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STUDY OF THE THERMOMECHANICAL BEHAVIOR OF COMPACTED EARTH CONTAINING FIBERS FOR ITS USE AS CONSTRUCTION MATERIAL

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DEDICATION

I dedicate this work to:

- *my beloved parents.*
- *my dear Sister RIP.*
- *Everyone who has contributed, whether directly or indirectly, to the success of this work.*

LABIAD Yacine

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Abstract

Recent studies have increasingly focused on incorporating sustainable materials into construction. This research examines the impact of sisal or Alfa fibers on the thermomechanical behavior of compacted earth block (CEB) utilizing local resources, specifically red clayey soil from the Msila region (East of Algeria), blended with brick waste (BW). In this study, the plasticity criteria are maintained at the maximum BW of 20%. Later, the effects of fiber and cement incorporation on CEB engineering properties, comparing different compositions, are evaluated. Sisal and Alfa fibers are introduced at proportions ranging between 0 to 0.5%, with cement added at 0%, 5%, 7%, and 9% for Sisal fibers, while for Alfa fibers-reinforced soil, cement is fixed at 7 %, all based on the weight of the modified soil. Serial tests on properties such as density, capillary absorption rate, thermal conductivity, abrasion, tensile and compressive strengths at wet and dry states are performed.

The findings indicate that incorporating Sisal or Alfa fibers reduces the weight of CEB, with a 0.5% fiber content leading to a density decrease of 5.7% and 3.5%, respectively. However, this also increases capillary absorption and reduces water resistance, though cement stabilization helps mitigate these effects. Fiber incorporation improves thermal insulation, lowering thermal conductivity by up to 21% for Sisal fibers and 13% for Alfa fibers. Furthermore, compressive strength increases significantly, reaching 150% for Sisal fiber-reinforced CEB at 0.5%, while in cement-stabilized CEB, strength peaks at 0.2% before declining. Similarly, Alfa fiber incorporation enhances compressive strength with a 111.25% increase at 0.5%. Tensile strength consistently improves with increasing cement and fiber content, whereas abrasion resistance decreases at higher fiber content. Also, the study reveals that fibers alone do not provide sufficient stability for CEB in humid conditions, as the blocks lose their strength completely upon water exposure. This underscores the importance of proper water protection or cement stabilization to enhance durability.

Finally, this research confirms that Sisal or Alfa fibers are a viable reinforcement material for CEB, while introducing an environmentally friendly solution for brick waste (BW) management recovery. Incorporating BW into CEB production promotes sustainable construction practices, supporting eco-conscious development and resource-efficient building strategies.

Keywords: Fibers; Compressed earth block (CEB); Thermal conductivity; Brick waste (BW); Strength, durability

الملخص

ركزت الدراسات الحديثة بشكل متزايد إلى دمج المواد المستدامة في قطاع البناء. يدرس هذا البحث في تأثير ألياف السيزال أو الحلفاء على السلوك الحراري والميكانيكي لكتلة التربة المنضغطة، باستخدام موارد محلية، تحديدًا التربة الطينية الحمراء من منطقة المسيلة (شرق الجزائر)، ممزوجة بمخلفات الطوب. في هذه الدراسة، تم الحفاظ على معايير اللدونة عند الحد الأقصى لوزن الكتلة وهو 20%. لاحقًا، تم تقييم آثار دمج الألياف والأسمنت على الخصائص الهندسية لكتلة التربة المضغوطة بمقارنة التركيبات المختلفة. تم إضافة ألياف السيزال والحلفاء بنسب تتراوح بين 0% و0.5%، بينما تمت إضافة الإسمنت بنسبة ٪0، 5٪، 7٪ و9٪ مع ألياف السيزال، في حين تم تثبيت محتوى الإسمنت عند 7٪ في التربة المدعمة بألياف الحلفاء، وجميع النسب محسوبة بناءً على وزن التربة المعدلة. يتم إجراء اختبارات متسلسلة على خصائص مثل الكثافة، معدل الامتصاص الشعيري، التوصيلية الحرارية، والتآكل، وقوة الشد والضغط في الحالات الرطبة والجافة. تشير النتائج إلى أن إضافة ألياف السيزال أو الحلفاء تقلل من وزن بلوكات التربة المضغوطة، حيث أدى محتوى الألياف بنسبة ٪0.5إلى انخفاض الكثافة بنسبة 5.7٪ و3.5٪ على التوالي .ومع ذلك، فإن ذلك يزيد أيضًا من الامتصاص الشعري ويقلل مقاومة الماء، على الرغم من أن تثبيت الإسمنت يساعد في تقليل هذه التأثيرات . إضافة الألياف العزل الحراري، خفضت التوصيلية الحرارية بنسبة تصل إلى 21٪ لألياف السيزال و13٪ لألياف الحلفاء. علاوة على ذلك، تزداد قوة الضغط بشكل ملحوظ، لتصل إلى 150% في كتل التربة المضغوطة المدعمة بألياف السيزال عند 0.5٪ من محتوى ألياف، بينما في الكتلة المثبتة بالإسمنت، بلغت المقاومة ذروتها عند 0.2٪ ثم انخفضت بعد ذلك .وبالمثل، يُعزز دمج ألياف الحلفاء قوة الضغط بنسبة111.25 ٪ عند 0.5٪. تتحسن قوة الشد باستمرار مع زيادة محتوى الأسمنت والألياف، بينما تنخفض مقاومة التآكل عند زيادة محتوى الألياف. كما كشف الدراسة أن الألياف وحدها لا توفر استقرارًا كافيًا لبلوكات التربة المضغوطة في الظروف الرطبة، وهذا يبرز أهمية حماية كتل التربة المضغوطة من الماء أو تثبيتها بالإسمنت لتحسين متانتها.

أخيرًا، يؤكد هذا البحث أن ألياف السيزال أو الحلفاء تُعد مواد تدعيم فعالة لكتل التربة المضغوطة، كما أنها تقدم حلاً صديقًا للبيئة لإدارة مخلفات الطوب. يساهم دمج مخلفات الطوب في إنتاج كتل التربة المضغوطة في تعزيز ممارسات البناء المستدامة، مما يدعم التنمية البيئية الواعية واستراتيجيات البناء الفعالة في استخدام الموارد.

الكلمات المفتاحية: ألياف، كتلة التربة المضغوطة، العزل الحراري، مخلفات الطوب القوة، المتانة

Résumé

Des études récentes se sont de plus en plus concentrées sur l'intégration de matériaux durables dans la construction. Cette recherche examine l'impact des fibres de Sisal ou d'Alfa sur le comportement thermomécanique des blocs de terre compactée (BTC), en utilisant des ressources locales, notamment un sol argileux rouge de la région de M'sila (à l'est de Algérie), mélangé avec des déchets de briques (DB). Dans cette étude, le critère de plasticité est respecté en limitant la teneur maximale en DB à 20 %. Par la suite, les effets de l'incorporation de fibres et de ciment sur les propriétés mécaniques des BTC sont évalués en comparant différentes compositions. Les fibres de sisal et d'alfa sont introduites à des proportions variant de 0 à 0,5 %, avec un ajout de ciment à raison de 0 %, 5 %, 7 % et 9 % pour les fibres de Sisal, tandis que pour les sols renforcés par les fibres d'Alfa, la teneur en ciment est fixée à 7 %, le tout rapporté au poids du sol modifié. Des essais en série sont réalisés sur des propriétés telles que la densité, le taux d'absorption capillaire, la conductivité thermique, la résistance à l'abrasion, ainsi que les résistances à la traction et à la compression à l'état sec et humide

Les résultats montrent que l'incorporation de fibres de sisal ou d'alfa réduit le poids des BTC, une teneur en fibres de 0,5 % entraînant une diminution de la densité de 5,7 % pour le sisal et de 3,5 % pour l'alfa. Cependant, cette incorporation augmente également l'absorption capillaire et réduit la résistance à l'eau, bien que la stabilisation au ciment contribue à atténuer ces effets. L'ajout de fibres améliore l'isolation thermique, en réduisant la conductivité thermique jusqu'à 21 % pour le sisal et 13 % pour l'alfa. De plus, la résistance à la compression augmente de manière significative, atteignant 150 % pour les BTC renforcés au sisal à 0,5 %, tandis que dans les BTC stabilisés au ciment, la résistance maximale est observée à 0,2 %, avant de diminuer. De même, l'incorporation de fibres d'alfa améliore la résistance à la compression avec une augmentation de 111,25 % à 0,5 %. La résistance à la traction augmente de façon continue avec l'augmentation des teneurs en ciment et en fibres, tandis que la résistance à l'abrasion diminue à des teneurs élevées en fibres. L'étude révèle également que les fibres seules ne garantissent pas une stabilité suffisante des BTC en milieu humide, les blocs perdant complètement leur résistance après exposition à l'eau. Cela souligne l'importance d'une protection efficace contre l'humidité ou d'une stabilisation au ciment pour améliorer la durabilité.

Enfin, cette recherche confirme que les fibres de sisal ou d'alfa constituent un matériau de renforcement viable pour les BTC, tout en proposant une solution respectueuse de l'environnement pour la valorisation des déchets de briques (DB). L'intégration des DB dans la production des BTC encourage des pratiques de construction durables, soutenant un développement écoresponsable et des stratégies de construction économes en ressources.

Mots-clés : Fibres ; Blocs de terre comprimée (BTC) ; Conductivité thermique ; Déchets de briques (DB) ; Résistance ; Durabilité

TABLE OF CONTENTS

DEDICATION **2**

ACKNOWLEDGEMENTS **3**

LIST OF FIGURES **11**

LIST OF TABLES **14**

LIST OF NOTATIONS (ABBREVIATIONS) AND SYMBOLS **15**

GENERAL INTRODUCTION **1**

PART ONE: **4**

LITERATURE REVIEW **4**

CHAPTER I: .....

PROPERTIES AND CHARACTERISTICS OF EARTH MATERIALS IN CONSTRUCTION .....

I.1. INTRODUCTION **6**

I.2. HISTORY OF EARTH CONSTRUCTION **6**

I.3.EARTH CONSTRUCTION **8**

I.4.THE CLAYS **9**

I.5.PROPERTIES OF EARTH MATERIAL IN CONSTRUCTION **12**

I.5.1. Texture and granularity **12**

I.5.2. Plasticity **13**

I.5.3. Organic matter and sulfate content in earth materials **13**

I.6.EARTH CONSTRUCTION TECHNIQUES **14**

I.6.1. Wattle and daube **14**

I.6.2. Cob **15**

I.6.3. Rammed Earth **15**

I.6.4. Adobe **16**

I.7.COMPRESSED EARTH BLOCK (CEB) **17**

I.7.1. Production Technique **18**

I.7.2. Advantages of CEB **19**

I.7.3. Limitations of CEB **21**

I.7.4.CEB Construction around the world **21**

I.8.CONCLUSION **23**

CHAPTER II: .....

EARTH STABILIZATION TECHNIQUES .....

II.2. INTRODUCTION **25**

II.2. SOIL STABILIZATION **25**

II.2.1. Mechanical stabilization **25**
II.2.1.1. Influence of water content on density 27

II.2.2. Physical stabilization **28**

II.2.3. Chemical stabilization **29**
II.2.3.1. Lime 29
II.2.3.2. Cement 29
II.2.3.3. Mechanism of Cement stabilization 30

II.3. EFFECTS OF CEMENT ON THE PROPERTIES OF THE STABILIZED MATERIAL **31**

II.3.1. Mechanical strength **31**

II.3.2. Physical strength **34**

II.3.3. Durability of CEB **35**

II.4. FIBER STABILIZATION **36**

II.4.1. Types of Fibers **36**
II.4.1.1. Natural fibers 36
II.4.1.2. Synthetic fibers 38
II.4.1.3. Artificial fibers 38

II.4.2. Plant fibers **38**
II.4.2.1. Chemical Composition of Plant Fibers 38

II.4.3. Effect of Fiber Stabilization on Soil Properties **41**
II.4.3.1. Modification of Water Content and Density 41
II.4.3.2. Mechanical Properties 41
II.4.3.3. Water Absorption 44
II.4.3.4. Thermal Properties 45

II.5. UTILIZATION OF WASTE MATERIAL IN CIVIL ENGINEERING **47**

II.5.1. Incorporating wastes in CEB **48**

II.6. CONCLUSION **51**

PART TWO: .....

EXPERIMENTAL STUDY .....

CHAPTER III: .....

RAW MATERIALS AND EXPERIMENTAL METHODS .....

III.1. INTRODUCTION **54**

III.2. MATERIALS **54**

III.2.1. Soil **54**

III.2.2. Brick waste **56**

III.2.3. Cement **57**

III.2.4. Water **57**

III.2.5. Sisal fibers **57**

III.2.6. Alfa fibers **59**

III.3.EXPERIMENTAL PROCEDURE **61**

III.3.1.Mix compositions **63**

III.3.2. Optimization of water content **65**

III.4. TEST CONDUCTED **66**

III.4.1. Physical properties **66**
III.4.1.1. Density 66
III.4.1.2 Capillary Absorption test 67
III.4.1.3 Thermal properties 67

III.4.2. Mechanical properties **69**
III.4.2.1. Dry compressive strength 69
III.4.2.2. Wet compressive strength 69
III.4.2.3. Splitting Tensile Test 70

III.4.3. Abrasion resistance test **71**

III.5. CONCLUSION **72**

CHAPTER IV: .....

RESULTS AND DISCUSSION .....

IV.1. INTRODUCTION **74**

IV.2. EFFECT OF FIBER CONTENT ON PHYSICAL PROPERTIES **74**

IV.2.1. Density **74**

IV.2.2 Capillary absorption test 75
IV.2.3 Thermal properties 79
IV.3. EFFECT OF FIBER CONTENT ON MECHANICAL PROPERTIES 80
IV.3.1. Dry compressive strength 80
IV.3.2. Wet compressive strength 84
IV.3.3. Tensile strength 85
IV.4. ABRASION RESISTANCE TEST 87
IV.5. CONCLUSION 89
GENERAL CONCLUSION 92
FURTHER WORKS 94
REFERENCES 96
LIST OF PUBLICATIONS AND COMMUNICATIONS 117

List of figures

Chapter I

Figure I 1: Earth block structures in Jericho, Palestine, circa 6000 BCE. 7
Figure I 2: Archaeological excavation site in Anatolia (Turkey), approximately 6000 BCE. 7
Figure I 3: Section of the Great Wall of China, constructed using rammed earth technique, around 2,000 years ago. 7
Figure I 4: Earth block vault near to Luxor, Egypt, dating to approximately 1300 BCE 7
Figure I 5: Late Georgian cob townhouses in Dawlish, Devon, circa 1820. 8
Figure I 6: Earth Architecture around the World 8
Figure I 7: Structural elements: (a) and (b) the tetrahedrons, (d) and (e) the octahedrons. 9
Figure I 8: Schematic representation of Kaolinites. 10
Figure I 9: Diagram of Illite on the left, and of complex clay structure (Smectite) . 11
Figure I 10: The different types of clay 11
Figure I 11: Grain size ranges used for different earth construction techniques. 12
Figure I 12: The Zones of Atterberg Limits in Earthen Construction . 13
Figure I 13: a) Construction process using the Wattle and daube technique; b) House made of wattle and daube in Colmar, France. 14
Figure I 14: a) Cob construction technique; b) Masmak Castle in Riyadh, Saudi Arabia. 15
Figure I 15: a) Formwork used for traditional rammed earth; b) Rammers used to compact rammed earth [15]. 16
Figure I 16: a) Adobe brick manufacturing process; b) Construction of an adobe brick house. 16
Figure I 17: a) Detailed drawing of Cinva Ram block making press; b) Cinva-Ram filled with soil mixture. 17
Figure I 18: Various compressed earth blocks products 18
Figure I 19: Al Medy Mosque, Riyadh, Saudi Arabia002E 21
Figure I 20: Hotel Le Djoloff, Dakar, Senegal. 22
Figure I 21: The Centre for earth Architecture in Mopti, Mali. 23
Figure I 22: R+1 semi-collective housing in Sidi Bel Abbes, Algeria. 23

Chapter II

Figure II 1: Impact of compaction energy on soil structure 26
Figure II 2: Impact of compacting pressure on the compressive strength of CEB. 27
Figure II 3: Total absorption as a function of sand content 28
Figure II 4: Effect of cement content and compaction pressure on the dry density of CEB 34

Figure II 5: Water absorption resistance of unstabilized and 6% Portland cement-stabilized rammed earth. 35
Figure II 6: Variation of the water absorption rate over time in CEB stabilized with different cement contents. 35
Figure II 7: Classification of natural fibers. 37
Figure II 8: Schematic representation of a wood fiber. 39
Figure II 9: Variation of Compressive Strength Based on Sisal Fiber Content 42
Figure II 10: The Influence of Fiber Content on Compressive Strength 43
Figure II 11: Tensile Behavior of Compressed Earth Blocks Reinforced with Natural Fibers 43
Figure II 12: Effect of Steel Fiber Content on Tensile Strength for Compressed Earth Blocks Stabilized with 6% Cement 44
Figure II 13: Influence of Dry Density on the Thermal Conductivity of a Fiber-Reinforced CEB. 45
Figure II 14: Influence of Coconut Fiber Content on Thermal Conductivity 46
Figure II 15 : Thermal Characteristics of Soil Based on Dry Density 46
Figure II 16: Distribution of Waste by Source Sectors 47
Figure II 17: compressive strength percentage content of ceramics at 7 and 28 days 49
Figure II 18 : Wet and dry compressive strength of blocks. 50

Chapter III

Figure III 1: Grain size curve of the Soil. 54
Figure III 2: X-ray diffractogram of clay. 56
Figure III 3: Grain size curve of Brick waste. 56
Figure III 4: Sisal vegetable leaves and fibers 58
Figure III 5 : Analysis of sisal fibers (FTIR). 58
Figure III 6: Processing of Alfa fibers. 58
Figure III 7: X-ray diffractometer for Alfa fibers 60
Figure III 8: Analysis for Alfa fibers (FTIR) 61
Figure III 9: Flowchart of the method followed in the research 62
Figure III 10: The position of different soil mixes on a plasticity according to the XP P13-901 62
Figure III 11: Mold used for the production of CEB. 63
Figure III 12: Optimization of water content 66
Figure III 13: Schematic setup illustrating the principle of the capillary absorption test 67
Figure III 14: Thermal conductivity tester (CT-meter) 68
Figure III 15: Thermal conductivity tester (TPS) 68
Figure III 16: CEB specimen under compression testing following the procedure specified in XP P13-901 69
Figure III 17: CEB fully immersed in water 70

Figure III 18: Schematic diagram showing the setup for the tensile test 70
Figure III 19: Schematic Abrasion test: (left) Steel brush utilized, (right) appearance of the specimen after testing 71

Chapter IV

Figure IV 1: Effect of Sisal fibers on density 75
Figure IV 2: Effect of Alfa fibers on density 75
Figure IV 3: Effect of Sisal fibers and cement on the capillary absorption of unstabilized CEB 76
Figure IV 4: Effect of Sisal fibers and cement on the capillary absorption of stabilized CEB 77
Figure IV 5: Appearance of blocks after water immersion 77
Figure IV 6: Effect of Alfa fibers on the capillary absorption of stabilized CEB 78
Figure IV 7: Voids created by Alfa fibers 78
Figure IV 8: Variation of thermal conductivity of CEB for Sisal fibers 79
Figure IV 9: Variation of thermal conductivity of CEB for Alfa fibers 80
Figure IV 10: Variation of dry compressive strength of CEB without cement for Sisal fibers 81
Figure IV 11: Variation of dry compressive strength of CEB with cement for Sisal fibers 82
Figure IV 12: Variation of dry compressive strength of CEB for Alfa fibers 81
Figure IV 13: Effect of Alfa fibers on the stress-strain curves 81
Figure IV 14: Variation of wet compressive strength of CEB with cement. 84
Figure IV 15: Variation of dry tensile strength of CEB for Sisal fibers 86
Figure IV 16: Variation of dry tensile strength of CEB for Alfa fibers 86
Figure IV 17: Tensile failure of soil blocks 87
Figure IV 18: Abrasion coefficients of fiber-reinforced, unstabilized CEB 88
Figure IV 19: Abrasion coefficients of fiber-reinforced, stabilized CEB 88

List of Tables

Chapter I

Table I 1: Comparison between CEB and other masonry materials. 20

Chapter II

Table II 1: Compressive strength values of cement-stabilized soils 32
Table II 2: Chemical Composition of Some Natural Fibers. 40

Chapter III

Table III 1: Physical properties of the soil used. 54
Table III 2: Chemical composition of the soil used. 55
Table III 3: Chemical composition of Brick waste used. 57
Table III 4: Chemical composition of cement. 57
Table III 5: Definition of FTIR peak positions wave for Sisal fibers. 57
Table III 6: Definition of FTIR peak positions wave for Alfa fibers. 61
Table III 7: CEB Mix proposition for Sisal fibers 64
Table III 8: CEB Mix proposition for Alfa fibers 64

List of Notations (Abbreviations) and Symbols

CEB	Compressed Earth Block
BW	Brick waste
λ	Thermal conductivity
C_b	Capillary absorption
C_a	Abrasion coefficient
PI	Plasticity index
WP	Plasticity limit
WL	Liquidity limit
ρ	Density
OWC	Optimal Water Content
DD	Dry density
FTIR	Fourier transform infrared
OWC	optimal water content
C.D.E.	Centre for the Development of Enterprise
CRATerre	Centre International de la Construction en Terre
LMMS	Laboratory of Materials and Mechanics of Structures
TPS	Transient Plane technique Source

General Introduction

General Introduction

Throughout history, raw earth has been a fundamental building material due to its abundance and minimal energy requirements for processing, leading to low CO_2 emissions. Its excellent plasticity and ecological benefits position it as a promising candidate for future construction endeavors. The widespread presence of earthen architecture worldwide attests to the performance of such constructions. However, the rise of materials like concrete and steel has overshadowed the advantages of earth as a building material. In response to current ecological and economic challenges, numerous programs and scientific studies have renewed interest in earthen construction, focusing on enhancing its physical and mechanical properties, particularly its resistance to water, which remains a significant concern for earthen structures.

