acoustic properties are essential. In terms of thermal conductivity, both soils show a consistent improvement with increased CKD content, indicating CKD's robust role in enhancing thermal performance. Soil A continues to benefit from higher CKD percentages, while Soil B's increase showed after 5% CKD. The simultaneous assessment of thermal and acoustic properties emphasizes the need for a balanced approach to CKD stabilization, optimizing the percentage to achieve desired outcomes for both thermal and acoustic performance.

Table 14. Thermal Conductivity and Acoustic Absorption Data for C

Stabilizer Percentage	Thermal	Thermal	250 Hz	250 Hz	500 Hz	500 Hz	1000 Hz	1000 Hz
	Soil A	Soil B	Soil A	Soil B	Soil A	Soil B	Soil A	Soil B
0%	0.25	0.27	0.11	0.07	0.52	0.46	0.07	0.19
2.5%	0.29	0.30	0.01	0.045	0.36	0.11	0.54	0.47
5%	0.35	0.39	0.017	0.024	0.37	0.25	0.12	0.17
7.5%	0.37	0.31	0.016	0.010	0.18	0.19	0.20	0.02
10%	0.41	0.29	0.02	0.038	0.06	0.04	0.13	0.18
12.5%	0.43	0.29	0.086	0.044	0.20	0.14	0.28	0.06
15%	0.48	0.32	0.031	0.031	0.36	0.07	0.23	0.07

Moreover, Mid-frequency acoustic absorption (1000 Hz) reveals additional complexities.

Soil A achieves its maximum absorption (0.28 α) at 12.5% CKD, while Soil B peaks (0.18 α) at 10% CKD. This suggests that higher CKD percentages are more beneficial for high-frequency acoustic performance, especially for Soil A. These results, depicted in Figure 36, illustrate that CKD stabilization has a varied impact across different frequencies and soil types. The overall analysis indicates that while CKD consistently enhances thermal conductivity, its effect on acoustic absorption varies significantly. For optimal stabilization, it is crucial to consider both the specific thermal and acoustic requirements of the application.

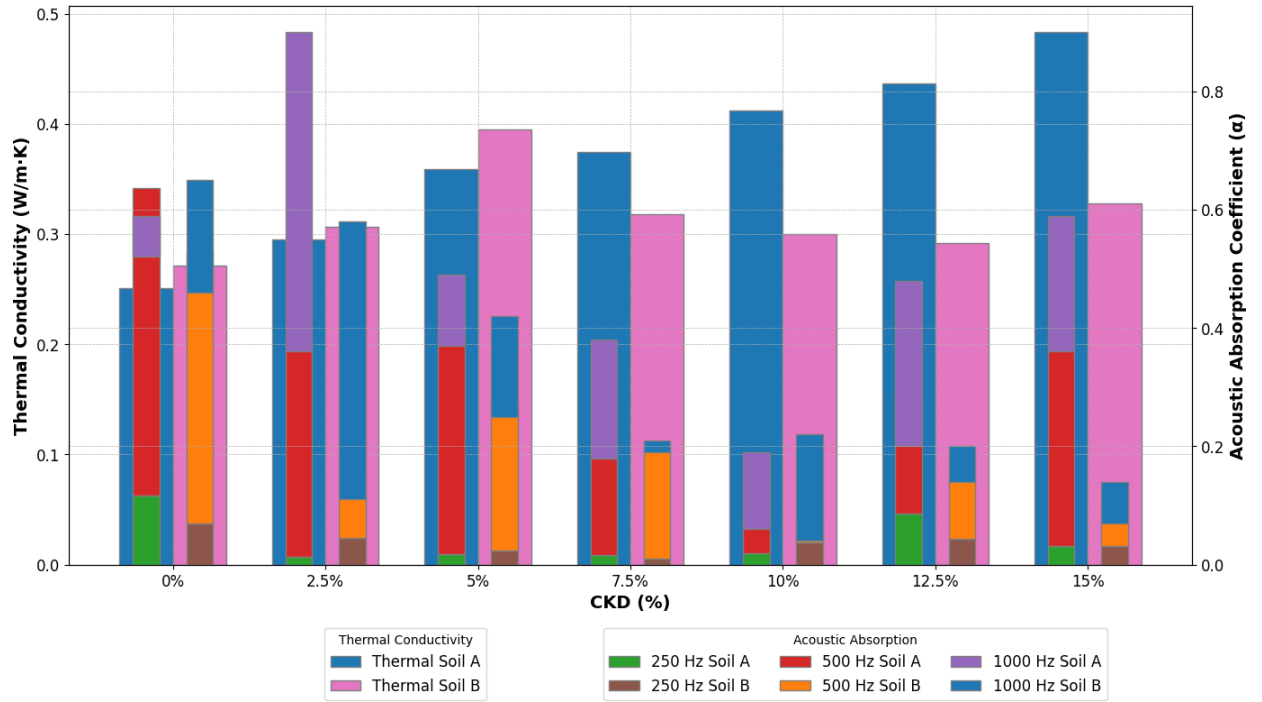


Figure 36. Thermal and Acoustic Performance of CKD-Stabilized Soils

CHAPTER 5

Conclusions

5.1 Introduction

This comprehensive research has rigorously investigated the impact of different stabilizers—cement, lime, and cement kiln dust (CKD)—on the thermal and acoustic properties of Hejaz soil, offering profound insights for the sustainable construction industry. By examining two soil types (Soil-A and Soil-B) under various conditions, the study identifies how each stabilizer uniquely influences the soil's thermal conductivity and acoustic performance.

5.2 Key Findings Thermal Conductivity:

5.2.1 Baseline Thermal Properties:

Soil A (light brown) initially exhibited a thermal conductivity (K) of $0.251 \text{ W/m}\cdot\text{K}$ under airtight conditions, which decreased to $0.154 \text{ W/m}\cdot\text{K}$ after twelve weeks of sun exposure, representing a reduction of 38.6%. While, Soil B (medium brown) showed an initial thermal conductivity of $0.271 \text{ W/m}\cdot\text{K}$, which reduced to $0.175 \text{ W/m}\cdot\text{K}$ after twelve weeks of sun exposure, indicating a decrease of 35.4%.

5.2.2 CKD's Remarkable Impact:

A significant increase in thermal conductivity was observed, especially in Soil A (214% increase) with 15% CKD under plastic wrap conditions. In terms of Thermal properties,

meticulous preparation and stabilization processes adhering to ASTM standards were followed.

5.2.3 Cement and Lime Effectiveness:

Both stabilizers effectively increased thermal conductivity, with variations depending on concentration and soil type. This study's conclusions have a big impact on the sustainable construction industry.

5.2.4 Impact of Stabilizers:

The impact of stabilizers on thermal conductivity revealed significant findings. The addition of 2.5% cement increased the thermal conductivity of Soil A to 0.528 W/m·K, representing a 110.36% increase from the untreated state. For Soil B, a 5% cement addition resulted in a thermal conductivity of 0.576 W/m·K, corresponding to an increase of 112.55%. Similarly, the addition of 2.5% lime increased the thermal conductivity of Soil A to 0.555 W/m·K and Soil B to 0.463 W/m·K. The inclusion of CKD at 2.5% raised the thermal conductivity of Soil A to 0.427 W/m·K and Soil B to 0.526 W/m·K. These results indicate that even at low concentrations, cement, lime, and CKD significantly increase the thermal conductivity of Hejaz soils, thereby enhancing their potential utility in sustainable construction applications where improved thermal properties are desirable.