The compressed earth block (CEB) technique, though relatively recent compared to traditional earth construction methods (daub, rammed earth, etc.), enables the production of blocks with customizable dimensions suitable for masonry. These blocks can serve both as infill within post-and-beam structures and as primary materials in load-bearing walls. To improve the mechanical properties of CEBs, such as reducing porosity, minimizing volumetric changes (swelling and shrinkage), and increasing resistance to climatic challenges (wind and rain erosion), various stabilizers are employed, including cement, lime, bitumen, and fibrous additives.

Fiber reinforcement, particularly with straw, has been utilized globally since antiquity to stabilize earth constructions. More recently, even industrial productions, such as adobe construction in the USA, continue to incorporate straw. Artisanal methods for producing straw-stabilized adobe bricks are diverse, and the application of fibers extends to techniques like wattle and daub, earth-straw mixtures, cob, compressed blocks, and rammed earth. Synthetic fibers are also used to reinforce soils, enhancing compressive strength.

Algeria has a longstanding history of earth construction, especially in rural and arid regions. Today, there is a resurgence of interest in this material, driven by initiatives aimed at fulfilling approximately 40% of the rural housing program and efforts to align national legislation with international sustainable development standards.

The manufacturing of fired bricks produces significant waste at different stages of the process, including non-compliant and damaged bricks. Recycling and repurposing this brick waste (BW) can alleviate storage challenges, reduce environmental pollution, and conserve natural resources. Incorporating such waste into building materials offers a practical solution to pollution problems.

This thesis aims to reduce energy consumption in construction, especially in arid zone climates, as much of Algeria experiences very hot weather, by utilizing local resources, recycling industrial waste (BW), and leveraging their properties for CEB production. The study investigates the influence of Sisal or Alfa fibers on the thermomechanical properties of CEBs made from local materials, combining clayey soil sourced from the M'sila region in Algeria, with 20% (BW), ensuring compliance with plasticity criteria. Subsequently, the impacts of fiber and cement additions on the engineering characteristics of CEBs are examined and compared across varying contents. Sisal and Alfa fibers are introduced at proportions ranging between 0 to 0.5%, with cement in added at 0%, 5%, 7%, and 9% for Sisal fibers, while for Alfa fibers-reinforced soil, cement is fixed at 7 % by weight of the modified soil. The study also examines the thermal conductivity of CEBs and employs various tests, including density, capillary absorption, wet and dry strength, tensile strength, and abrasion, to evaluate the durability of CEBs composed of clay and BW.

The thesis is organized into four chapters. The first chapter provides an overview of earth construction, particularly CEBs, discussing various techniques along with their advantages and disadvantages. The second chapter reviews the general context of earth reinforcement and stabilization methods, focusing on the chemical processes triggered by adding cement to soils. The literature review indicates that while mineral binders like cement and lime improve the mechanical strength and water resistance of CEBs, limited research has explored the use of sisal or Alfa fibers in CEBs. Notably, this study is among the first to investigate the combined effects of partially replacing soil with BW and incorporating Sisal or Alfa fibers on the mechanical and thermophysical properties of cement-stabilized CEBs. This study addresses this gap by evaluating the impact of fibers on the mechanical, physical, and thermal properties of CEBs, highlighting an environmentally sustainable approach by incorporating brick waste into CEB production to develop eco-friendly and durable construction materials. The third chapter examines the characteristics of the materials used in CEB manufacturing, providing an overview of the formulations and identifying the

fundamental physical, chemical, and mechanical properties of the raw materials. It then describes the experimental methods employed to test the mechanical and thermal resistance of the CEBs. The fourth chapter presents the results of our study, emphasizing the effects of Sisal or Alfa fibers, BW, and cement on the thermophysical and mechanical properties of CEBs for construction applications. Specifically, the research focuses on key thermophysical properties such as thermal conductivity, density, and capillary absorption, as well as mechanical behaviors including compressive strength (under dry and wet conditions), tensile strength, and abrasion. These findings elucidate how the incorporation of Sisal or Alfa fibers and cement influences the thermophysical properties and mechanical characteristics of CEBs, providing a basis for assessing their suitability as sustainable construction materials. Finally, the general conclusion synthesizes the findings from the preceding chapters and offers recommendations.

Part one:

LITERATURE REVIEW

Chapter I:

Properties and characteristics of earth materials in construction

I.1. Introduction

Earth has been one of the oldest and most reliable building materials used by humans for centuries. From ancient civilizations to modern sustainable architecture. This chapter provides an overview of earth construction, particularly CEB, discussing various techniques along with their advantages and disadvantages. A key focus is on CEB, a modern adaptation of traditional methods that offer durability, affordability, and environmental benefits. The chapter also looks at the composition of earth materials, their structural properties, and different construction techniques used worldwide.

I.2. History of earth construction

Earthen structures have a long history in the development of human civilization. Since ancient times, humans have used the earth to construct homes, monuments, temples, shelters, and more. Archaeological findings show that the first use of earth as a building material dates back to the Neolithic period, around 10,000 years ago, in the eastern Mediterranean and Mesopotamia, now encompassing Syria, Iraq, Iran, Anatolia (Turkey), Lebanon, Jordan, and Palestine [1]. Some of the oldest permanent dwellings are found in the areas of modern-day Turkey and Palestine.

Recent earth structures are found globally, including in Spain, Portugal, France, the Northern Africa region (including Algeria and Morocco), South and Central America, such as Brazil, Peru and Mexico. Numerous earth buildings, constructed over 1,000 years ago, still stand today. A notable example is the Great Wall of China, built around 2,000 years ago using locally sourced materials such as earth, stone, fired bricks, and wood.

Archaeological evidence also confirms the Phoenicians' use of earthen architecture in the Mediterranean region, particularly in Carthage, between 1500 and 300 BCE. Similarly, the ancient Egyptians mastered various earthen construction techniques, including compacted earth blocks reinforced with straw. Figure 1.4 illustrates a vault made of earth blocks, used as a storage area in the tomb of Ramses II, dating back to approximately 1300 BCE.

Advanced techniques for building with earth were also developed between 1000 and 1500 CE by pre-Columbian civilizations in Central America. The oldest earthen constructions in the world are the ruins of the Chanchan city in Peru.[1]. The oldest known earthen wall, located in the Taos Pueblo, New Mexico, dates back 900 years; however, to preserve it, annual maintenance is required. Towards the end of the 19th century and the beginning of the 20th century, there was a significant resurgence of interest in earth-based construction. Even after more than a century, many

residential buildings from this period, showcasing exceptional structural stability, durability, and environmental comfort.

However, due to their relatively quick building methods, materials like concrete and steel were preferred after the World War II reconstruction. In this context, earth construction became obsolete, and by the late 1950s, it had largely fallen out of use in the developed world. In 1979, the French laboratory CRATerre was founded and has since led numerous initiatives to promote earth-based construction. Additionally, academic institutions and universities around the world have begun offering instruction and coursework on building with Earth. In 1982, France launched a 72-home experimental housing project called Domaine de la Terre, employing various construction techniques, such as compacted earth block, rammed earth, and wattle and daube.

Figure I 2: Earth block structures in Jericho, Palestine, circa 6000 BCE

Figure I 1: Archaeological excavation site in Anatolia (Turkey), approximately 6000 BCE

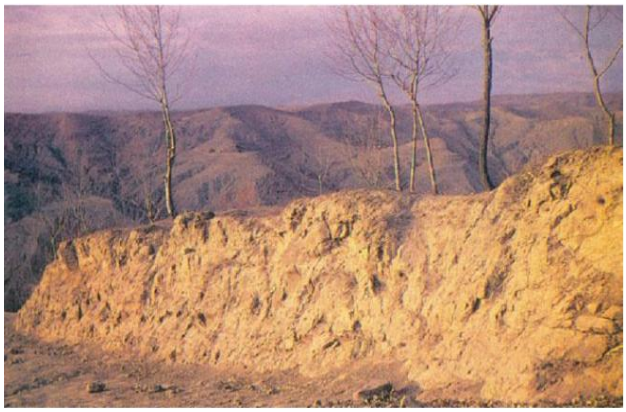


Figure I 3: Section of the Great Wall of China, constructed using rammed earth technique, around 2,000 years ago [2]

Figure I 4: Earth block vault near to Luxor, Egypt, dating to approximately 1300 BCE

Figure I 3: Late Georgian cob townhouses in Dawlish, Devon, circa 1820 [2]

I.3.Earth Construction

Clay-rich soil has been used as a primary construction material for around ten millennia. Today, nearly two out of three people worldwide live in homes constructed wholly or in part from raw earth. These earth-constructed areas span across all continents**.** Figure I.6

Figure I 4: Earth Architecture around the World [3]

I.4.The clays

In engineering science, soil particles are classified according to their diameter. Particles with diameters smaller than (< 2 µm) are called clay, while those between 2 µm and 0.08 mm are known as silt. Particles ranging from 0.08 to 2 mm are classified as sand, while larger ones are identified as gravel and stones. Loam, a distinct soil category, consists of a mixture of clay, silt, and sand and may occasionally contain larger aggregates as gravel and stones [2].

To understand the behavior of soil-based materials, it is necessary to study one of its main components: clay, particularly the monomineralic behavior of clays, their structures, and their affinities with water.

The clays group into micelles, which consist of several clay crystals of varying shapes. A crystalline unit, known as a sheet, is composed of multiple layered structures and interlayer spaces. These spaces contain water and, depending on the type of clay, tightly bound ions [3]. The stacking of these different layers gives rise to the diverse nature of clays.

The clay network is based on a set of silica tetrahedrons (SiO_4). These tetrahedrons share three of their vertices in a hexagonal plane, while the remaining vertex is shared with an aluminum octahedron (AlO_6). Different combinations of tetrahedrons and octahedrons exist depending on the type of clay[4, 5].

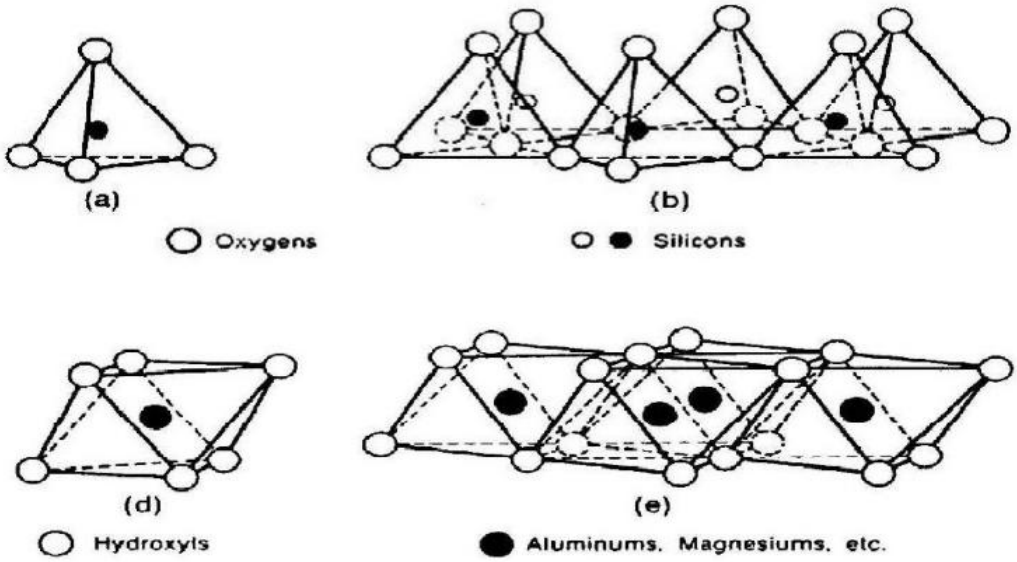


Figure I 5: Structural elements: (a) and (b) the tetrahedrons, (d) and (e) the octahedrons [8]

Kaolinites are 1:1 or else (T-O) dioctahedral clays, with each sheet measuring around 7.2 Å thick (Figure 1.8). When two kaolinite sheets align, the oxygen ions (O-) on the upper surface bond with the hydrogen ions (H+) on the lower surface, forming a strong O-H hydrogen bond. This bond, along with Van der Waals forces, provides the sheets with significant stability, making them highly resistant to water. As a result, the structure of the particles remains intact, and water does not disrupt their fundamental arrangement [6].

Other, more complex sheet structures also exist. Like kaolinite, these structures are composed of a first silica layer, an alumina layer, and then a second silica layer. The difference between these clays lies in the nature of the interlayer space. This space contains compensating cations that ensure bonding between the sheets. In this case, the size of a sheet and its interlayer space is around 10 Å.

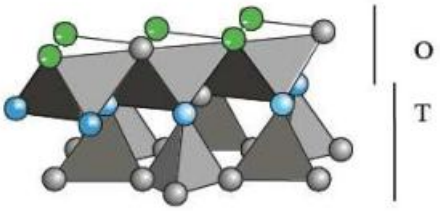


Figure I 6: Schematic representation of Kaolinites [7]

- **Illite** The substitution of some silica ions with aluminum ions creates a difference in ionic charge that is compensated in the case of illite by a K+ ion. This strong bond prevents water molecules from entering between the different layers, making illite less sensitive to water [3], [5].
- **Smectite (Montmorillonite)** Just like illite, some of the ions in the base structure are replaced. Aluminum atoms are substituted with magnesium or even iron. The compensatory cations are either sodium or calcium. The interlayer bonds formed in this way are much weaker, allowing Water to penetrate between the different layers and react with these compensatory ions, leading to soil swelling[3], [5].

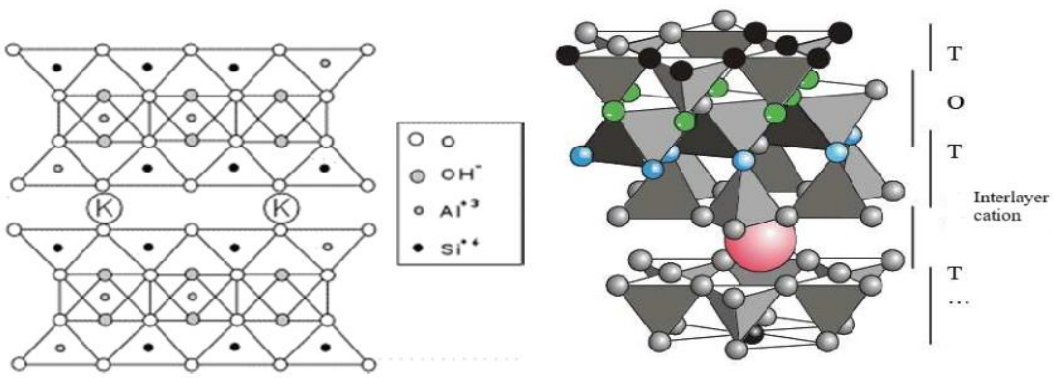


Figure I 7: Diagram of Illite on the left [19] and of complex clay structure (Smectite) [21]

The following figure presents the main types of clay.

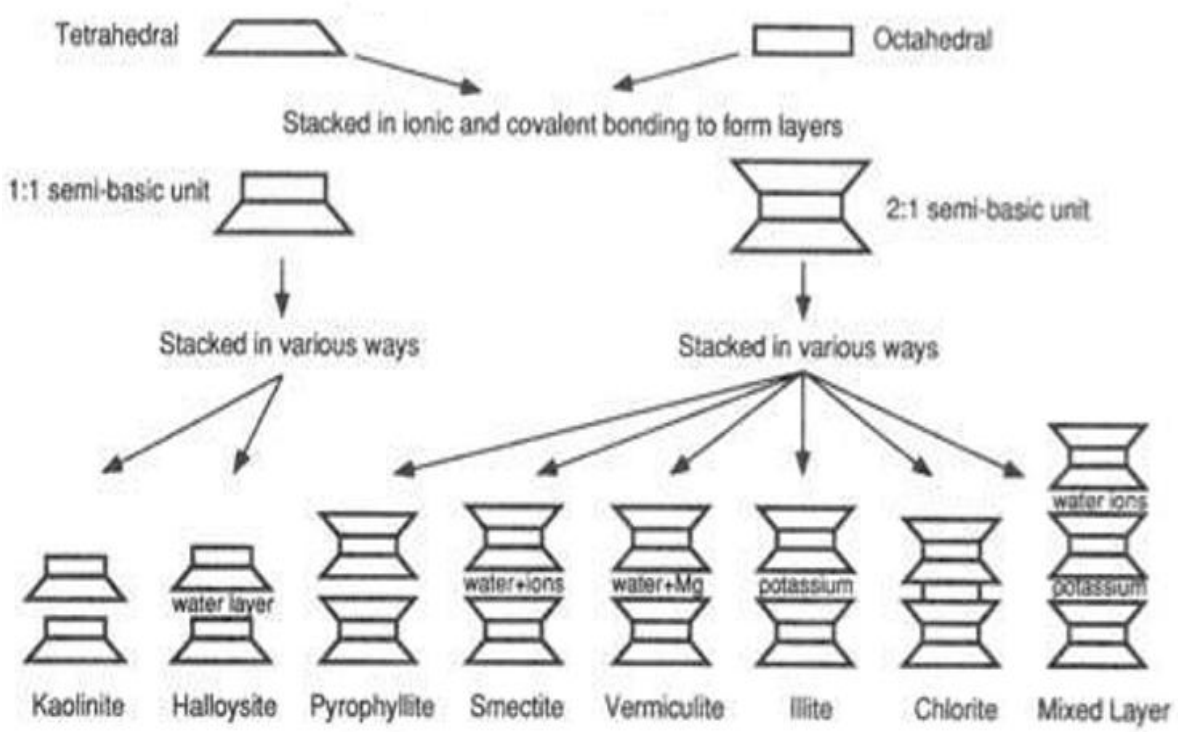


Figure I 8: The different types of clay

I.5.Properties of earth material in construction

I.5.1. Texture and granularity

Granularity is measured by grain size analysis through sieving for coarse grain fractions (gravel, sand, silt) and by sedimentation analysis for clay fractions. Elements such as gravel and sand form the skeleton of the material, while clays ensure the cohesion of the whole and control the plasticity and how the soil reacts to moisture. Consequently, clays govern shrinkage and swelling.

Experiences from earthen construction techniques allow for the definition of reference granular zones. It is very important to adhere to the minimum clay content for all techniques (see Figure I.11). This minimum could be established at 5%. The common clay percentage in all recommendations was found to be between 10% and 22% for compressed earth blocks (CEB) and between 10% and 15% for rammed earth. However, the silt content ranges from 10% to 25% for CEB[7]. Doat et al [8] demonstrated that a too-high silt fraction leads to excessive shrinkage in dried BTC, while a too-high fraction of larger-sized elements reduces the performance of BTC due to a lack of clay and cohesion. Guettala et al [9] showed that it is essential to properly fragment cohesive soil, as there is a critical size for clay soil clumps. Beyond a size of 5 mm, these clay clumps reduce the mechanical resistance of the treated soil.

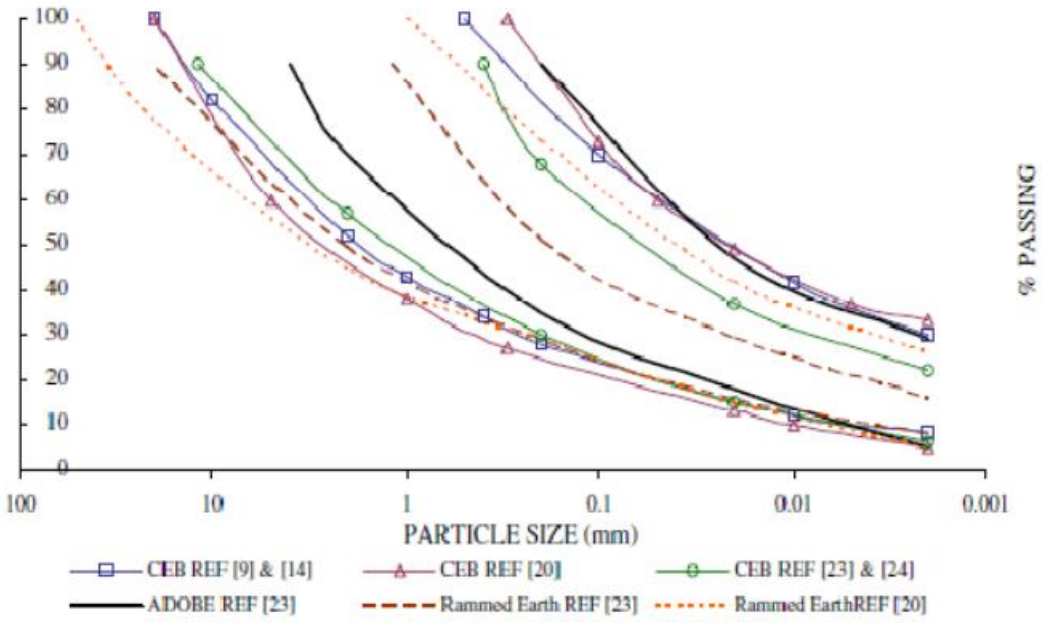


Figure I 9: Grain size ranges used for different earth construction techniques [10]

I.5.2. Plasticity

Plasticity defines the ability of soil to deform without significant elastic reaction, which could otherwise lead to cracking or crumbling. The plasticity of a soil, along with the transition between different consistency states, is determined by measuring the Atterberg limits. Figure I.12 represents the zones of Atterberg limits for earthen construction. Plasticity is similar for rammed earth and compressed earth blocks; however, the use of adobe requires a higher liquid limit and plasticity index compared to drier construction techniques like CEB or rammed earth. Generally, good construction earth has a plasticity index (PI) between 16% and 28% and a liquid limit (LL) between 32% and 46%[7].

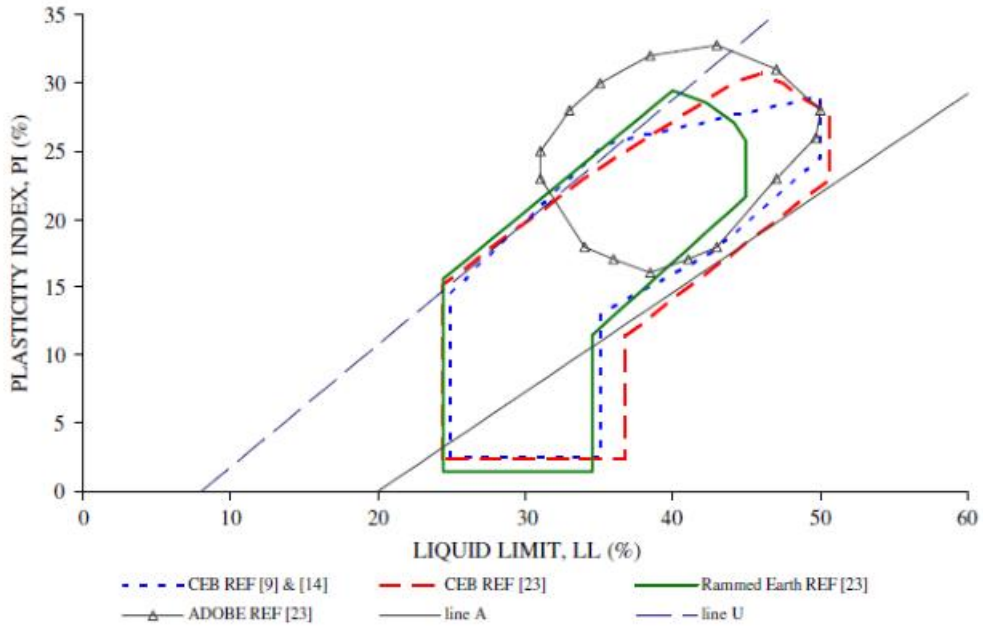


Figure I 10: The zones of Atterberg limits in earthen construction [10]

I.5.3. Organic matter and sulfate content in earth materials

In soil, the term soil organic matter encompasses all organic constituents, both dead and alive, of plant, animal, or microbial origin, whether transformed or not, that are present in the soil. Their effects include delaying the pozzolanic reaction because they coat the surface of the clay, thus hindering the lime/cement-clay reaction. According to Houben and Guillaud [10], organic matter content exceeding 1% in the soil represents a potential hazard. Vénuat [11], proposed another threshold of 2% for organic matter that should not be exceeded for soil treatment.

Soils can contain variable amounts of sulfate, which can lead to swelling under certain conditions (sulfate levels, sulfate solubility, distribution in the soil) due to the formation of ettringite. Sulfide minerals oxidize and react with other minerals present in the soil to form sulfates. This transformation induces an increase in volume due to changes in the atomic structure, in addition to the incorporation of water into the mineral structure. Houben and Guillaud recommended conducting a specific study for soils containing more than 2% to 3% sulfates.[10]**.**

I.6.Earth construction techniques

The idea of Earth construction involves using local soil as the primary building material. Structures can be built using a variety of techniques, such as compacted earth block or rammed earth [5]. Each methodology differs in the type of soil used, the compaction technique, the initial water content in the material, and the drying process [6].

I.6.1. Wattle and daube

This technique uses a wooden framework filled with soil or, more commonly, a mixture of soil and plaster. In this method, the material in its plastic state is pressed to fill the gaps. Here, the earth does not serve a structural purpose; instead, the wooden reinforcements provide the primary load-bearing capacity.

Figure I 11: a) Construction process using the Wattle and daube technique; b) House made of wattle and daube in Colmar, France

I.6.2. Cob

Cob is considered the most basic of all earthen construction techniques. It uses very few tools and doesn't require formwork or an internal framework, relying on stacking and molding mud to create walls. For this type of construction, the soil is moderately wet and often mixed with organic fibers to help the mud maintain its shape when stacked. The mud is shaped by hand or with a trowel or and is placed directly to build up the structure.

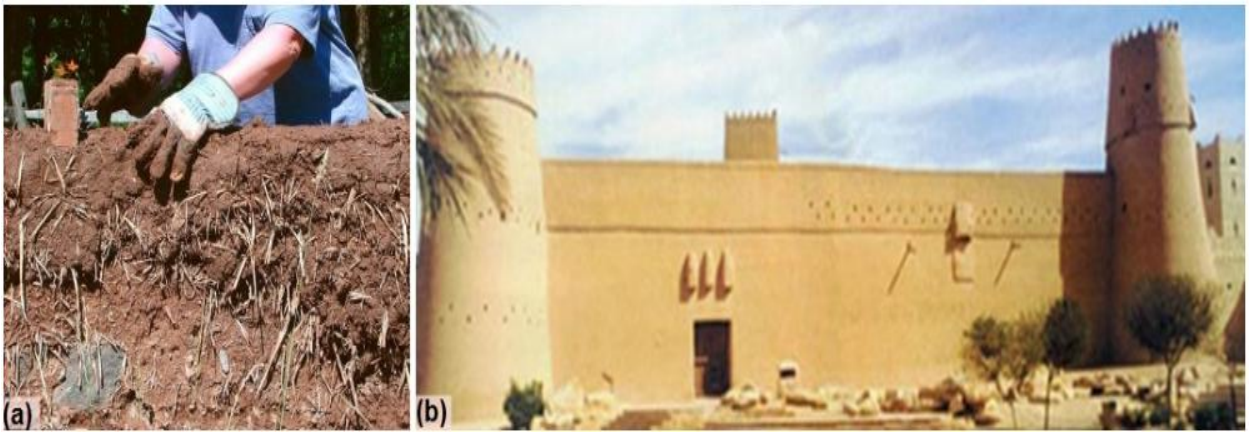


Figure I 12: a) Cob construction technique; b) Masmak Castle in Riyadh, Saudi Arabia

I.6.3. Rammed Earth

Rammed earth walls are constructed by compacting soil with temporary molds. These molds typically consist of two parallel surfaces connected by spacers, as illustrated in Figure I.15. The soil mixture is compacted layer by layer, with each layer being about 15 cm thick, using a tamper. The average wall thickness is around 50 cm. Once one mold is filled, another is positioned on top, and the process continues until the desired wall height is reached. The molds can be removed as soon as the next layer above is being formed.

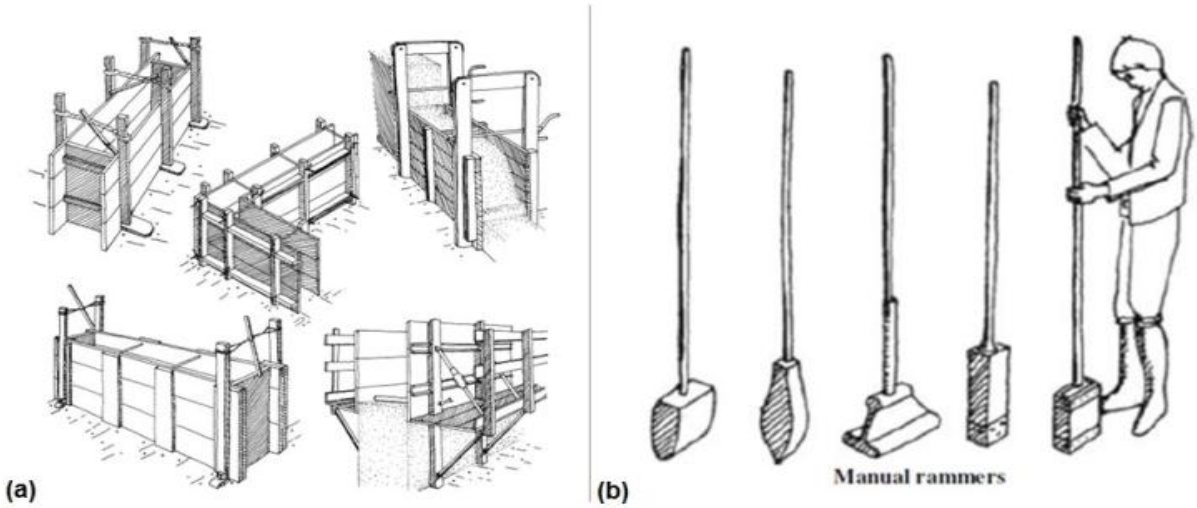


Figure I 13: a) Traditional rammed earth formwork; b) Rammers used for compacting rammed earth [15]

I.6.4. Adobe

Adobe is an ancient construction method that involves pouring a wet mixture of clay-rich earth into rectangular molds similar in size to conventional bricks. Organic fibers can be added to the wet soil mixture. Next, the adobe bricks are then sun-dried for several days before being used in masonry construction, much like regular fired bricks. The mortar used is typically composed of the same soil as the bricks. This construction method is commonly found in both urban and rural structures, as illustrated in Figure I.16.

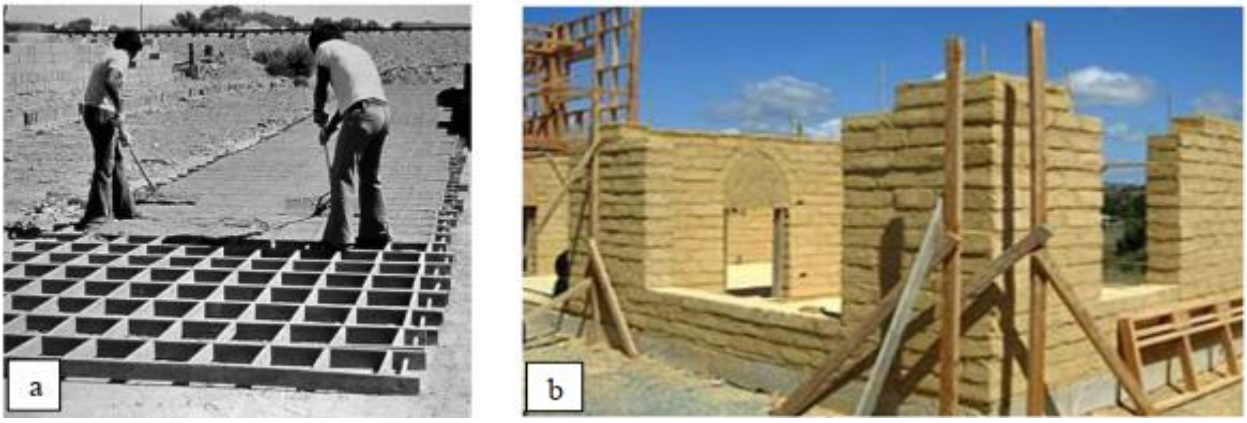


Figure I 14: a) Adobe brick manufacturing process; b) Construction of an adobe brick house

I.7.Compressed Earth Block (CEB)

Concerning traditional earthen construction, the CEB technique is considered a relatively recent development. This method was introduced in 1952 when Colombian engineer Raul Ramirez created a manually operated machine that produced CEBs and tiles for low-cost housing construction. While working at the CINVA Center, the Inter-American Housing and Planning Center in Bogotá, Colombia, Ramirez developed a manual press known as the Cinva-Ram. The device consists of a steel box with a base that is filled with earth and a lid connected to a lever that compresses the earth. When the lever is released, the lid is removed, and the bottom plate can be lifted to extract the CEB. With this process, a few workers can produce up to five hundred blocks per day. The low cost, user-friendliness, and ease of handling make this device highly practical for CEB production. It is still widely used around the world[12], as shown in Figure I.17, which illustrates the Cinva-Ram.

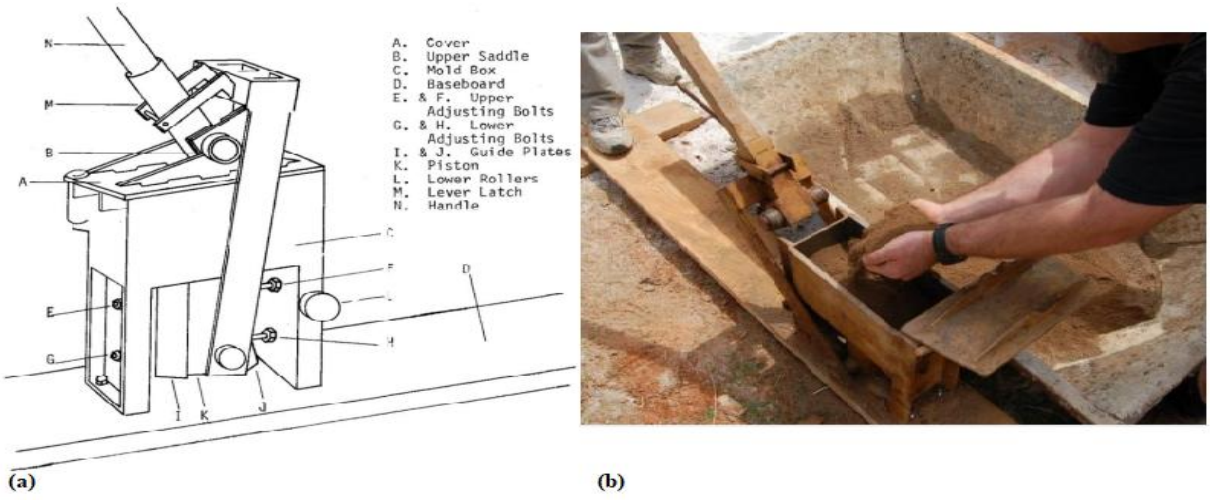


Figure I 15: a) Schema of Cinva Ram block making press; b) Cinva-Ram filled with soil mixture

CEB and the technologies used in their production have significantly evolved since they first emerged as a promising construction material in the 1950s. During the 1970s and 1980s, advancements in CEB production equipment included the improvement of manual block presses and the development of motorized hydraulic compression systems powered by gasoline, diesel, or electricity [13].

The French standard **XP P 13-901, 2001**[14] defines CEB as masonry elements of reduced dimensions and regular characteristics, produced by static or dynamic compaction of moist earth,

followed by immediate demolding. The use of various types of presses also enhances productivity, allowing for a wide range of products with diverse shapes and sizes. Although CEB can be compressed into different forms, the most common shape is a prismatic block. Typical block dimensions are approximately **29.5×14×9 cm,** with a weight of around 6 to 8 kg, allowing for walls with thicknesses of 15, 30, or 45 cm [15]. Figure I.18 illustrates some models of CEB.

Figure I 16: Various compressed earth blocks products [20]

I.7.1. Production Technique

The production of CEB involves moistening the clay, with or without a chemical stabilizer, then pouring it into a mold to compress it using either a motorized or manual press. Compaction can be carried out using a double-plate or single-cylinder press, with pressures typically varied from 3 to 8 MPa, although there is no fixed standard for compaction energy.[10]. The production process for CEB generally consists of five main stages, described below**.**

- **Soil preparation**: This stage involves drying, sieving, and disaggregation to obtain dry, homogeneous soil. Sieving removes undesirable elements such as roots, leaves, or particles larger than 15 mm. Disaggregation breaks down clumps bound by clay and crushes certain gravels to obtain smaller aggregates.
- **Mixing**: To ensure a uniform mixture, mixing is first done in a dry state, followed by a wet mixing process after adding water.
- **Compression**: The mixture is then compressed within a mold, either statically or dynamically, and immediately demolded to release the formed block.
- **Curing**: After demolding, CEBs can be stored immediately, though it's essential to avoid rapid drying for optimal strength. There is no standardized curing method, and variations exist in the literature regarding hardening processes. For non-stabilized CEBs, drying can occur over several days, protected from sun and wind, similar to adobe. However, if a

binder is added, the curing period is extended to allow two processes to occur: physico-chemical reactions between the soil minerals and additives, and gradual drying as manufacturing moisture evaporates [10]. During curing, humidity and heat conditions are crucial to achieving maximum strength. Blocks should be stored under a tarp or plastic cover in a humid environment with relative humidity over 70%. This curing period should last at least 7 days. After wet curing, the tarp is removed for the drying phase to allow for complete evaporation. For cement-stabilized blocks, a full curing period of 28 days is recommended [11][12].

I.7.2. Advantages of CEB

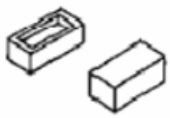
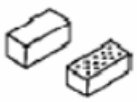
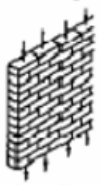
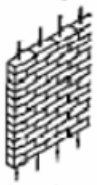
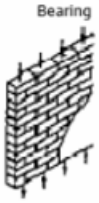
CEB offers numerous technical and ecological advantages as a construction material:

- Local availability: Earth is a readily available material, often sourced on-site or nearby, reducing transportation, fuel use, time, and costs.
- Ecological benefits: CEB has significantly lower greenhouse gas emissions compared to other construction materials. For example, CEB emits only 22 kg of CO_2/ton, while concrete blocks emit 143 kg of CO_2/ton, and fired clay bricks emit 200 kg of CO_2/ton. Using cement-stabilized clay blocks can decrease embodied energy by 62% compared to reinforced concrete frame structures and by 45% compared to masonry with fired clay bricks and solid reinforced concrete slabs. Turner et al. [73] estimate the embodied energy of masonry with CEB at 550-700 MJ/m³, compared to about 2200 MJ/m³ for fired clay bricks.
- Structural versatility: CEB is suitable for load-bearing structures and does not require plastering. The production equipment is versatile, available in both manual and motorized forms, and scalable from small communities to industrial levels.
- Employment opportunities: CEB production creates jobs by providing training opportunities for unskilled and unemployed individuals.
- Cost-effectiveness: The cost of CEBs is generally lower than that of fired bricks, though it varies based on local materials, labor, and equipment.
- Comparative Advantages of CEBs Over Other Materials:
- CEB vs. Adobe Bricks: CEBs offer higher compressive strength and durability than adobe bricks, thanks to the compaction process. They also provide smoother, more regular surfaces and come in various shapes.

- CEB vs. Rammed Earth: CEBs allow greater flexibility in architectural design and reduce wall cracking due to drying shrinkage, as cracking occurs in individual blocks rather than across an entire wall.
- CEB vs. Fired Bricks: CEBs have superior thermal performance and require no firing energy, unlike fired bricks.

Table I.1 presents a comparative analysis of CEB with other masonry materials, including fired bricks, adobe, and concrete blocks. The comparison covers aspects such as shape and size, surface finish, compressive strength, thermal properties, density, durability, and suitability for use in masonry applications. CEBs stand out for their smooth surface, moderate to high compressive strength, and environmental benefits, while also providing a balance between durability and cost-effectiveness. Unlike adobe, CEBs have a more regular shape and better durability, and they provide thermal insulation comparable to concrete blocks.

Table I 1: Comparison between CEB and other masonry materials [21]

	Unit	CEB	Fired Bricks	Adobes	Concrete blocks
shape and size Type L x l x h	cm	 29,5 x 14 x 9	 22 x 10,5 x 6,5	 40 x 20 x 10	 40 x 20 x 15
ASPECT - Surface aesthetic interest		**Smooth** **Medium to good**	**Rough to smooth** **good to excellent**	**Irregular** **Poor**	**Rough** **Medium**
PERFORMANCES **Compressive strength** **Moist** **- reversible thermal expansion** **- Thermal insulation** **- Apparent density** **- Durability**	Mpa % W/m°C kg/m³	1 à 4 0,02 à 0,2 0,81 à 1,04 1 700 à 2 200 Low to Very Good	0,5 à 6 0 à 0,02 0,7 à 1,3 1 400 à 2 400 poor to excellent	0 à 5 - 0,4 à 0,8 1 200 à 1 700 Poor	0,7 à 5 0,02 à 0,05 1,0 à 1,7 1 700 à 2 200 Low to very good
Use in Masonry		Bearing  Without Plaster	Bearing  Without Plaster	Bearing  With Plaster	Filling  With Plaster

I.7.3. Limitations of CEB

The traditional construction of walls using earth as a building material directly, in any form, has certain disadvantages:

- Correct identification of suitable soil is necessary; otherwise, the soil may not be suitable or readily available.
- Lower technical performance in terms of strength, durability, and load-bearing capacity compared to concrete.
- Achieving large spans, tall, or long buildings is difficult due to structural limitations of CEB.
- Untrained teams producing low-quality products.
- Durability issues, such as sensitivity to water and dimensional instability, can lead to shrinkage and cracking of CEB. [16].

I.7.4.CEB Construction around the world

Many notable CEB buildings have emerged in recent years, showcasing the potential of this construction technique. When well-designed and properly executed, CEB buildings offer significant benefits in terms of architecture, economy, comfort, and durability. An example of this exceptional work is the Al Medy Mosque in Saudi Arabia. The mosque covering 420 m², features a vaulted roof and a minaret that stands 18.05 meters high. Remarkably, it was constructed in just 49 days using CEB.