5.2.5 Implications: Sustainable Construction:

The possibility of using stabilized soil for constructing environmentally friendly and energy-efficient infrastructure. Effectiveness of CKD: CKD is highlighted as an extremely effective stabilizer, especially at higher concentrations. While cement and lime work well enough, CKD turns out to be an extremely effective stabilizer, especially at higher

concentrations. In order to meet the growing demand for sustainable building practices, these insights are essential for developing construction materials that are both thermally efficient and structurally sound.

5.2.6 *Limitations and Future Directions:*

5.2.6.1 Scope of Study:

This study primarily focused on specific soil types and stabilizers.

5.2.6.2 Further Research Needed:

Investigating a broader range of soil compositions, environmental conditions, and long-term effects on the environment and stability.

This research contributes significantly to the advancement of sustainable construction practices. By demonstrating the potential of various soil stabilizers to enhance the thermal properties of Hejaz soil, it opens new avenues for the development of more efficient and environmentally conscious construction materials.

5.3 Key Findings on Acoustical Characteristics (AC)

The study provides a comprehensive examination of the effects of soil stabilization agents—Ordinary Portland Cement (OPC), hydrated lime, and Cement Kiln Dust (CKD)—on the acoustic properties of soils from the Hejaz region. Measurements adhering to ASTM preparation and stabilization standards, along with ISO 10534-2 for acoustical characteristics, reveal significant insights. Notably, untreated Soil A and Soil B show substantial sound absorption at certain frequencies (e.g., untreated Soil A at 500 Hz shows

an absorption coefficient of 0.9, and untreated Soil B at 630 Hz shows 0.92), underscoring their potential in eco-friendly construction practices.

5.3.1 Stabilization Effects (Cement, Lime, and CKD)

The impact of stabilizers on sound absorption typically results in a reduction of the Sound Absorption Coefficient (SAC), though specific concentrations can occasionally improve SAC at particular frequencies. For example, the introduction of 2.5% lime reduced the sound absorption coefficient of Soil A from 0.9 to 0.07 at 500 Hz, indicating a significant decrease in its ability to absorb sound. Similarly, Soil B experienced a reduction in sound absorption coefficient from 0.85 to 0.12 at 500 Hz with the same 2.5% lime addition. This suggests that while stabilization agents like lime, cement, and CKD are effective in increasing the thermal properties of soils, they generally tend to decrease their sound absorption capabilities, which must be carefully managed depending on the specific application requirements in construction.

5.3.2 Implications

The implications of these findings are profound, highlighting the essential need for a detailed understanding of material properties and their interactions with sound waves. This knowledge is critical for optimizing the use of natural materials in construction, ensuring that both structural integrity and acoustical performance are maintained.

5.3.3 Limitations and Future Directions

While the study lays a substantial groundwork in the field of sustainable construction, it also opens avenues for further investigation. Future research should explore a wider array of soil types, stabilization agents, and their acoustical properties across an expanded range

of frequencies to maximize the potential of natural materials in reducing the ecological impacts of construction activities.

5.3.4 Environmental and Industry Impact

By advancing the understanding of the acoustic properties of soil stabilization materials, this research not only contributes to the scientific community but also steers the construction industry towards more sustainable practices. It emphasizes the potential of natural materials to achieve environmental benefits without compromising on acoustic integrity, encouraging the industry to adopt more environmentally conscious construction methods.