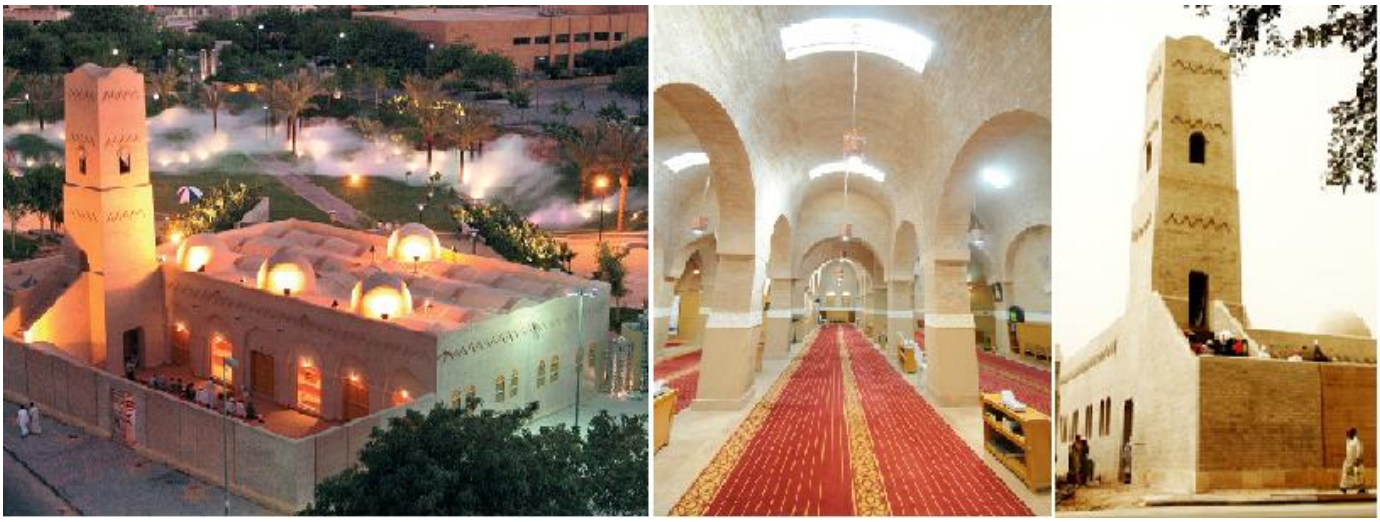


Figure I 17: Al Medy Mosque, Riyadh, Saudi Arabia

The Djoloff Hotel in Senegal is a citizen-driven, responsible, and ecological project. Like its other creations, this building is extremely well thought out and executed to fully benefit from the advantages of earth construction. The walls are made from CEB, ensuring a stable and comfortable interior temperature due to the material's thermal inertia. Concrete beams provide structural support, while an overhanging metal roof shields the walls from weather exposure and offers shade from the sun. Ventilation openings in the walls facilitate natural airflow, enhancing comfort. The entire structure showcases a contemporary architectural style while harmoniously integrating with its surrounding environment.[17].

Figure I 18: Hotel Le Djoloff, Dakar, Senegal

Figure I.21 illustrates the Earth Architecture Center in Mopti, Mali. CEB were used in the construction, particularly for forming both the walls and barrel vaults. This construction system is particularly well-suited to the local climatic conditions, offering benefits such as thermal regulation and sustainability. At the local level, an example is the semi-collective R+1 housing in Sidi Bel Abbes, Algeria (Figure I.22).

Figure I 19: The Centre for earth Architecture in Mopti, Mali

Figure I 20: R+1 semi-collective housing in Sidi Bel Abbes, Algeria [24]

I.8.Conclusion

The chapter begins with an overview of earthen construction, including the composition of earth, its structural properties, and various associated techniques. It further examines the advantages and disadvantages of CEB and concludes with an overview of construction practices around the world.

Chapter II:

Earth stabilization techniques

II.2. Introduction

Soil stabilization enhances strength, durability, and suitability for construction. It can be achieved through mechanical, physical, chemical, and fiber-based methods. While mechanical and physical approaches modify soil density and structure, chemical stabilization with lime and cement improves bonding and strength. Incorporating fibers enhances flexibility and crack resistance, while waste materials provide a sustainable alternative, reducing environmental impact and improving performance. This chapter examines cement and fiber stabilization, along with the benefits of waste-based stabilization in earth construction.

II.2. Soil stabilization

Soil stabilization encompasses all techniques aimed at improving the physicochemical, mechanical, and hydraulic properties of soils. It should enable the following:

- The reduction of porosity.
- The reduction of shrinkage and swelling.
- Achieving better cohesion.
- Improving resistance to erosion and surface waterproofing.
- Achieving better dry and wet compression, tension, and shear resistance.

Three main stabilization techniques are distinguished: mechanical, physical, and chemical.

II.2.1. Mechanical stabilization

Soil is mechanically stabilized by increasing its density through compaction. This method reduces the porosity of the soil. Compaction produces a material with high mechanical properties; however, these materials remain highly sensitive to water. When exposed to water, the materials become plastic again and lose all resistance to compression. This is why compaction is typically combined with other methods, such as chemical stabilization. Compaction is usually influenced by three factors: the method, the energy applied, and the granularity of the soil.

There are essentially four main methods of compaction: static compaction, dynamic compaction by vibration, dynamic compaction by impact, and kneading compaction. Each of these compaction methods corresponds to a specific mode of production or application of the earthen material [10]. Dynamic compaction provides approximately 50% higher resistance compared to vibro-compaction and about 20% more than static compaction [18].

Regardless of the type of soil and the compaction method used, a higher compaction energy reduces the optimal moisture content (OMC) and leads to a higher dry density, as shown in Figure II.1 [19, 20] However, excessively high compaction energies can cause additional phenomena that are detrimental to the quality of the material. For instance, excessive pressure during compaction can lead to stratification in the produced blocks.[11][10]. Guettala et al. [9]. showed in their work on stabilized earth blocks that the mechanical strengths increase with the compaction stress up to an optimum of 17.5 MPa, beyond which there is a decrease in mechanical strength (Figure II. 2).

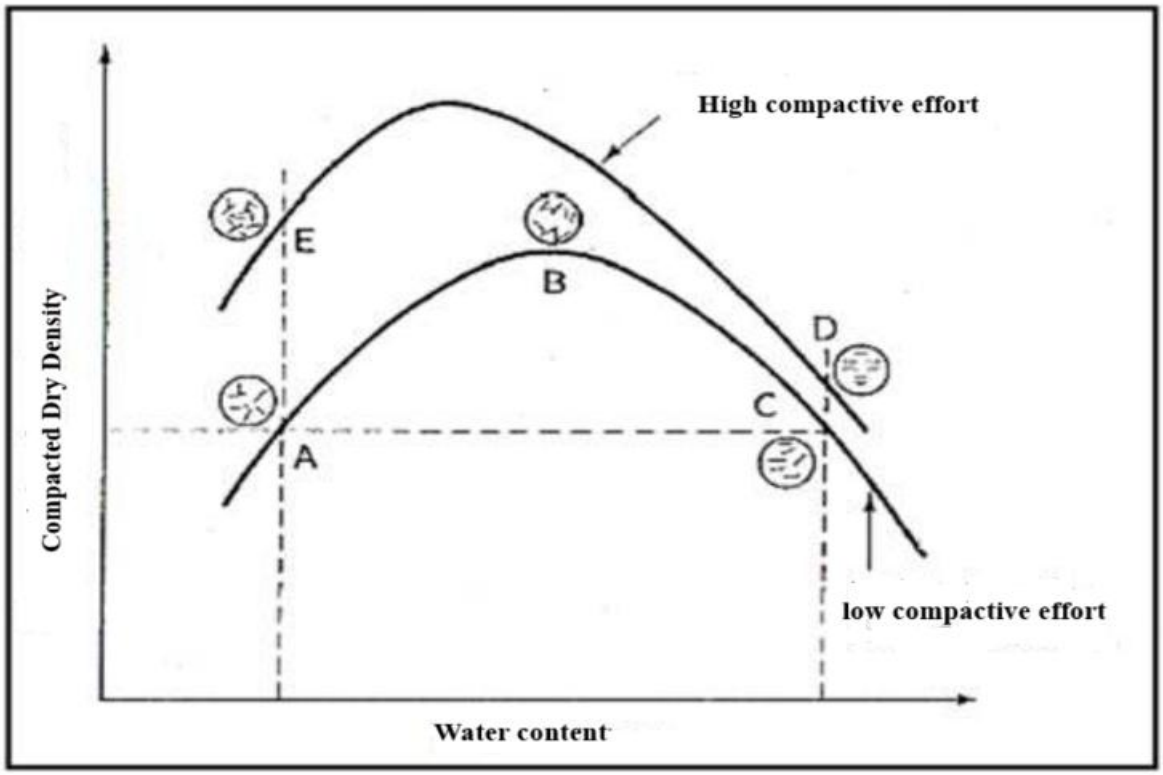


Figure II 1: Impact of compaction energy on soil structure [27]

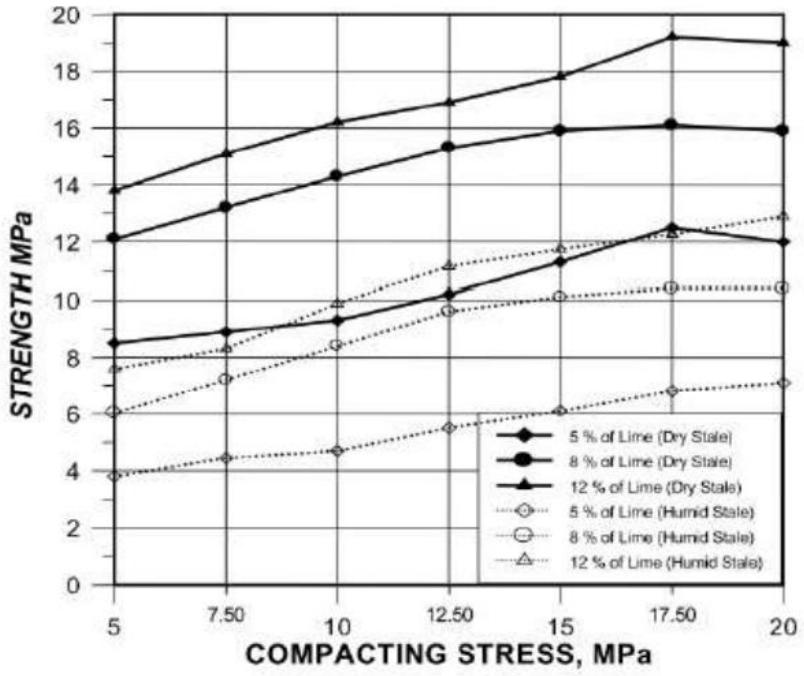


Figure II 2: Impact of compacting pressure on the compressive strength of CEB [12]

II.2.1.1. Influence of water content on density

The density of a CEB depends on several physical parameters: granularity, density of the soil particles, water content, compaction effort, and compaction method. It is noted that the properties of compressed earth are more influenced by the water content than by any other parameter [7]. Almost all soils exhibit a similar relationship between dry density and water content when compacted [19]. The maximum compaction of a soil is achieved when its void ratio is at a minimum, and this state is reached at what is called the optimal water content of the soil. A soil that is "too dry" will experience significant friction between soil particles. Conversely, if the soil is too wet, compaction becomes less effective, as a substantial portion of the compaction energy is absorbed by the incompressible water, preventing its transmission to the soil particles.

In the case of CEB formulation, the determination of the OWC is carried out in the laboratory. In road geotechnics, the OWC is determined using the Proctor test, which involves compaction. This test is not recommended for clay soils, as it causes localized saturation of the sample under the compaction hammer, resulting in a sample that is heterogeneous in terms of density [21].

Mesbah et al. [22] showed that static compaction is better suited for clay soils. Consequently, the Proctor test has proven to be of little use and not representative of the manufacturing conditions

for compressed bricks. It is nearly impossible to fabricate test samples using the Proctor mold, but more importantly, it has been demonstrated that there is no relationship between "Proctor energy" and the static compaction energy used in block manufacturing[23]. It is preferable to proceed as on-site, meaning that the optimal water content should be determined directly using the block press [24]

II.2.2. Physical stabilization

Soil is physically stabilized by modifying its texture and improving its characteristics through granularity adjustment. Izemmouren and Guettala [25] studied the effect of the sand content on the durability of CEB. Two types of crushed sand were used for stabilization by adjusting the soil's particle size distribution. The results showed that the mechanical strength in both dry and wet conditions increased with the sand content. However, the sand content does not have a significant effect on total absorption (Figure II. 3).

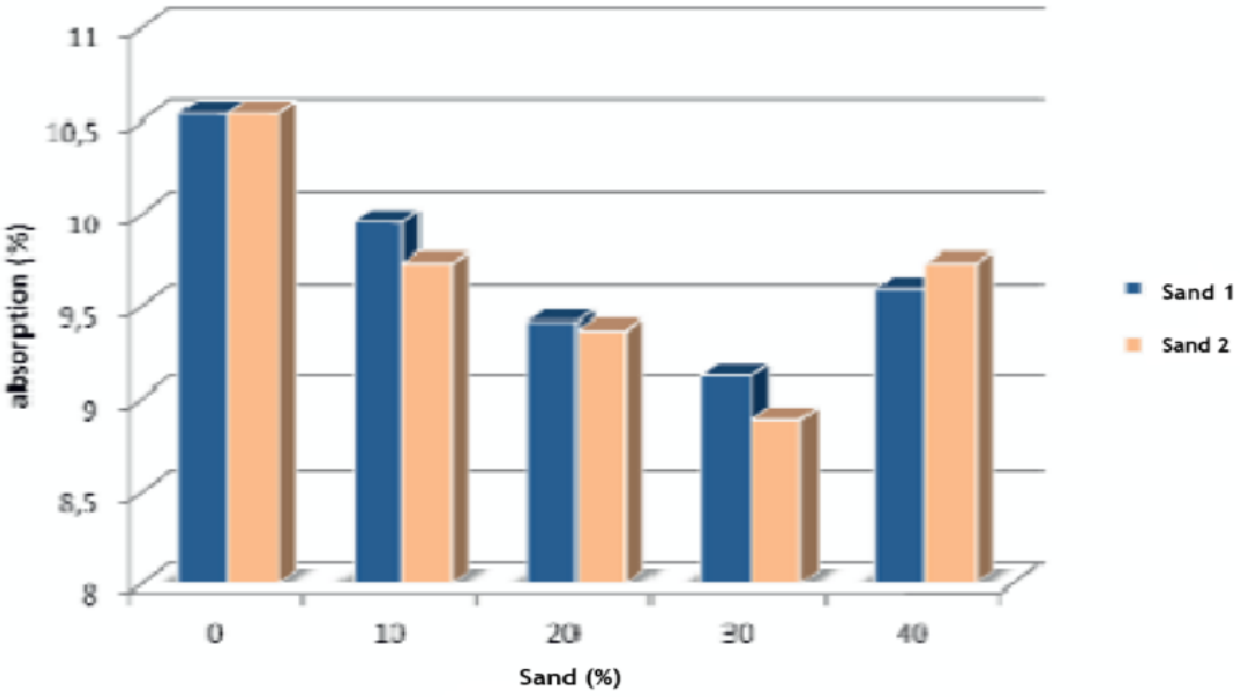


Figure II 3: Total absorption as a function of sand content [32]

II.2.3. Chemical stabilization

Chemical stabilization modifies the properties of the soil through the addition of certain substances. To enhance mechanical properties and reduce water sensitivity, hydraulic binders (such as cement, lime) or chemical products are often used, making the treated soils less hydrophilic and reducing their sensitivity to water. Numerous chemical stabilizers exist, each offering different improvements to the soil depending on their properties.

II.2.3.1. Lime

Stabilization of soil with hydraulic binders generally leads to an improvement in the mechanical properties of the treated soil. In the case of lime treatment, the pozzolanic reaction results in desirable mechanical characteristics. Locat [26] showed that these characteristics gradually increased throughout the study (one year). The change in the plasticity index is linked to the amount of lime added. These alterations in the rheological behavior of the soils result in enhanced functional properties of the treated clays.

II.2.3.2. Cement

Cement is undoubtedly one of the best stabilizers for CEB. Adding cement before compression improves the material's properties, particularly its water resistance, due to the irreversible bonds it creates between the larger particles. Cement primarily acts on the sand and gravel, much like in concrete or a sand-cement mortar. Therefore, it is unnecessary and even detrimental to use soils that are too clay-rich (over 30%)[27].

Venuat [11], after studying the use of all cement grades in stabilization, asserts that all standardized cements are suitable for soil stabilization, but it is preferable to use lower-grade cements, as high strength is not necessary. However, other authors[28] suggest using a specific type of cement depending on the nature of the soil.

For soil with a high clay content, a cement rich in alite (C_3S) and belite (C_2S) is required, which produces a significant amount of portlandite ($Ca(OH)_2$) after hydration. Verdeyen [29] recommends using cement for soils with a clay content that does not exceed 20 to 30% (plasticity index Ip < 25%) [30].

II.2.3.3. Mechanism of Cement stabilization

Cement powder contains several different phases. The main phases are: alite (C_3S), belite (C2S), tricalcium aluminate (C_3A), tetracalcium aluminoferrite (C_4AF), and periclase (MgO). Minor phases are also found, such as free lime (CaO), and sodium and potassium sulfates (Na_2SO_4 and K_2SO_4) [31]. Depending on the proportions of these elements, cements can have different properties. For example, a high C3S content will result in high strength, whereas a cement with a high C_3A content will have low resistance to the effects of aggressive water. Once the mixture with the soil is made, the cement will dissolve and hydrate if there is enough water to form hydrated compounds. The primary reaction comes from the hydration of the two calcium silicates (C_3S and C_2S), which form two new compounds: portlandite (CH) and calcium silicate hydrate (C-S-H: $3CaO.2SiO_2.3H_2O$).

$$C_2S + 2H \rightarrow C\text{-}S\text{-}H + CH \quad (1)$$

$$C_3S + 3H \rightarrow C\text{-}S\text{-}H + 2CH \quad (2)$$

The hydration of tricalcium aluminates (C3A) depends on the gypsum content in the cement. In the presence of gypsum, ettringite is formed, which contributes to an increase in strength.

$$C_3A + 3CSH_2 + 26H \rightarrow C_6AS \quad (3)$$

In the absence of gypsum, C3A reacts with water to form C_4AH_{13}, C_2AH_8, and C_3AH_6. C_4AH_{13} and C_2AH_8 are unstable and, under the influence of the heat of hydration, they transform into C_4AH_8.

The ferrite phase (C4AF) reacts quickly in the presence of gypsum to form ettringite according to the following reaction:

$$C_4AF + {}_3CSH_2 + 30H \rightarrow C_6AS_3H_{32} + FH_3 + CH \quad (4)$$

II.3. Effects of cement on the properties of the stabilized material

For CEB, the compressive strength remains highly dependent on the dosage, with 8% cement often being an economically acceptable upper limit [8]. Gooding [32] states that stabilized earth blocks with 3% to 12% cement by weight are the most common formulation. Heathcote [33] shows that the minimum content, below which strength becomes independent of the amount of cement used, is 0.75%. This contrasts with the conclusions of various studies suggesting that a range of 5% to 12% is more appropriate. For instance, Walker[34] states that blocks containing under 5% cement tend to be too brittle to withstand handling. Subsequently, Walker [35] acknowledges that the clay content in soil should range from 5% to 20%, the plasticity index should vary from 2.5 to 30%, and the cement content should be within 4% to 10%.

II.3.1. Mechanical strength

Considering compressive strength, studies on soil stabilization highlight an increase in compressive strength of clay soils, regardless of the mineral nature of the clays, as shown in Table I-2 [18], [35]–[43]. The hydration products of cement formed through the pores create rigid bridges between the clay and sand particles. These bridges strengthen the material and increase the overall strength of the soil [18]. Consequently, increasing the proportion of cement enhances the compressive strength of the soil.

Reddy [43] studied the microstructure of cement-stabilized soil. He showed that increasing the proportion of cement reduces the porosity volume of soil samples by forming hydrates that group together the sand and clay particles. Horpibulsuk [44] studied the development of compressive strength with a fixed water content and a significant variation in the proportion of cement. Cement hydration can be divided into three categories:

- The active phase, for low cement proportions (0 to 10%), is a phase where the compressive strength of the soil increases significantly due to the substantial formation of hydrates.
- The inert phase, for cement proportions ranging from 10% to 30%, sees a less significant increase in strength with the appearance of a plateau.
- The deterioration phase, for cement proportions above 30%, results in a decrease in compressive strength after this proportion is reached. The water content in the soil is insufficient to form hydrates.

The water content, which depends on the Proctor optimum, is also a determining factor for the development of cement hydrates. A water content 20% higher than the normal Proctor optimum allows for optimal hydrate production, thereby providing the soil with better mechanical performance, despite the increased porosity of the soil.

Over time, curing of the stabilized samples increases the compressive strength of the soil. Bahar[18] indicates that 70% of the compressive strength is achieved after 7 days for cement proportions below 10%, and 50% for cement proportions above 10%. This observation is also reported by Meukam [45] for stabilizer proportions below 10% on lateritic soil.

The clay content in cement-stabilized soil influences the material's performance. Walker [35] shows that an increasing proportion of clay decreases the compressive strength of compressed earth blocks (CEB).

Table II 1: Compressive strength values of cement-stabilized soils

Reference	Technique	Specimen Format [cm]	Characterization Method	Slenderness	Cement %	Fc [MPa]
Walker [35]	CEB	29.5 x 14 x 12.5	Test with fretting	0.42	5 and 10%	0.05 to 1.2
	Mortar	Cube of 5	Test with fretting	1	5, 10, 15%	0.20 to 4.73
Guettala [36]	Static Compression [15MPa]	10 x 10 x 20	RILEM	2	5 and 8%	15.4 and 18.4
Jayasingue [41]	Rammed earth	100 x 14 x 65	Test with fretting	1.5	6.8 and 10%	2.06 to 3.09
						1.69 to 2.35
						1.52 to 1.92

Bahar [18]	Static, Dynamic, and Vibro-static Compression	Proctor normal diameter 12 x height 18	RILEM Test	1.5	0, 4, 6, 8, 10, 12, 15, and 20%	1.5 to 6.5
Ngowi [40]	CEB	26 x 12 x 9	British Standard		0, 5, 7, 10, and 15%	1.84 to 8.5 1.8 to 10.6
Hakimi [37]	CEB	29.5 x 14 x 9.3	RILEM	1.4	0 and 4%	1.54 to 1.8
	Static	Ø 8 x 12		1.5		2.67 to 3.93
Reddy [43]	CEB	30.5 x 14.3 x 10	Test with fretting	0.33	6, 8, 12%	3.13 to 7.19
Basha [39]	Static	Ø 5 x 10	British Standard	2	0, 2, 4, 8, 12%	0.1 to 0.32
Hossain [42]	Static	Ø 3.9 x 7.8	ASTM	2	0, 2, and 4%	0.1 to 0.68
Miquelleiz [38]	Static	Ø 6.5 x 3	Test without fretting	0.46	3, 4, 9, 12, 15, and 18%	5.2 to 11

Regarding tensile strength, few studies have characterized that of raw earth products stabilized with cement. As with non-stabilized materials, the splitting tensile strength varies depending on the size, the type of clay, and the manufacturing technique.

Hakimi [37]studied the splitting tensile strength on cylinders with a slenderness ratio of 1.5 and on CEBs using three-point bending. The addition of cement increases the tensile strength of the soil by 20 to 40%, depending on the specimen format used. However, the overall strength remains low, averaging around 0.2 MPa.

The method used to manufacture bricks influences the tensile strength of a soil sample. Pkla [46] studied the tensile strength of adobe and CEBs. He observed that adobe has a better bending/compression ratio due to its higher water content during production, which, after drying, makes the clay more cohesive.

The clay nature of a soil can indicates whether a stabilized earth material will perform well or poorly. Mollard [47] studied the extrusion of bricks made from a stable clay, kaolinite, and a swelling clay, palygorskite. Using a stable clay combined with a significant amount of cement (30%) can increase the tensile strength of an earth product up to six times.

II.3.2. Physical strength

Kerali[48], through the results of his research presented in Figure II.4, observed that the incorporation of cement into the soil mixture improves the dry density of CEB. However, the improvement is more significant with an increase in compaction pressure.

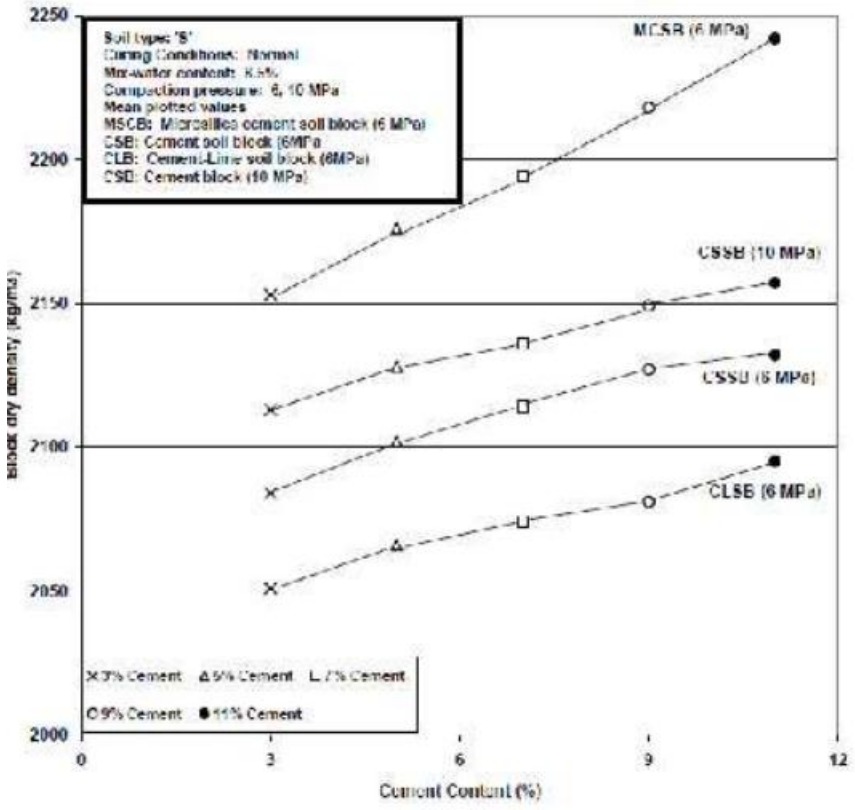


Figure II 4: Effect of cement content and compaction pressure on the dry density of CEB [58]

II.3.3. Durability of CEB

The addition of cement reduces the deterioration of earth by water. Raw earth bricks stabilized with 5% and 8% cement show no signs of material disintegration after exposure to climatic conditions for 2 years. Cement provides better resistance to this phenomenon than hydraulic lime at the same percentage [36]. Hall [49], [50] studied the saturation time of compressed cubic samples of rammed earth. After 1 hour of water injection, the rammed earth stabilized with 6% cement showed no signs of deterioration, unlike the unstabilized rammed earth (Figure II.5).

The results of Meukam [51] study show that adding cement improves the moisture resistance of stabilized earth blocks. Figure II.6 illustrates the variation in water absorption rate over time for different cement contents. The study revealed that with higher cement content, the water absorption rate decreases.

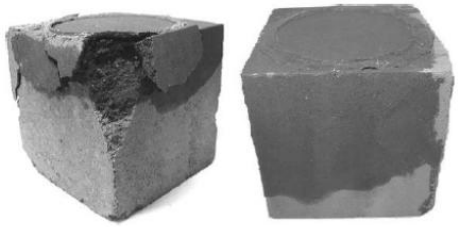


Figure II 5: Water absorption resistance of unstabilized and 6% Portland cement-stabilized rammed earth [60]

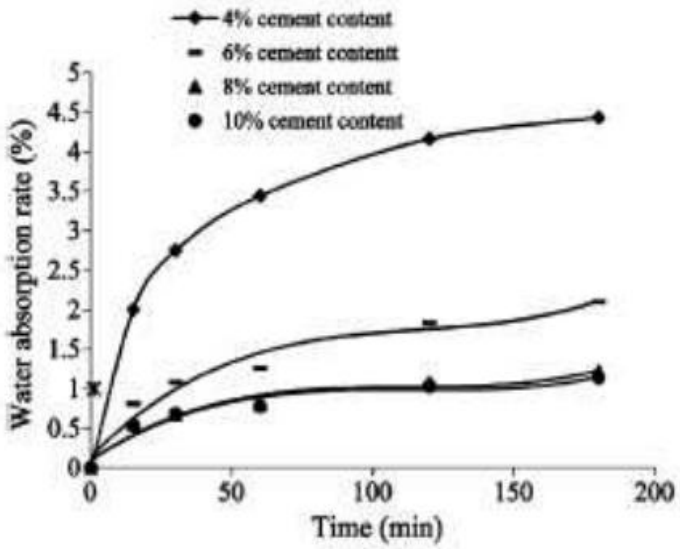


Figure II 6: Variation of the water absorption rate over time in CEB stabilized with different cement contents [61]

II.4. Fiber stabilization

Fiber reinforcement stabilization is widely used around the world in earthen construction. Fibers are primarily used in the production of molded blocks through kneading, typically with clayey soils that often exhibit significant shrinkage. The artisanal production of adobe bricks stabilized with straw is highly varied, but fibers are also known to be used in the construction of wattle and daub, earth-straw mixtures, cob, CEBs, and rammed earth [52] . In the case of synthetic fibers, they are generally used for soil reinforcement to increase shear and compressive strength [53], [54].

II.4.1. Types of Fibers

We can say that under the term "fibers" lies a large family of materials that have been introduced into the market with new uses. They are classified according to their origin (artificial, natural, and synthetic), their shape (needle, wavy, straight, etc.), their dimension (micro or macro-fiber), and also by their mechanical properties. However, to choose fibers to use for a given application, it is necessary to consider the compatibility of the fiber with the matrix and the performance mode of the composite. Several types of fibers are used in construction; they can be classified by family.

II.4.1.1. Natural fibers

Natural fibers can be categorized into three main groups based on their source as illustrated in Figure II.7 [55].

-Plant fibers: The incorporation of plant fibers to strengthen composite materials provides two key benefits. Firstly, these fibers are abundant and cost-effective, making them a valuable resource for integrating agricultural materials into construction. Secondly, using plant fibers helps minimize environmental impact compared to traditional composites, as they are renewable, biodegradable, carbon-neutral, and require minimal energy for production.

Plant fibers comprise:

- fibers from seed hairs (cotton, kapok),
- bast fibers extracted from plant stems (flax, hemp, jute, nettle),
- fibers extracted from leaves (sisal), trunks (palm tree), and fruit husks (coconut).

– **Animal fibers**: The most prominent and commonly used fiber is wool, valued for its exceptional thermal insulation properties, high absorbency (16-18%), and remarkable elasticity (45%).

- Mineral fibers: Asbestos is the only naturally occurring mineral fiber. Its resistance to heat, chemical exposure, fire, and electricity, along with its absorbent properties, made it highly desirable for industrial applications and construction. However, due to its carcinogenic risks, its use has been progressively banned.

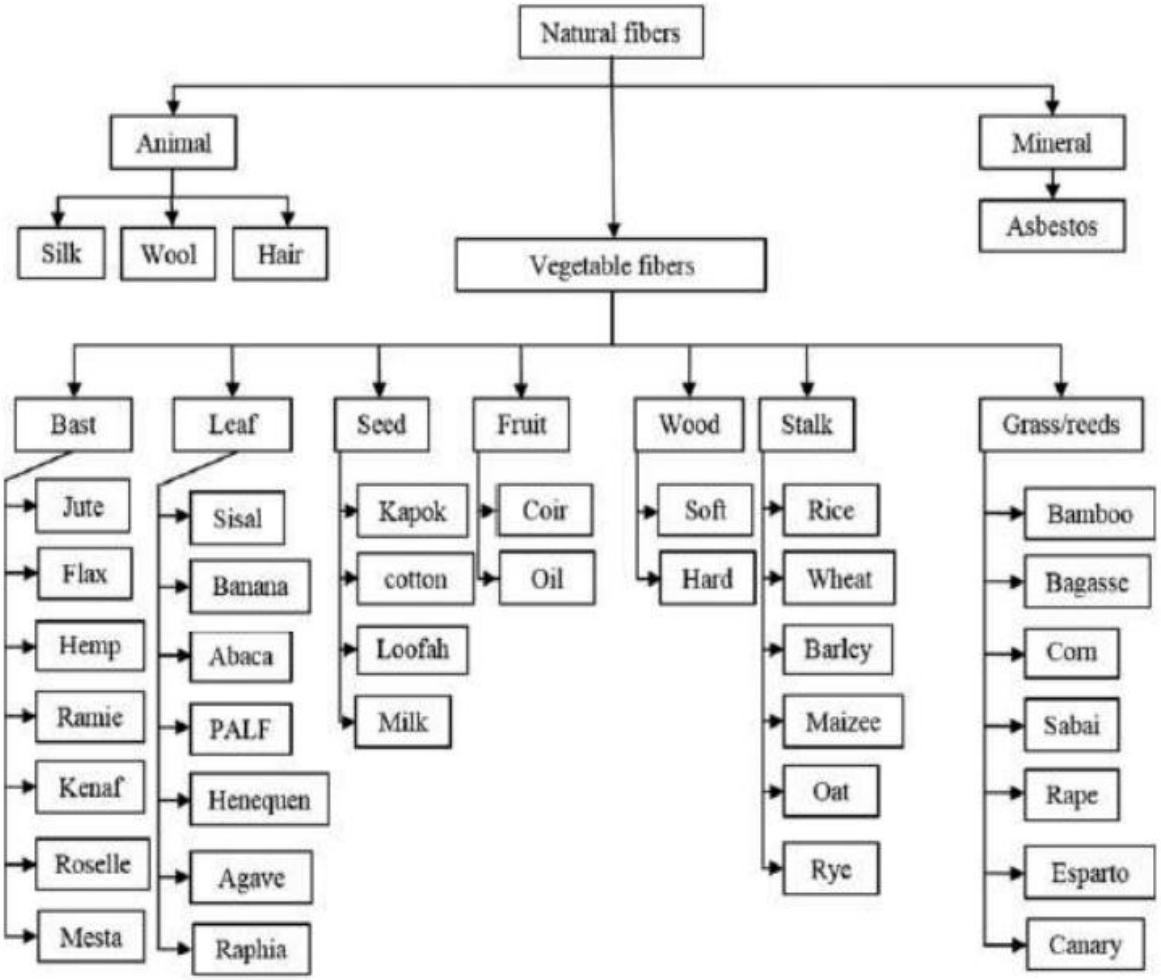


Figure II 7: Classification of natural fibers [66]

II.4.1.2. Synthetic fibers

Synthetic fibers are manufactured from synthetic polymers derived from substances or compounds provided by the petrochemical industry. They made their appearance in the early 20th century, following the success of viscose fiber. Since that time, numerous synthetic fibers have emerged, each possessing properties tailored to specific applications. Like artificial fibers, these fibers are produced through spinning. They attract significant interest from many industries due to their low cost, availability, independence from seasons, and especially the ability to modify and adapt their properties. However, they are heavily criticized for their environmental impact during production and post-use, as well as the challenges involved in recycling. The primary categories of commercially available synthetic fibers are Polyesters, Polyamides (Nylons), Polyvinyl derivatives, Polyolefins: Polypropylenes and Polyethylenes, the latter of which are becoming increasingly significant and now represent approximately 8% of all synthetic fibers.

II.4.1.3. Artificial fibers

This category of fiber is the most widely utilized in the industrial sector overall, and particularly in civil engineering. It encompasses glass fibers, steel fibers, carbon fibers, and others. Today, these fibers are the most prevalent in the construction industry.

II.4.2. Plant fibers

Plant fibers are natural fibrillar structures primarily composed of cellulose, pectins, hemicelluloses, and lignin, along with smaller amounts of non-nitrogenous extractives, crude protein, lipids, and mineral matter. The proportion of these constituents varies significantly depending on the plant species, age, and specific plant parts.

II.4.2.1. Chemical Composition of Plant Fibers

Plant biomass is made up of several macromolecules that are intricately bound together within the plant cell wall. As previously discussed, the primary components include cellulose, hemicelluloses, pectins, and lignin. These elements are organized in a highly complex structure.

In wood, cellulose is concentrated inside the fiber (Figure II. 8). The outer walls of the fiber are mainly composed of lignin and hemicelluloses, while the inter-fiber junction lamellae are composed almost entirely of lignin. An additional network of pectins (acidic polysaccharide

polymers) increases the complexity of the matrix. The polysaccharide network can also be reinforced by a secondary network of HRGP (Hydroxyproline Rich Glyco Proteins).

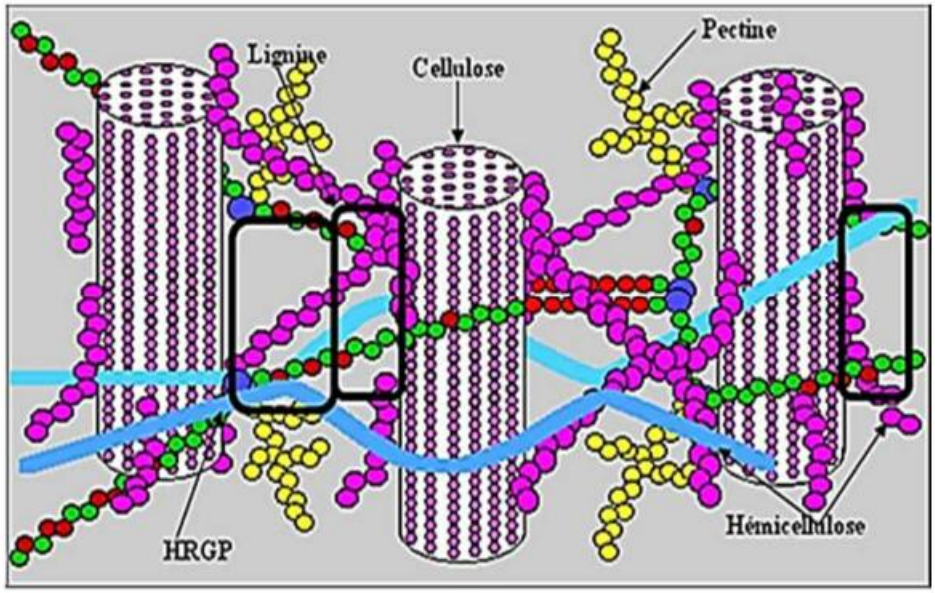


Figure II 8: Schematic representation of a wood fiber [67]

Cellulose is a glucose polymer and a primary component of the plant cell wall. It serves as the biopolymer responsible for providing most of the mechanical strength in plants lacking secondary tissues, owing to its highly crystalline structure and well-ordered arrangement. This quantity increases over time; thus, a young plant will have weaker mechanical resistance because it will contain less cellulose [56]. Its predominantly crystalline organization makes cellulose insoluble in most solvents, including water, although it remains highly hydrophilic. However, if the crystalline structure of cellulose is modified, for example, when transitioning from cellulose I, which is highly crystalline, to cellulose II, which is amorphous, the mechanical properties are degraded[57].

Lignin, which is a highly hydrophobic compound, exists as a three-dimensional polymer with a complex structure that varies depending on the species, as well as the morphological elements (vessels, fibers, etc.). Its hydrophobic nature imparts rigidity and impermeability to plants. Additionally, lignin contributes to the cohesion of fibers in the lignocellulosic woody parts of the xylem, giving them with significant compressive strength.

Hemicelluloses are polysaccharides with shorter chains than those of cellulose and have an amorphous structure. They are hydrophilic and can swell upon contact with water. This swelling

is responsible for the dimensional instability of wood. Additionally, hemicelluloses are soluble in water and can be extracted from the cell wall, particularly through alkaline soaking.

Pectins are acidic polysaccharides. found in substantial amounts in the middle lamella, ensuring cell cohesion of. Like hemicelluloses, pectins are water-soluble compounds. Notably, the composition and structure of both hemicelluloses and pectins vary across plant species, adding to their complexity [58].

Table II 2: Chemical Composition of Some Natural Fibers [70].

Type of Fibers	Cellulose (%)	Hemicelluloses (%)	Lignin (%)	Others (%)
Rice	28-36	-	12-16	-
Wheat	29-35	27	16-21	11-23
Sugar	32-44	22	19-24	26-8
Bamboo	26-43	15	21-31	9-35
Alfa (Esparto)	33-38	-	17-19	-
Sabai	22	-	23.9	-
Flax	43-47	16	21-23	13-20
Kenaf	31-39	19	15-19	23-35
Jute	45-53	15	71-76	5-11
Abaca (Manila)	50.8	20	8.8	10
Sisal (Agave)	43-56	17	7-9	23-38
Cotton Linters	80-85	-	-	-

II.4.3. Effect of Fiber Stabilization on Soil Properties

II.4.3.1. Modification of Water Content and Density

The hydrophilic and absorbent nature of sisal fiber leads to an increase in the optimal water content for compaction. This increase in water is accompanied by a decrease in the dry density of compaction [53], [59]. The increase in fiber length, while maintaining the same fiber proportion, intensifies this phenomenon [53]. Mohamed [60] explains this decrease by the lightness and porosity introduced by the fiber.

The addition of plastic fibers has less impact on these two characteristic values. Polyester [61] and polypropylene [62] do not significantly influence the Proctor values.

II.4.3.2. Mechanical Properties

The mechanical performance of fiber-reinforced soils varies greatly depending on the type of fiber, the sample preparation technique, the fiber length, the fiber percentage, and the nature of the soil[63].

The use of sisal fibers in wet soils increases the compressive strength of the soil. An optimum of 0.5% added fiber and a length of 25 mm increases compressive strength by 800% [53], [59]. The addition of sisal also enhances the ductility of the material. Ghavami [64] explains that after reaching maximum strength, the fiber dislodges from the mineral matter. The use of coconut fibers similarly increases the compressive strength of the soils used by Ghavami. He observed a 25% increase in maximum strength accompanied by an increase in ductility.

In contrast, Khedari [65]indicates that increasing the proportion of coconut fibers reduces the compressive strength of compressed earth bricks stabilized with cement. He explains that the reduction in the weight of the compressed material and the weakening of the bonds between clay particles and cement decrease the strength of the bonds within the brick. This observation is echoed by Mohamed [60] regarding the addition of straw in unstabilized expansive clay. Increasing the proportion of straw in the clay matrix reduces the clay's ability to withstand compressive forces. Weak points (voids) form between the absorbent fiber and the clay after the fiber dries, which decreases the adhesion between the fiber and the clay [66][60].

Namango observed that, within certain limits, there is a significant increase in compressive strength in the dry state with the addition of sisal fibers (Figure II.9). However, beyond these limits,

the presence of sisal fibers harms the strength of the CEBs [67]. For his part, Minke [68] observed that incorporating fibers such as sisal or human hair, coconut, animal, bamboo, agave, and straw can help minimize shrinkage by reducing the clay content and allowing the fibers' pores to absorb a portion of the water. Similarly, Villamisar [69]et al. demonstrated that the addition of cassava peels significantly enhanced the dry strength of the mixtures, making them more resistant to breakage during handling, which is particularly beneficial for CEB production.