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Appendix A

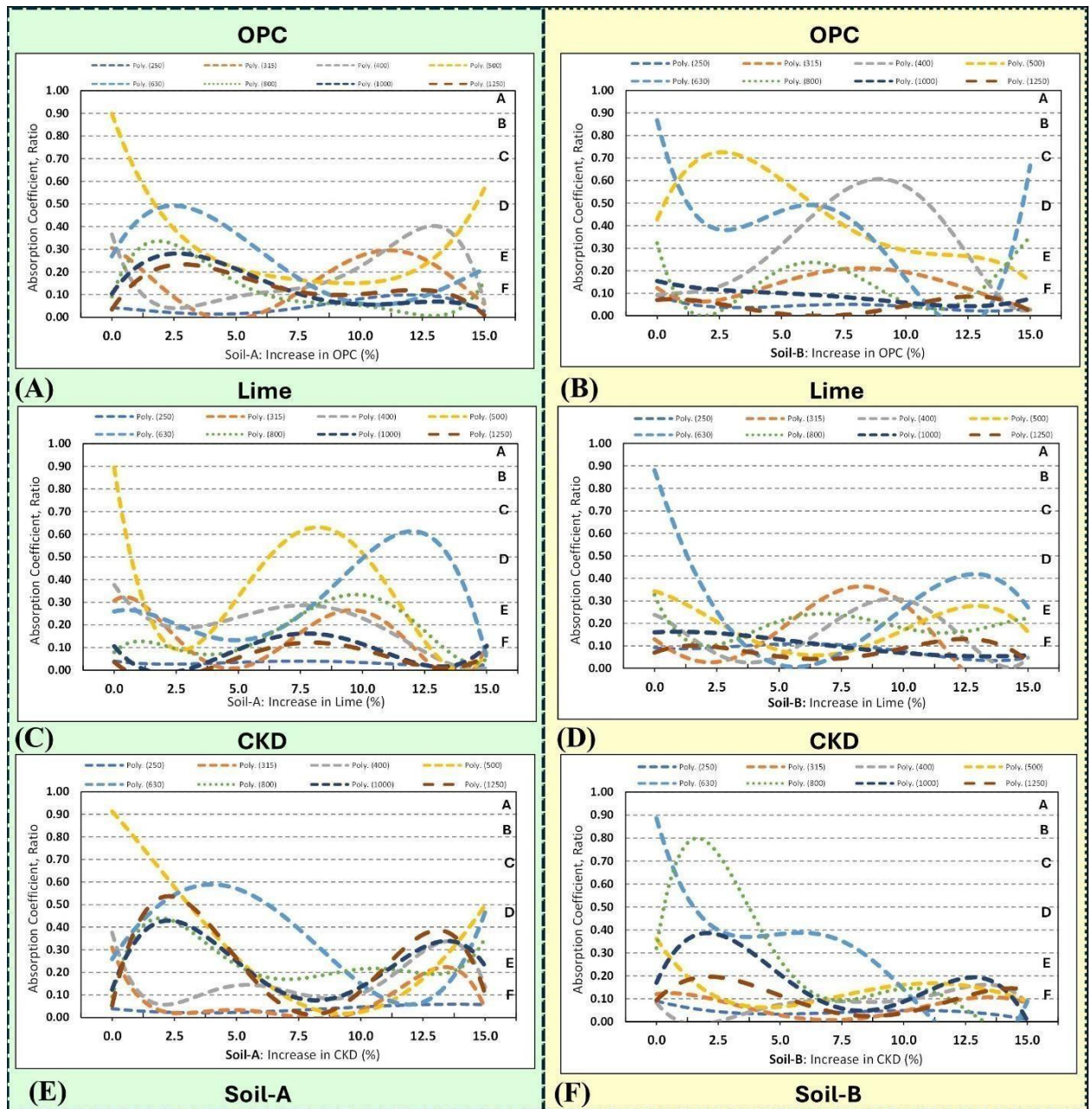


Figure 37.1/3 octave-band frequencies and α_n trends in acoustical characteristics of tested materials."

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Investigating the Acoustical Characteristics of Stabilized Soils for Sustainable Construction	Article (Applied Acoustics)	Under Review
Thematic Explorations and Conceptual Mappings of BIM and Digital Twin Integration: A Systematic Review	Systematic Review (Automation in Construction)	Under Review
Magnesia-Based Binders for Stabilizing and Improving Soft Soils	Conference Paper (Italy)	Published: https://doi.org/10.1016/B978-0-443-28824-1.50231-3
ML Integrating Smart Technology in Building Designs for Optimized Energy Efficiency and User Wellbeing	Conference Paper (UK)	Accepted (To be published post-conference)