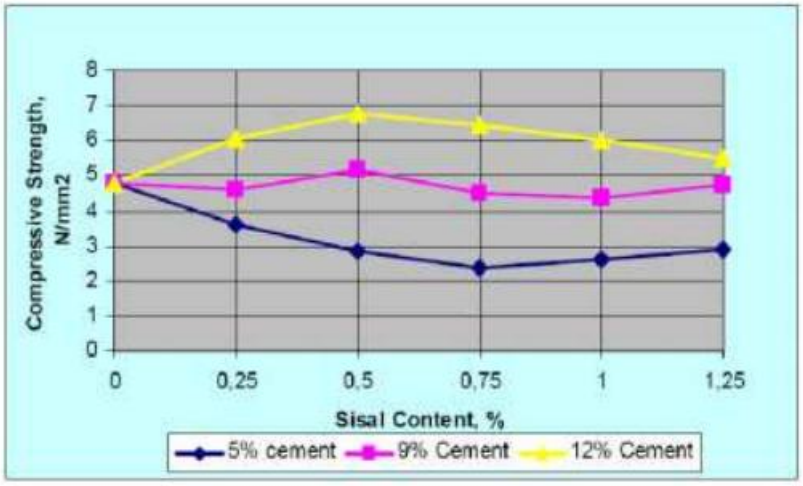


Figure II 9: Variation of Compressive Strength Based on Sisal Fiber Content [83]

Khedari et al. studied bricks made of compressed lateritic clay stabilized with coconut fibers. The results show a slight decrease in compressive strength (Figure II.10). The authors attributed this reduction in strength to the effect of fiber dimensions, surface conditions, and the number of fibers present in a given volume. Therefore, increasing the coconut fiber content leads to a reduction in adhesion stress, resulting in a decrease in compressive strength [65].

Olivier and El Gharbi conducted a study on stabilized earth blocks with sisal fibers and concluded that the weak point lies at the interface between the earth mortar and the earth blocks. The authors attempted to improve this interface by reinforcing the compressed earth blocks with sisal fibers, as well as the earth mortar. They also assessed the benefits of using sisal [70] .

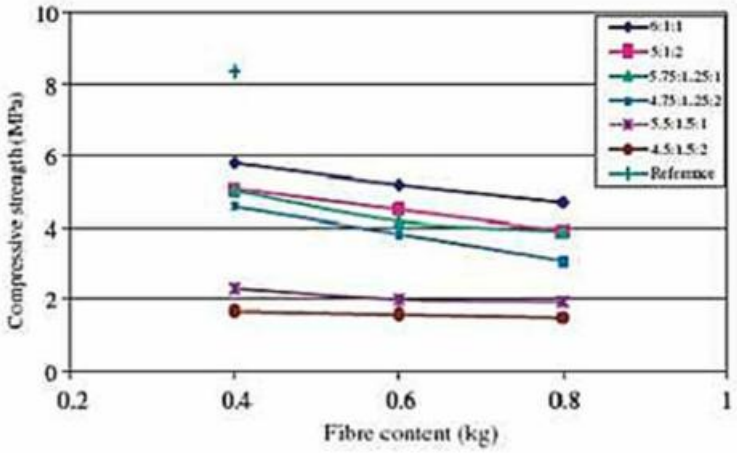


Figure II 10: The Influence of Fiber Content on Compressive Strength [81]

As part of a study on the development of a direct tensile test on compressed earth blocks (CEB) with natural fibers, Mesbah et al [71]state that the advantages of using natural fibers as reinforcement in compressed earth blocks include both the improvement of tensile ductility (Figure II-11) compared to a block without reinforcement, and the inhibition of crack propagation after its initial formation. According to the authors, it appears that the fibers do not have a significant effect on the material's behavior before cracking.

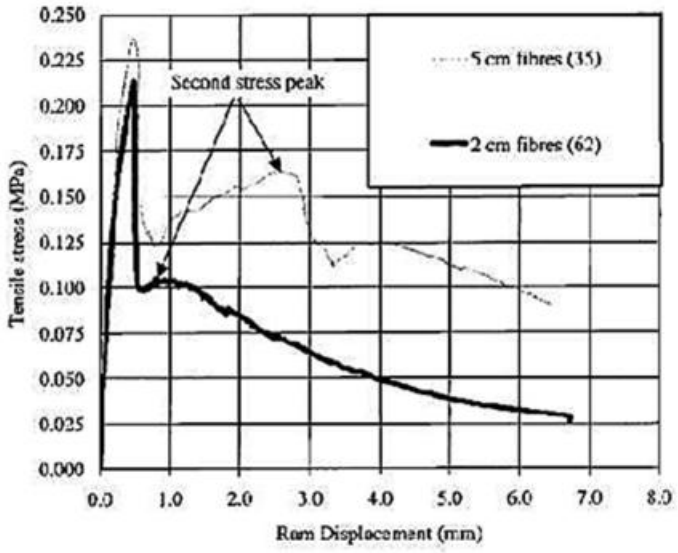


Figure II 11: Tensile Behavior of Compressed Earth Blocks Reinforced with Natural Fibers

In addition to natural fibers, other researchers have also used synthetic or artificial fibers to reinforce compressed earth blocks. For example, we can mention the study conducted by Eko et al[72]. In this study, the authors used lateritic soil stabilized with 6% cement and reinforced with three fiber contents: 1.7%, 2%, and 2.7%, in three lengths: 20 mm, 35 mm, and 50 mm. They observed that the tensile strength increased with the rise in fiber content up to an optimal value, beyond which the strength decreased when the fiber content was further increased (Figure II. 12).

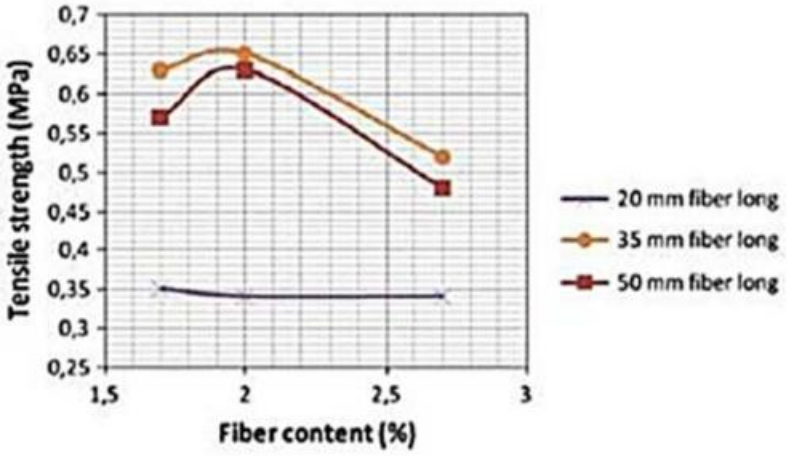


Figure II 12: Effect of Steel Fiber Content on Tensile Strength for Compressed Earth Blocks Stabilized with 6% Cement

II.4.3.3. Water Absorption

Plant fibers have a hydrophilic nature, which promotes water absorption, whereas other types of fibers, such as polypropylene fibers, are hydrophobic. This high sensitivity to water in plant fibers is a weakness when using them in the production of raw earth products. This issue has led researchers to study and evaluate the extent of this problem.

Sallehan and Yaacob [73] conducted water absorption tests on compressed earth blocks (CEB) reinforced with raw palm fibers and concluded that there is a slight increase in water absorption with the increase in fiber content. Ravishankar and Raghavan confirmed that for lateritic soils stabilized with coconut fiber, the rate of water absorption increases as the coconut fiber content increases [74].

II.4.3.4. Thermal Properties

The addition of plant fibers to soil decreases its dry density. Laurent [75]studied the thermal characteristics of unstabilized adobe based on different types of soil. The thermal conductivity of adobe follows a general law that can be applied to any type of adobe:

$\lambda sec=0.103.10^{0,517d}$ with d is the dry density of the adobe.

Rim [76]shows that the thermal conductivity of soil stabilized with cement and containing wood chips is linearly dependent on the dry density. The conductivity ranges from 0.24 to 0.07 W/(m·K) for densities between 1.2 and 0.35. The addition of straw reduces the dry density. In a compressed earth block (CEB), the addition of plant fibers aims to reduce the thermal conductivity of the soil. Introducing 1% coconut fiber into a laterite-based CEB reduces the dry density by 10% and decreases the thermal conductivity by 30% (Figure II-13) [91].

Khedari et al[65]. observed that the thermal conductivity of compressed lateritic clay bricks stabilized with coconut fibers decreases with the increase in fiber content (Figure II-14)

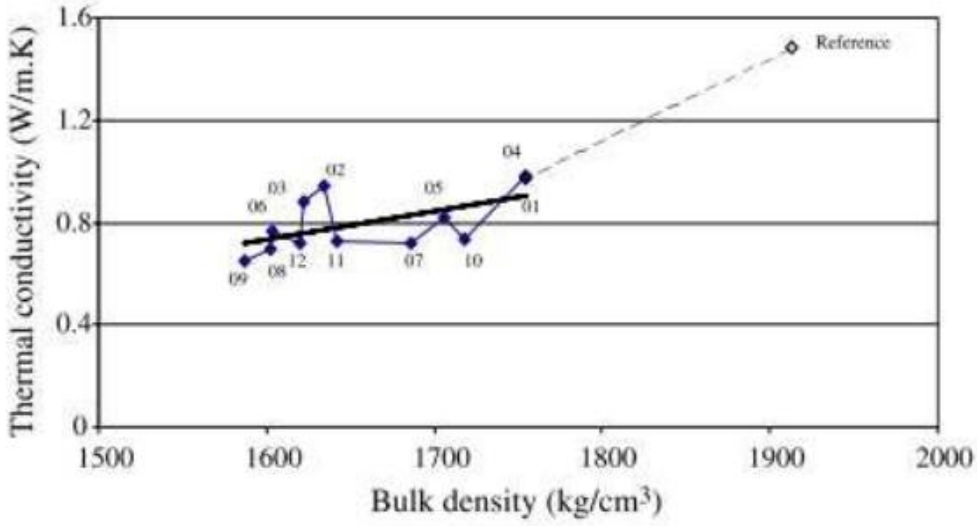


Figure II 13: Influence of Dry Density on the Thermal Conductivity of a Fiber-Reinforced CEB [91]

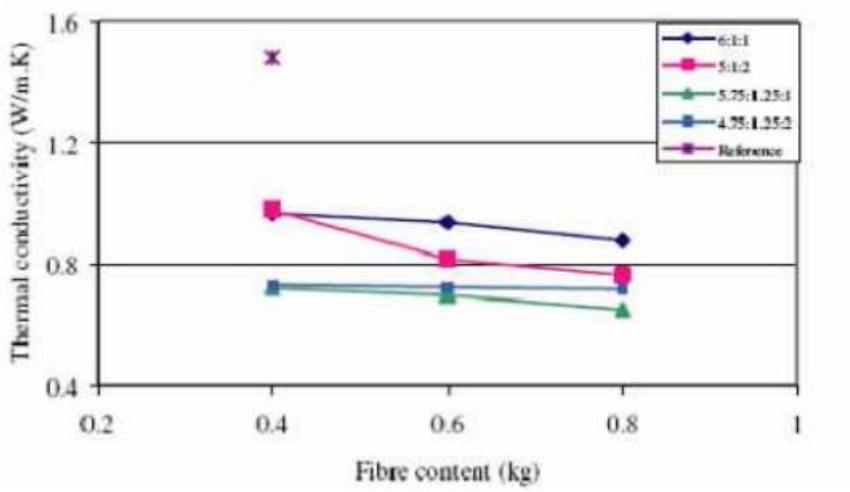


Figure II 14 : Influence of Coconut Fiber Content on Thermal Conductivity [81]

The German standard for earth construction provides generalized characteristic values for thermal conductivity based on the dry density of the manufactured walls [77].

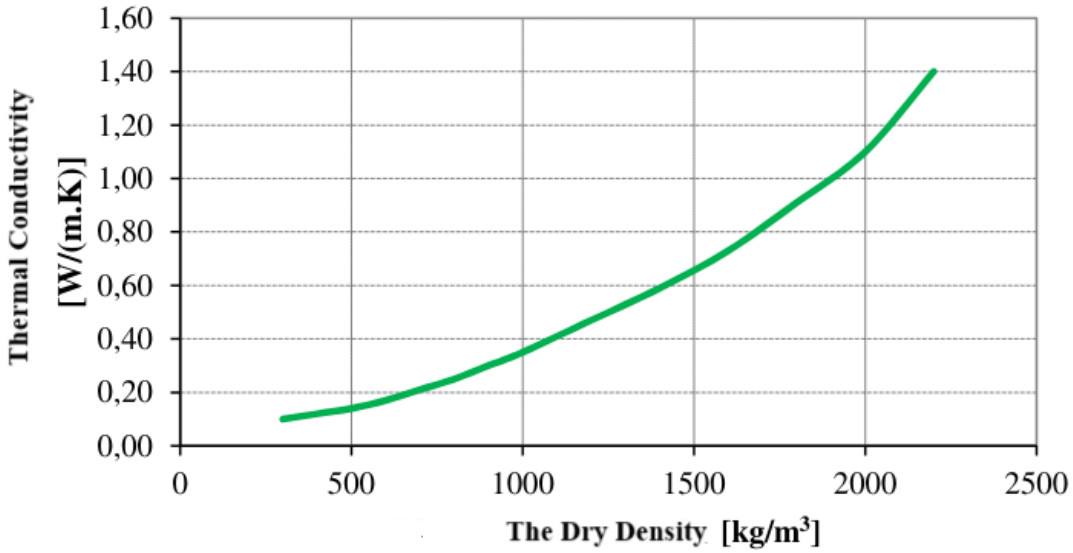


Figure II 15 : Thermal Characteristics of Soil Based on Dry Density [92]

II.5. Utilization of waste material in civil engineering

Waste is defined as the reduction in a material's volume, value, or quality, making it equivalent to discarded residue that is no longer functional, usable, or valuable [78]. The sources of waste production or undesirable materials can be classified according to the collection methods: Residential, Industrial, commercial, and institutional (ICI), Construction and demolition (CD).

Two main sources of waste production commonly encountered in the field of civil engineering are construction waste and demolition (C&D) and industrial by-products. In the USA, 31.5 million tons of construction waste are produced each year, representing nearly a quarter of municipal solid waste. In Europe, 259 million tons of construction waste are produced annually, as shown in Figure II-16. In the United Kingdom, 24 million tons of demolition materials and construction debris are produced each year [79]. However, in Algeria (C&D), which is generally classified as industrial waste, remains largely unknown and is estimated to amount to millions of tons per year [80]. According to a study conducted by Bedjou [81], waste generated from the building sector is estimated at 2.2 million tons per year.

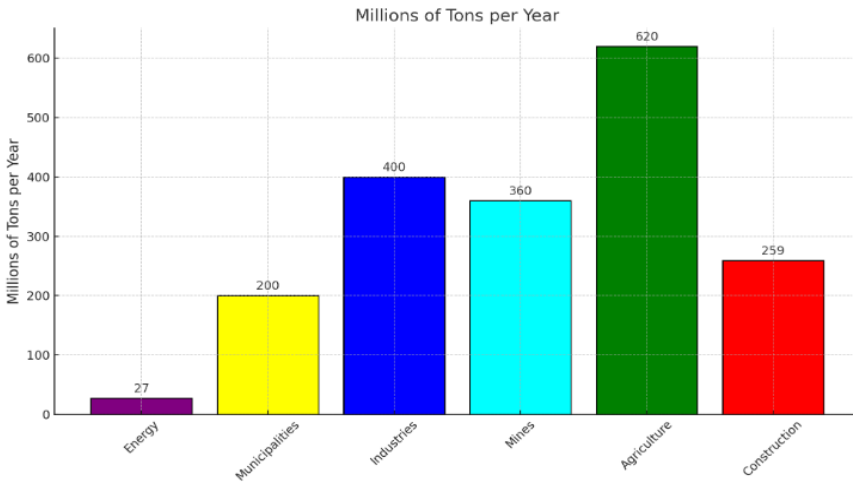


Figure II 16: Distribution of Waste by Source Sectors [93]

On the other hand, industry is the primary source of by-products and waste used in the field of civil engineering. Enormous quantities are continuously produced and are ever-increasing, leading to large areas of land being occupied by stored waste, reduced availability of land, and environmental pollution with all its consequences. Civil engineering is considered a key domain for utilizing industrial waste for both geotechnical and materials applications, offering immediate practical and economic benefits, as many secondary products and residual wastes can replace natural raw materials and a wide range of construction materials.

Among the by-products and waste used in civil engineering are blast furnace slag, fly ash, incinerator bottom ash (or Clinker), fired clay, rubber, and plastics. Fired clay debris is generally classified as demolition waste, whether intended for recycling or reuse as a lightweight aggregate. This includes unfired clay, fired clay, crushed bricks, over burnt and under burnt bricks from brickyards, as well as brick debris found in demolition waste and rubble, collectively referred to as fired clay debris [82]. For simplicity, and in line with the focus of our research on brick waste from brickyards, we will classify these materials as industrial by-products.

In Algeria, fired clay bricks are most commonly used as masonry components in the construction sector. Given Algeria's economic development and its commitment to the construction and building materials industry, these materials hold significant importance. As part of efforts to promote the use of local materials, the Algerian government encouraged the manufacturing industry of red products in 1989. At that time, 12 production projects were initiated during 1988; however, the supply, with an estimated satisfaction rate of 45%, fell far short of meeting national market demand. The projected needs by 1994 were approximately 7 million tons per year of red products and 5 million tons per year for tiles [83].

II.5.1. Incorporating wastes in CEB

Industrial waste has been incorporated in CEB production in three forms: as powders, aggregates, and fibers. A study conducted by Ali et al [84], demonstrate that incorporating 75% ceramic waste into the composition of CEBs was optimal, as it resulted in the highest compressive strength, as shown in Figure II.17.

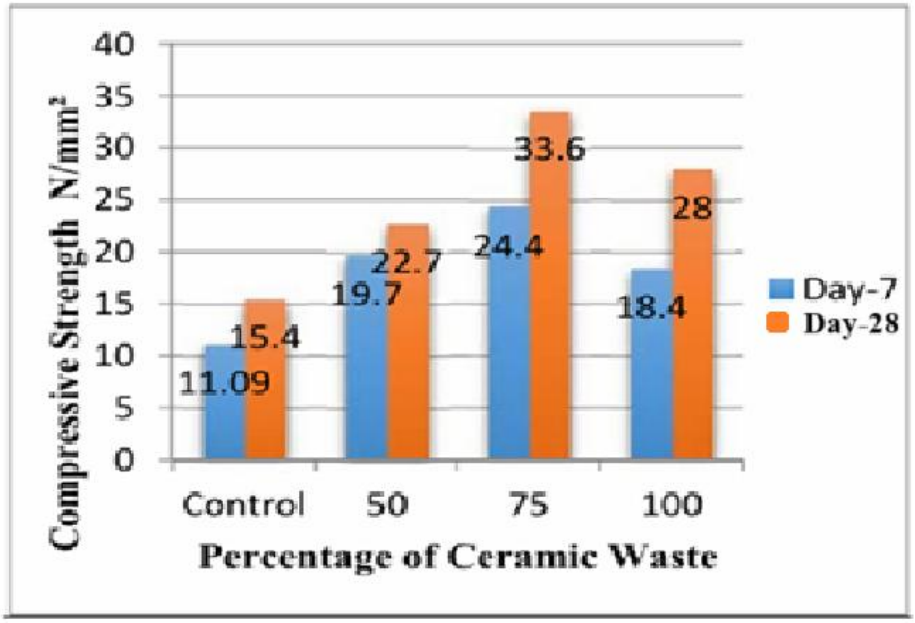


Figure II 17: compressive strength percentage content of ceramics at 7 and 28 days [84]

Alexandre Bogas[85] explored the production of CEB using a 20% replacement of soil with recycled construction waste materials. The findings revealed that unstabilized CEBs were unsuitable for building applications directly exposed to water. However, incorporating cement as a stabilizer and adding water-repellent admixtures significantly enhanced their water resistance, making them more viable for such conditions.

Nagaraj et al [86] conducted a study investigating the use of iron mine spoil waste (MSW) in the production of CEB. The research explored varying MSW proportions, ranging from 30% to 50%, combined with cement and lime as stabilizers. The findings revealed that the wet compressive strength of CEB exceeded 5 MPa after six months of curing, making them suitable for residential construction.

In recent years, the use of brick waste (BW) in earthen construction materials has gained significant attention. Research has investigated the incorporation of BW in the production of earth bricks. For example, Oti et al. [87] Studied the addition of waste brick dust combined with granulated blast furnace slag as a substitute for a portion of the soil in mud brick manufacturing at various substitution levels. They reported that incorporating up to 20% of these materials enhances compressive strength and increases water absorption.

Joshi et al[88]. Conducted a study on the utilization of crushed brick (CB) demolition waste as a replacement for soil in the production of stabilized adobe blocks. The research examined the effects of replacing natural soil with different proportions of fired brick waste—ranging from 0% to 100% in increments of 20% to assess the physical properties of the resulting adobe bricks. The findings indicated that substituting 60% to 80% of natural soil with crushed brick waste significantly improved the physical properties of the adobe bricks.

Identically, Tripura and Kasinikota [89] investigated the durability and the mechanical properties of CEB by incorporating BW as a replacement for the soil-sand mixture. Their findings revealed that incorporating 24% BW with a particle size of 0–4.75 mm into the soil-sand mixture enhances both dry and wet compressive strength, as illustrated in Figure II.18. Rajurkar et al.[90] developed cement-stabilized CEB by using varying amounts of demolition waste, such as crushed brick and mortar, as a replacement for natural sand to improve the strength properties of the bricks. The best results were observed when 40–45% of the soil was replaced with demolition waste. The authors propose that demolition waste can serve as a viable alternative material.

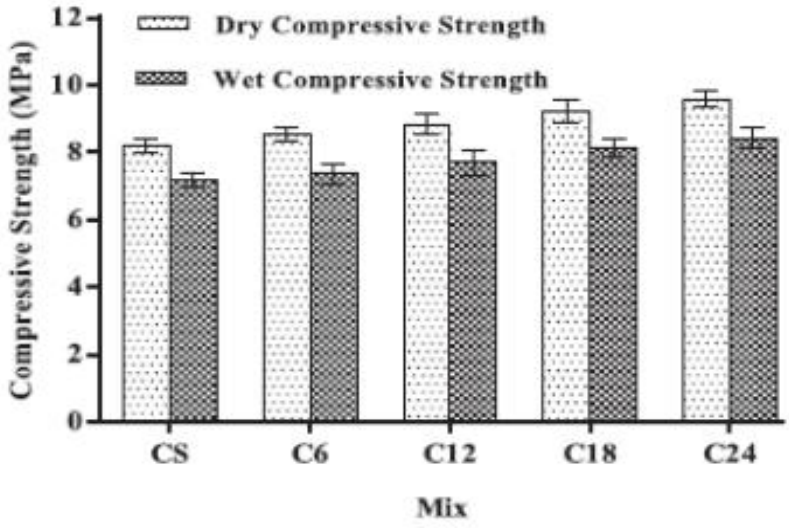


Figure II 18: Wet and dry compressive strength of blocks [104]

II.6. Conclusion

This chapter provided an overview of the general context of Earth Reinforcement and various stabilization methods, with a particular focus on the chemical processes triggered by adding cement to soils. The literature review revealed that several research studies have confirmed that the use of mineral binders (cement and lime) as stabilizers improves the mechanical strength and water resistance of CEB. However, limited research has investigated the use of Sisal or Alfa fibers in CEBs. As far as we are aware, no studies have investigated the combined effects of partially replacing soil with crushed bricks and incorporating Sisal or Alfa fibers on the mechanical and thermophysical properties of CEB stabilized with cement. This study aims to address this gap by evaluating the impact of Sisal and Alfa fibers on mechanical, physical, and thermal properties of CEB. Additionally, it highlights an environmentally sustainable approach by incorporating BW into CEB production, contributing to the development of an eco-friendly and durable construction material.

PART TWO:

EXPERIMENTAL STUDY

Chapter III:

Raw materials and experimental methods

III.1. Introduction

The third chapter aims first to analyze the characteristics of the various materials used in manufacturing CEBs, then provide a summary of the formulations. Next, it outlines the different experimental methods employed to assess the thermal and mechanical resistance of the CEBs.

III.2. Materials

The materials used in this research are: soil and brick waste as a main matrix, cement as a chemical stabilizer, and Sisal or Alfa fibers and water.

III.2.1. Soil

The soil used in our research comes from the Chaaba EL HAMRA, Msila region (Algeria), and it was chosen based on its availability and abundance in the area. it is sieved to 2 mm. Houben [10] indicated that the finer particles should not be allowed to form nodules larger than 10 mm; the presence of 50% of nodules larger than 5 mm could potentially reduce the compressive strength by half. Figure III. 1 shows the particle size distribution was determined using the standards NF P 94–056. The soil plasticity was assessed through Atterberg limit and Methylene blue tests performed according to NF P 94–051 and NF P 94–068, respectively. The results obtained for our soil show that it is characterized by low plastic clays. The physical and chemical characteristics of the soil are presented in Table III.1 and III.2, whereas the X ray diffractogram is shown in Figure III. 2.

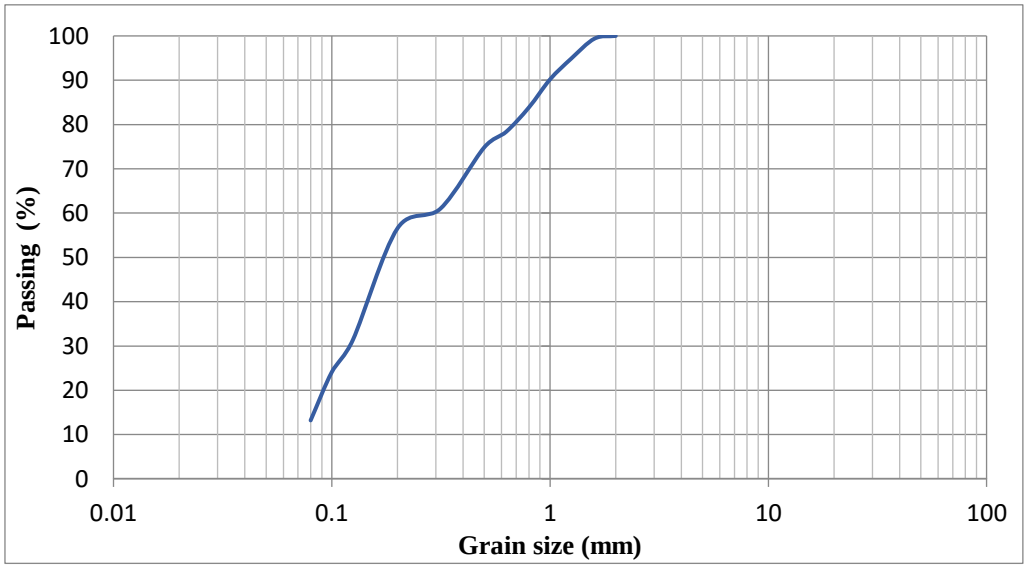


Figure III 1: Grain size curve of the Soil

Table III 1: Physical properties of the soil used

	Property	Value
Physical properties	Specific density (kg/m^3)	2500
	Methylene blue value	1.62
	Liquid limit, %	26
	Plastic limit, %	28
	Plasticity index, %	8
Compaction characteristics	Optimum water content, %	12.5
	Maximum dry density, Kg/m^3	20.05

Table III 2: Chemical composition of the soil used

Element	**SiO2**	**AL2O3**	**FeO3**	**CaO**	**MgO**	**SO3**	**Cl**	**K2o**	**Na2O**	**PAF**
%	34,62	9,16	3,44	22,52	4,66	0,94	0,63	1,1	0,14	22,98

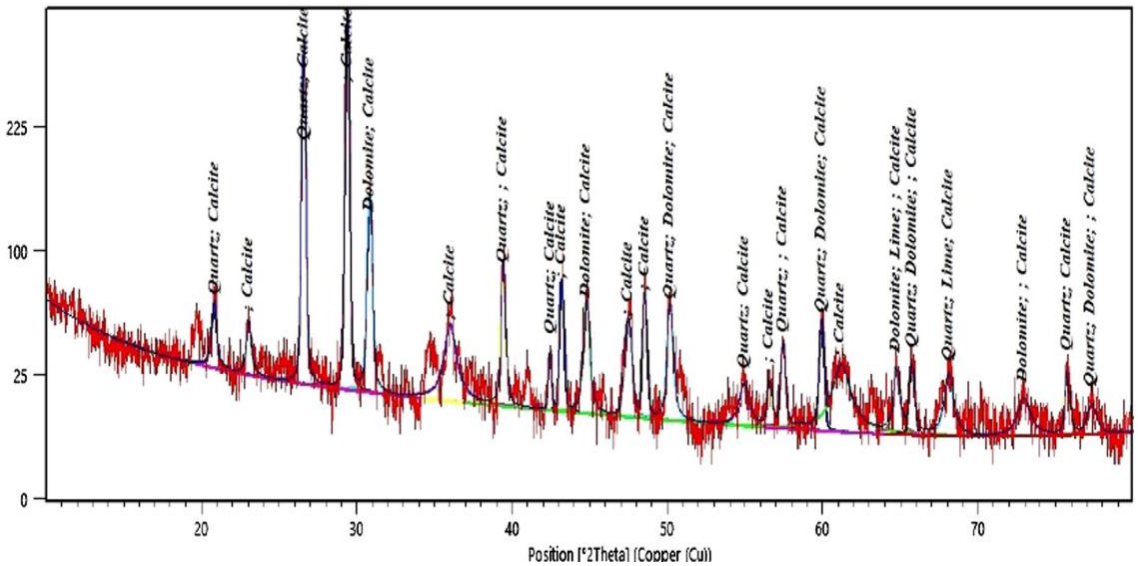


Figure III2 : X-ray diffractogram of clay

III.2.2. Brick waste

The brick waste used in this research was collected from construction sites and had a density of 2358 kg/m^3, is utilized as a partial substitute for clay. The discarded bricks were mechanically crushed into fine particles (less than 2 mm) using a laboratory shredder. The particle size is illustrated in Figure III.3. According to the chemical analysis, the brick waste primarily consists of silica 32.45% and calcium oxide 21.19 % as shown in Table III.3.

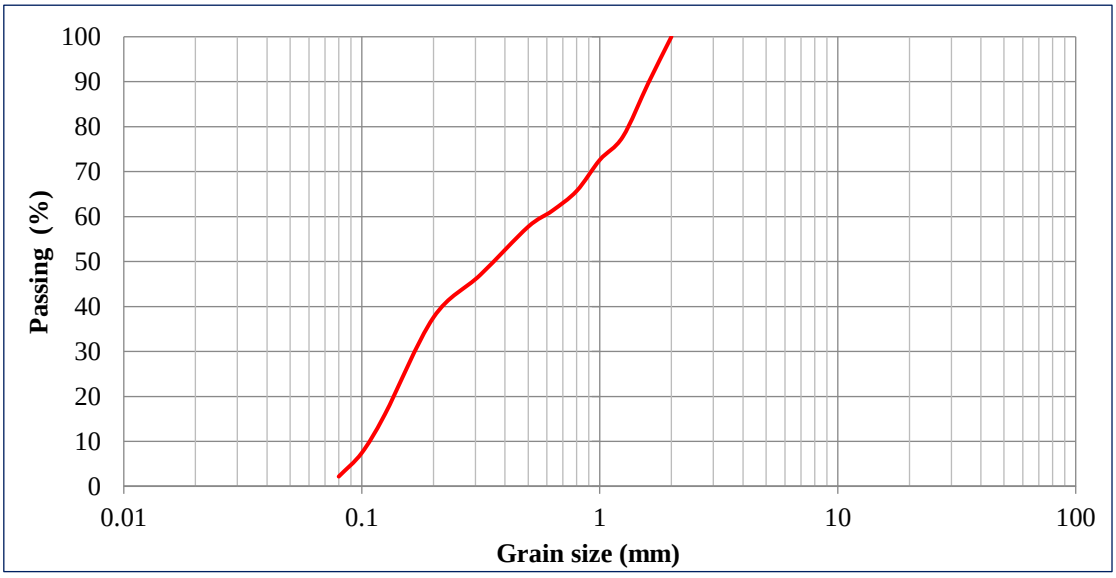


Figure III 3: Grain size curve of Brick waste

Table III 3: Chemical composition of Brick waste used

Element	SiO2	AL2O3	FeO3	CaO	MgO	SO3	Cl	K2o	Na2O	PAF
BW %	32.45	9,84	4.31	21.19	2.76	5.89	0,371	0.86	0.97	20.94

III.2.3. Cement

The binder used in this study is commercially abundant cement CEM II/B class 42.5 produced by Ain Touta factory (Algeria) with a density of 3150 kg/^{3}. The chemical properties of cement are shown in Table III.4. As noted in several studies[13], [71], [91]. The optimal cement dosage for compressed earth blocks (CEB) typically falls between 5% and 10%. Therefore, three cement contents within this range were selected for the study: 5%, 7%, and 9% for Sisal fibers and 7% for Alfa fibers.

Table III 4: Chemical composition of cement

Element	SiO2	AL2O3	FeO3	CaO	MgO	SO3	Cl	K2o	Na2O	PAF
	21.45	4.31	4.56	61.43	1.24	2.28	0.018	0.61	0.39	2.19

III.2.4. Water

The water used in the mixtures is potable water from the LMMS laboratory; it contains low levels of sulfate and is supplied at a temperature of around 20 ± 2 °C, depending on the time of year. Its quality meets the requirements of the NFP 18-404 standard.

III.2.5. Sisal fibers

In this study, commercially available sisal fibers, measuring 40 mm in length, with a diameter ranging from 0.2 to 0.4 mm, and a tensile strength of 500 MPa, were used to reinforce the compressed earth blocks (CEB) (see Figure III.4). As suggested by the literature[92]–[95]The fiber length was maintained consistently across all tests. These fibers are readily available locally and are commonly used in civil engineering applications, including soil stabilization and plaster panel reinforcement. Additionally, they possess high initial tensile strength, comparable to polyester

fibers, making them effective as reinforcements[53][96]. FTIR (Fourier transform infrared) spectroscopy analysis of the Sisal fibers is presented in Figure III.5, with a summary of the observed bands provided in Table III.5. The specific peaks and types of chemical stretching were identified by comparison with the findings from [97]. Five different fiber concentrations, ranging from 0.1% to 0.5% of the total dry mass of all components, were used to reinforce the blocks.

Figure III 4: Sisal vegetable leaves and fibers

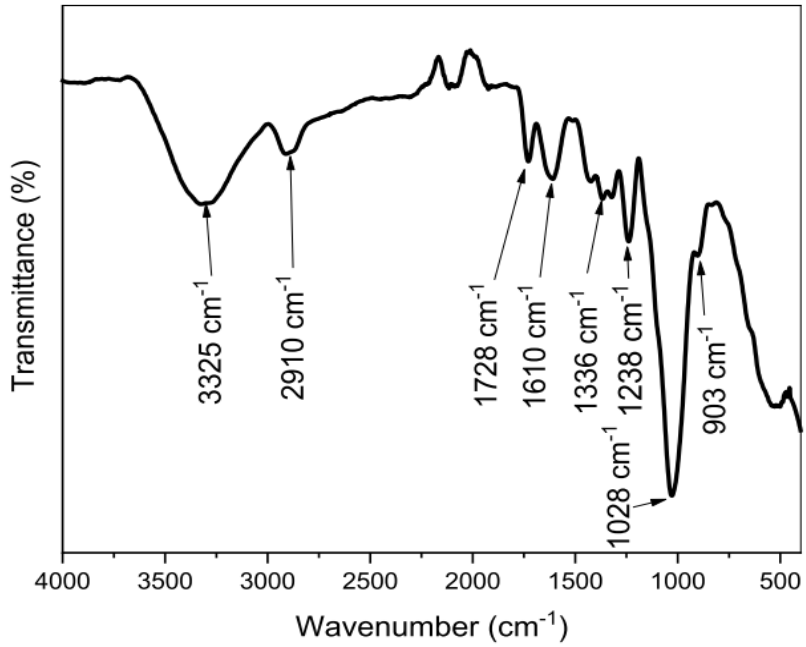


Figure III 5 : Analysis of Sisal fibers (FTIR)

Table II 5: Definition of FTIR peak positions wave for Sisal fibers

Wave number (cm^{-1})	Origin
3325	N–H stretching (amide)
2910	C–H stretching
1728	C=O stretching of hemicellulose
1610	OH absorbed water
1336, 1238	C–O stretching
1028, 903	C–OH stretching of lignin

III.2.6. Alfa fibers

Harvested from the M'sila area in Algeria, Alfa grass was chosen to enhance the mechanical properties of CEB due to its widespread availability in the area. This plant typically reaches a height of about 1 meter and features cylindrical stems**.** The preparation of Alfa fibers involves several steps, as illustrated in Figure III.6. Initially, the fibers undergo a one-month soaking process in water to facilitate the removal of the outer layer through biological retting[98], [99]. Following this, a wire brush is used to eliminate the outer layer. The extracted fibers are then rinsed with distilled water until all undesirable impurities are removed. Subsequently, they are oven-dried at 70 °C for six hours. Finally, the dried fibers are cut into lengths ranging from 3 to 5 cm. The Alfa fibers used had an average diameter 113 µm and a density 0.89. X-ray analysis was conducted on the fibers over an angle range of 10° to 70°, with the resulting spectrum presented in Figure. III.7. The degree of crystallinity (CI), which represents the proportion of crystalline material in cellulose, was determined for Alfa fibers using the Segal method [100] and yielded a value of 52%. FTIR analysis is presented in Figure. III.8, with a summary of key band indications provided in Table III.6. The specific peaks and corresponding types of chemical stretching were identified by referencing earlier research. To evaluate the impact of Alfa fibers, different concentrations were used as reinforcement in the blocks, ranging from 0.1% to 0.5% of the overall dry weight of the mixture, with an increment of 0.1%

Figure III 6 Processing of Alfa fibers

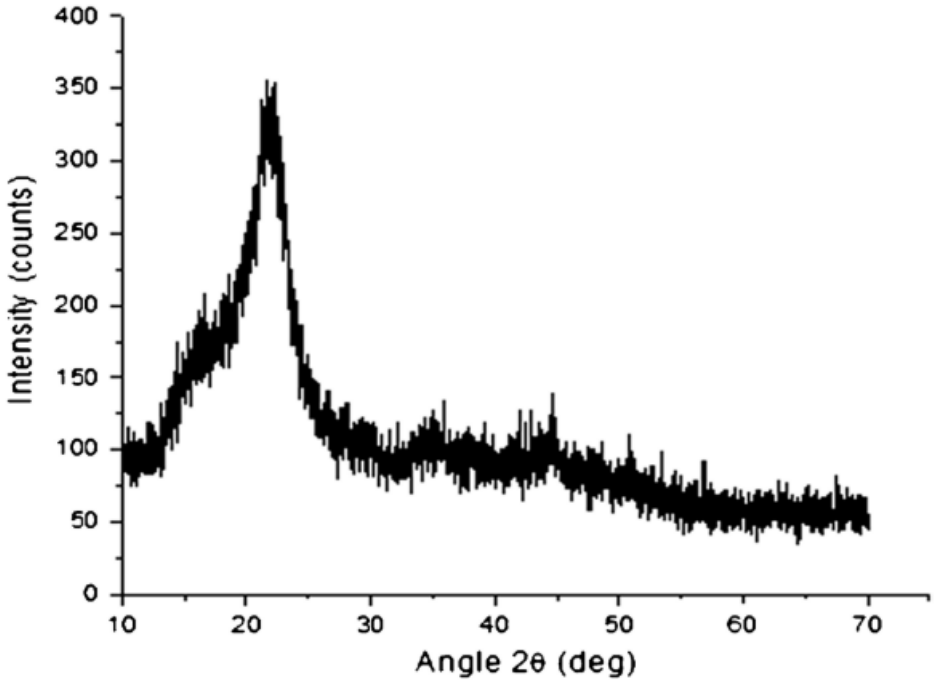


Figure III 7 X-ray diffractometer for Alfa fibers

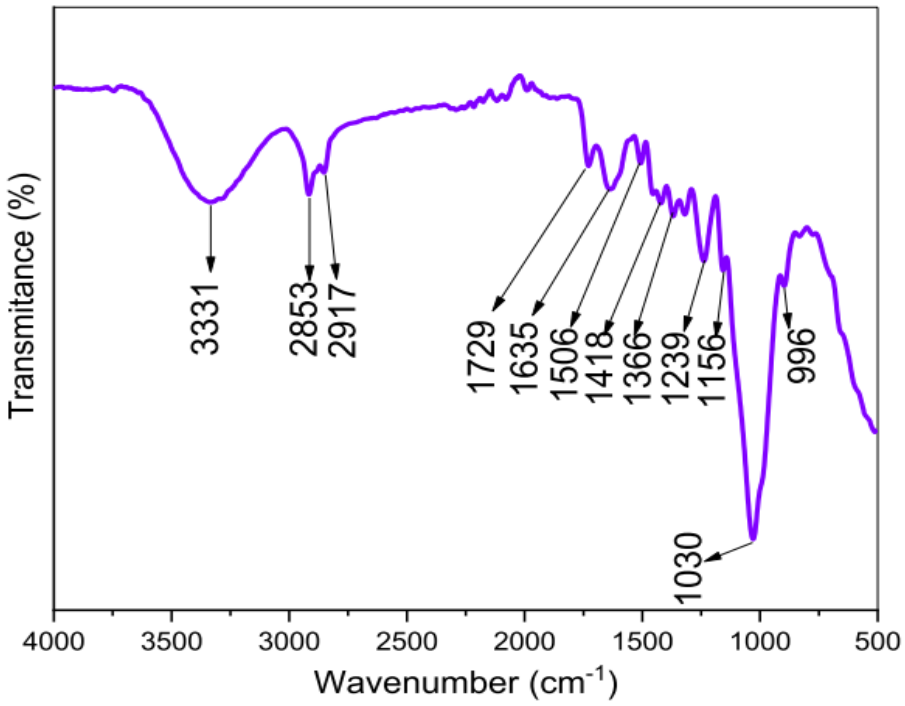


Figure III 8: Analysis of Alfa fibers (FTIR)

Table II 6: Definition of FTIR peak positions Wave for Alfa fibers

Wavenumber (cm^{-1})	Origin
3331	N–H stretching (amide)
2853, 2917	C-H stretching
1729	C=O stretching of hemicellulose
1635	OH absorbed water
1506	C=O, NH_2, NH, C=C, C=N functional group stretching
1418	CH_2 symmetric bending
1239, 1366	C-O stretching
1156	C–O–C stretching

III.3.Experimental procedure

This study aims to incorporate Brick waste into compressed earth blocks (CEBs) to produce an eco-friendly material. Additionally, the research investigates the effects of Sisal or Alfa fibers and cement on the engineering properties of blocks is shown in the flowchart of Figure III.9. As per the specifications set by (Centre International de la Construction en Terre) CRATerre [30], the soil

used for producing compressed earth blocks (CEBs) must meet specific criteria concerning its plasticity. Accordingly, the maximum allowable proportion of brick waste has been set at 20% while staying within the limits specified in Figure III.10.

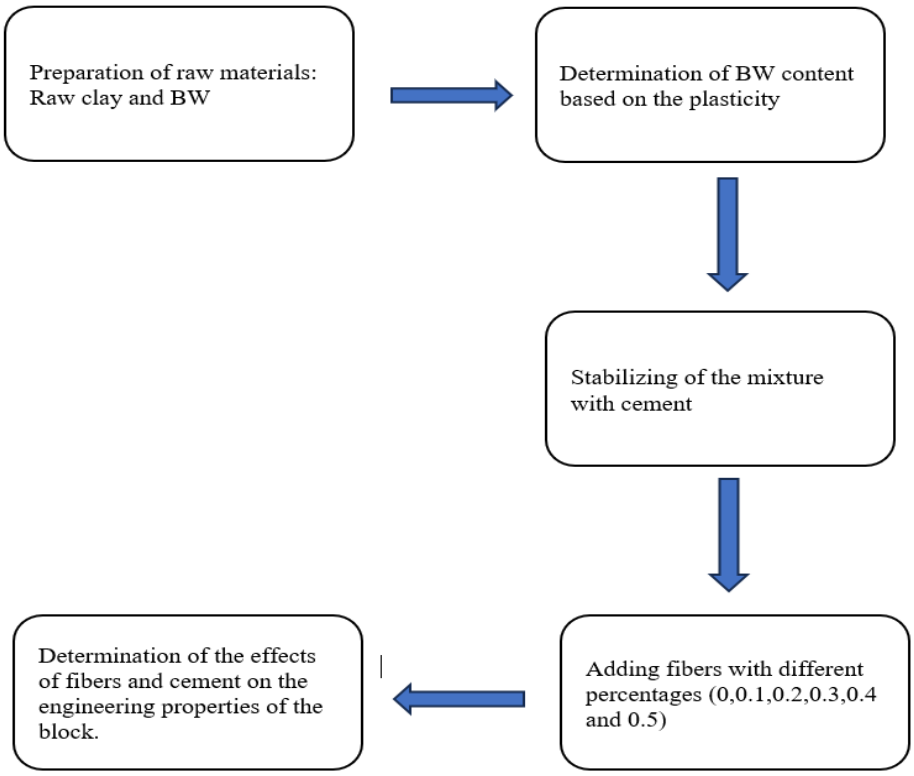


Figure III 9: Flowchart of the method followed in the research

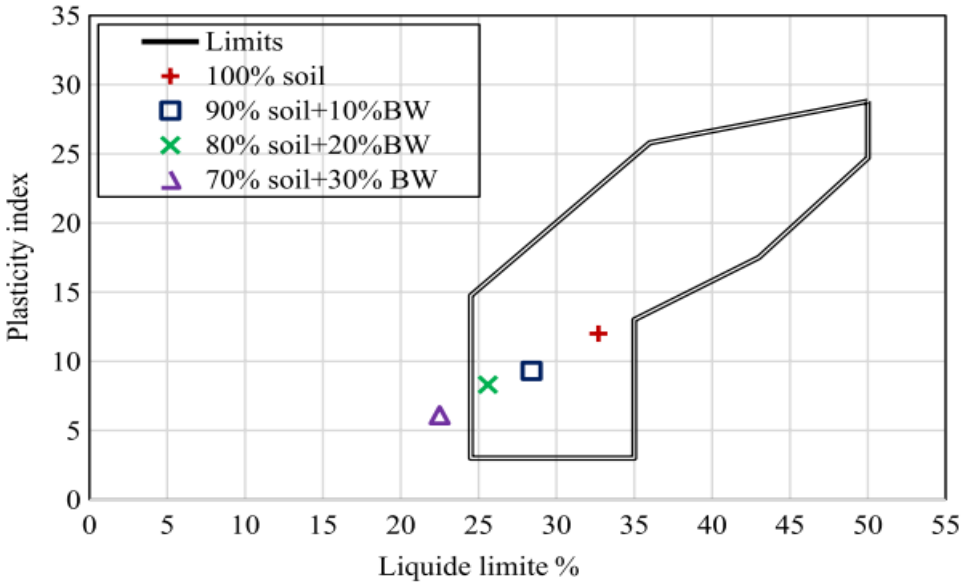


Figure III 10: The position of different soil mixes on a plasticity according to the XP P13-901[18]

III.3.1.Mix compositions

Once the mixture is ready, it is placed into a rigid mold and immediately compressed using a hydraulic press. The prismatic specimens (70x70x280 mm³ for Sisal fibers and 40x40x160 mm³ for Alfa fibers) used for various tests specified in our experimental program were prepared using molds manufactured explicitly for this purpose. Each mold consists of 5 elements made of hardened steel (Figure III.11). According to the authors[101], [102]. The Proctor test is not suitable for determining the optimal water content, as the energy applied during a Proctor test differs from the energy used in the static compaction process for manufacturing CEBs. As a result, the Centre for the Development of Enterprise (C.D.E.) [103] proposed a static compaction method, which was applied to establish the optimal water content for soil and BW mixtures with varying stabilizer amounts. The study involved producing a series of blocks using a blend of 80% soil and 20% waste brick, which was stabilized with varying cement contents (0%,5%, 7%, and 9%) to examine the effects of fiber and cement stabilization on the engineering properties of CEB. Three blocks were created for each test to obtain average results, as detailed in Tables 3.7 and 3.8. Based on Michel[104], the best mixing conditions are achieved when the soil is dry to ensure a uniform material and reduce sample variability, which requires pre-drying. The soil and BW were dried in an oven for 24 hours at 63°C. The dry components (soil, brick waste, and cement) are mixed until a uniform blend is obtained. The fibers are then evenly distributed over the mixture and blended again for 180 seconds. Afterward, water is added, and the mixture is stirred for another 180 seconds. Once the mixture is ready, it is placed into a rigid mold and immediately compressed using a hydraulic press, the method found to be particularly suitable for CEB blocks according to numerous studies[21], [22], [97], [105], [106].

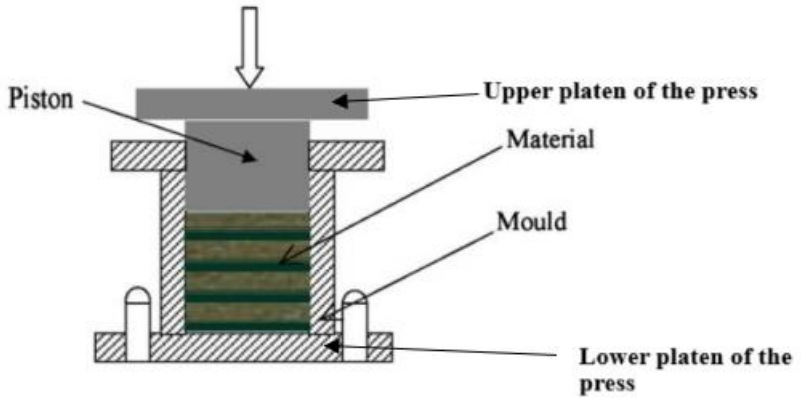


Figure III 11: Mold used for the production of CEB

Table III 7: CEB Mix proposition for Sisal fibers

Mix	Soil (%)	BW (%)	Cement (%)	Fibers (%)
C0 F0	80.0	20.0	0	0
C0 /F0.1	79.92	19.98		0.1
C0 /F0.2	79.84	19.96		0.2
C0 /F0.3	79.76	19.94		0.3
C0 /F0.4	79.68	19.92		0.4
C0 /F0.5	79.6	19.9		0.5
C5 F0	76	19	5	0
C5 /F0.1	75.92	18.98		0.1
C5 /F0.2	75.84	18.96		0.2
C5 /F0.3	75.76	18.94		0.3
C5 /F0.4	75.68	18.92		0.4
C5 /F0.5	75.60	18.9		0.5
C7 F0	74.40	18.6	7	0
C7 /F0.1	74.32	18.58		0.1
C7 /F0.2	74.24	18.56		0.2
C7 /F0.3	74.16	18.54		0.3
C7 /F0.4	74.08	18.52		0.4
C7 /F0.5	74.00	18.5		0.5
C9 F0	72.8	18.2	9	0
C9 /F0.1	72.72	18.18		0.1
C9 /F0.2	72.64	18.16		0.2
C9 /F0.3	72.56	18.14		0.3
C9 /F0.4	72.48	18.12		0.4
C9 /F0.5	72.4	18.1		0.5

Table III8: CEB Mix proposition for Alfa fibers

Mix	Soil (%)	BW (%)	Cement (%)	Fibers (%)
C7 F0	74.40	18.6	7	0
C7 /F0.1	74.32	18.58		0.1
C7 /F0.2	74.24	18.56		0.2
C7 /F0.3	74.16	18.54		0.3
C7 /F0.4	74.08	18.52		0.4
C7 /F0.5	74.00	18.5		0.5

III.3.2. Optimization of water content

This test is used to determine the ability of soil to be compacted under the influence of a variable compaction force, applied directly with a specific press for the production of CEBs.

The test protocol is as follows:

- Take a quantity of moist material with a given binder content (Cement) at a water content of approximately W = 7 to 10 %;
- Produce three to four blocks using the press;
- Measure the wet mass (m_W in g) and the dimensions of each block (length L, width l, and thickness h in cm);
- Calculate the dry density of each block using: Dry Density (DD)=$100\times m_w/L\times l\times h\times(100+W)$
- Prepare quantities of material with water content approximately 1 to 2% higher than the previous sample and repeat the process until the bricks appear too wet (visually) upon demolding;
- Plot a graph of dry density as a function of water content;
- By analyzing the graph, determine the optimal water content (OWC) corresponding to the maximum dry density (DD).

Figure III.12 shows the optimization obtained for the soil and BW stabilized without and with 9% cement, which were used as references. For the remaining mixtures, the water content was adjusted according to the specific case studied. The mixtures are compacted using a single action static method with a hydraulic press, where the lower platen moves, pushing the entire setup including the mold, mixture, and piston while the upper platen remains fixed. The process continues until the target pressure appears on the display. In this study, all specimens were subjected to a compaction pressure of 6 MPa. After compaction, the blocks are immediately demolded, then carefully stored in plastic bags under laboratory conditions for 28 days, followed by drying in an oven until a stable mass is achieved, as outlined in the standard XP 13-901[107].

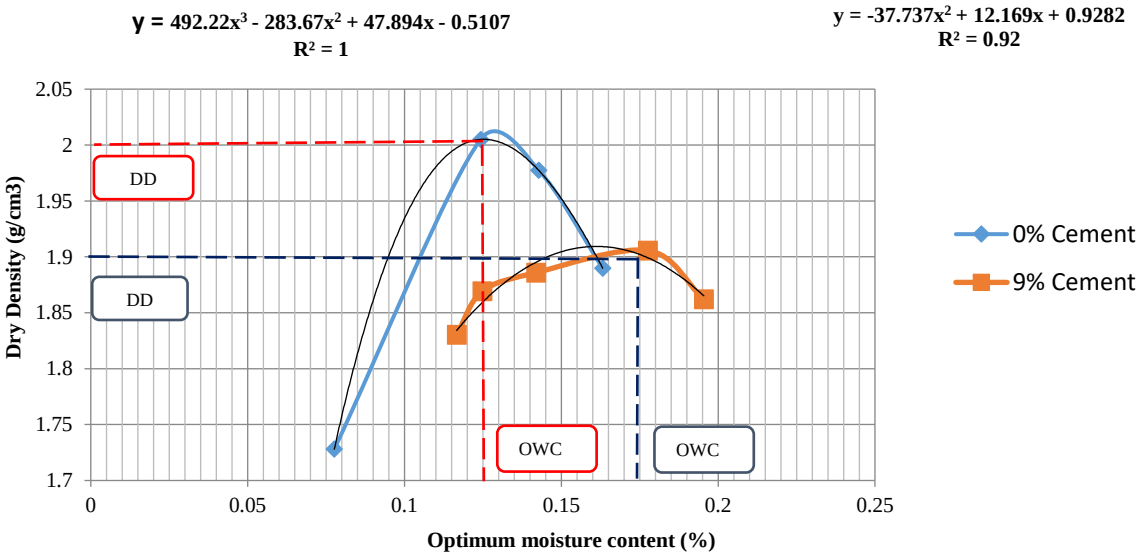


Figure III 12: Optimization of water content

III.4. Test conducted

III.4.1. Physical properties

III.4.1.1. Density

The density (ρ) was determined by the ratio of the sample's weight to its volume, following the NF P18-559 AFNOR French standard.

$$\text{Density } \rho = \frac{M}{V}$$

In this context, M represents the dry mass of the sample in kilograms (kg), and V indicates the volume of the sample in cubic meters (m^3).

III.4.1.2 Capillary Absorption Test

Water absorption by capillarity is measured using the test described in the experimental standard NF XP 13-901. The method involves partially immersing the block to a depth of 5 mm (see Figure III.13). The water absorption coefficient, C_b , corresponds to the absorption rate after 10 minutes. The coefficient C_b is calculated using the following formula:

$$Cb = \frac{100 \times (M1 - M0)}{s\sqrt{t}}$$

With:

- M1−M0 represents the mass of water, in grams, absorbed by the block during the test
- S: surface area of the submerged face, in square centimeters
- t: duration of the block's immersion, in minutes

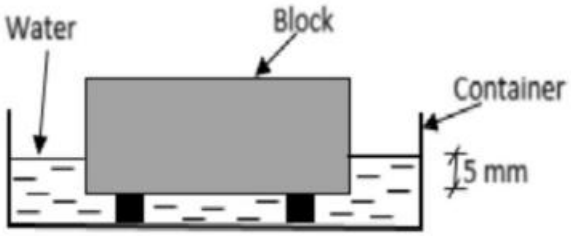


Figure III 13: Schematic setup illustrating the principle of the capillary absorption test

III.4.1.3 Thermal properties

The thermal conductivity was determined in Sisal fibers using a CT-meter device following the standard ISO 8894 1: 1987 as illustrated in Figure III.14. The operating principle involves using a combination of a heat source and a temperature sensor (both integrated within the same probe) to measure the temperature increase detected by the sensor during a controlled heating period. This period is set by the user depending on the material being tested and the type of probe used.

The CT-meter consists of two components: the control unit, responsible for generating the heating power and interpreting the temperature rise curve induced in the material being tested, and the probe, which transmits the heating power and collects the induced temperature.

And on the other hand, the thermal conductivity was measured in Alfa fibers using the transient plane technique source (TPS), as illustrated in Figure III. 8. With this approach, a TPS probe connected to an electrical circuit was placed between two specimens. Change in resistance across the Wheatstone bridge terminals generated a potential difference, ΔE(t). This, in turn, allowed the establishment of a relationship between ΔE(t) and the temperature fluctuations within the TPS component.

Figure III 14: Thermal conductivity tester (CT-meter)

Figure III 15: Thermal conductivity tester **(**TPS**)**

III.4.2. Mechanical properties

III.4.2.1. Dry compressive strength

This test is conducted to determine the dry compressive strength of CEB intended for masonry, allowing for comparative results that are independent of the block format. The test is used according to the standard XP P 13-901. It involves subjecting a sample, consisting of two half-blocks stacked and bonded with a cement mortar joint, to simple compression until failure as shown in Figure III.16.

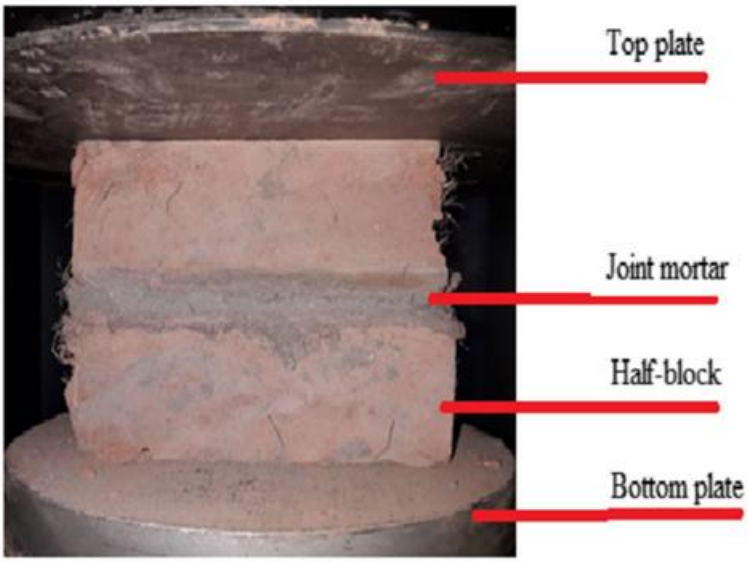


Figure III 16: CEB specimen under compression testing following the procedure specified in XP P13-901

III.4.2.2. Wet compressive strength

Constructions are often exposed to water damage, mainly through capillary action and splashing, though they are rarely fully submerged. Wet blocks have lower mechanical properties (tensile and compressive strength) compared to their dry state. Therefore, it is useful to test them when wet to determine their minimum characteristics under the most unfavorable conditions. This experiment is similar to the dry compressive strength test, except that the sample is fully immersed in water for two hours before testing.

Figure III 6: CEB fully immersed in water

III.4.2.3. Splitting Tensile Test

This test is based on the splitting tensile test (Brazilian test). It involves applying compression to a cured block along two rods positioned on opposite sides. This generates an average tensile stress along a vertical plane between the rods. The procedure follows the guidelines set by C.D.E as illustrated in Figure III.18

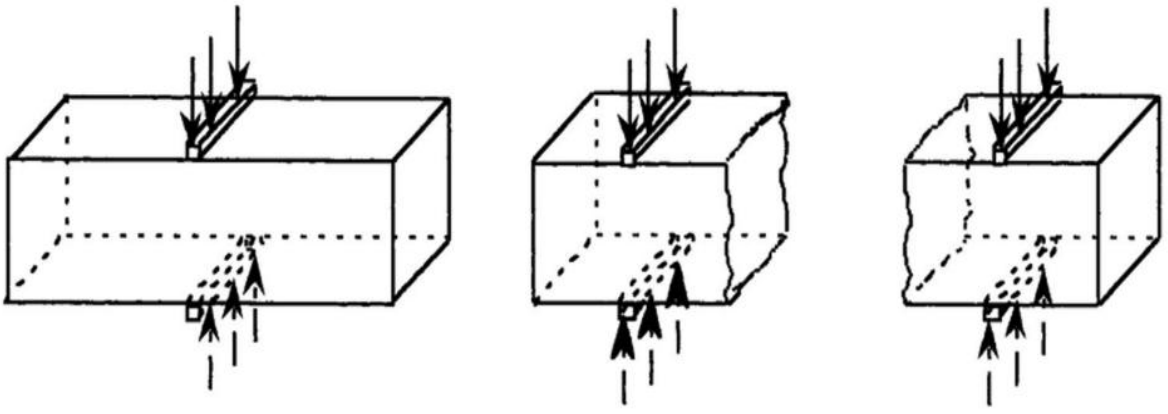


Figure III 78: Schematic diagram showing the setup for the tensile test

III.4.3. Abrasion resistance test

The abrasion resistance of compressed earth blocks is tested according to the experimental standard NF XP 13-901. The purpose is to subject the block to friction using a 25 mm wide metal brush (see Figure III.19). The brushing motion consists of 1 round trip per second for one minute, resulting in 60 strokes in total. From this test, the abrasion coefficient (Ca) of the block is determined, representing the material loss caused by brushing on the abrasion surface.

$$\boldsymbol{Ca(cm2/g) = \frac{s}{m0 - m1}}$$

With:

- Ca = abrasion coefficient of the block
- S = abrasion surface area of the block in cm²
- m 0 = initial mass of the brick before abrasion in grams
- m 1 = mass of the brick after the abrasion test in grams.

Figure III 19 Schematic Abrasion test: (left) Steel brush utilized, (right) appearance of the specimen after testing

III.5. Conclusion

This chapter presented the characteristics of the different raw materials used in the composition of the fiber reinforced compressed earth blocks developed in this research. The materials consist of soil and brick waste, along with stabilizers such as cement and fibers. The fibers used in this study are of vegetable origin, specifically Sisal and Alfa fibers. The data presented in this chapter were obtained from the literature or characterization tests conducted during our study. The results of the various tests performed will be presented in Chapter IV.

Chapter IV:

RESULTS AND DISCUSSION

IV.1. Introduction

The synthesis of prior studies highlights the importance of further investigation into the impact of Sisal or Alfa fibers and cement on the thermophysical properties and mechanical of CEBs for use in construction materials. Specifically, the research focuses on essential thermophysical properties, including density, capillary absorption and thermal conductivity as well as key mechanical behaviors, such as compressive strength (in both dry and wet conditions) and tensile strength. Additionally, durability is assessed through an abrasion test. This chapter presents and analyzes the results obtained from laboratory experiments. These findings shed light on how the incorporation of Sisal or Alfa fibers and cement impacts the thermophysical properties and mechanical characteristics of CEBs, providing a basis for assessing their suitability as sustainable construction materials.

IV.2. Effect of fiber content on physical properties

IV.2.1. Density

The sample density was measured 28 days after production. Figures IV.1 and IV.2 illustrate the effect of varying concentrations of Sisal and Alfa fibers on the density of CEB. A slight reduction in density was observed as fiber content increased, attributed to the lower unit weight of the fibers compared to clay. For Sisal fiber-reinforced CEB blocks, the density decreased from 2250 kg/m³ in the unreinforced control block to 2120 kg/m³ at 0.5% fiber content, reflecting a 5.7% reduction. Similarly, for Alfa fiber-reinforced blocks, the density declined from 1965 kg/m³ in the control sample to 1896 kg/m³ at 0.5% fiber content, corresponding to a 3.5% decrease. This observation aligns with findings from several authors, who have reported that the addition of fibers tends to reduce the density of compressed earth blocks. For example, Mohamed et al[60]. assessed how adding hay fibers influences the density of earth blocks and observed a decrease in dry density as the hay content increased. Likewise, Taallah et al[108]. explored the addition of both untreated and alkali-treated palm fibers, concluding that higher fiber content lowers density. A decrease in density is beneficial as it makes the earth blocks lighter

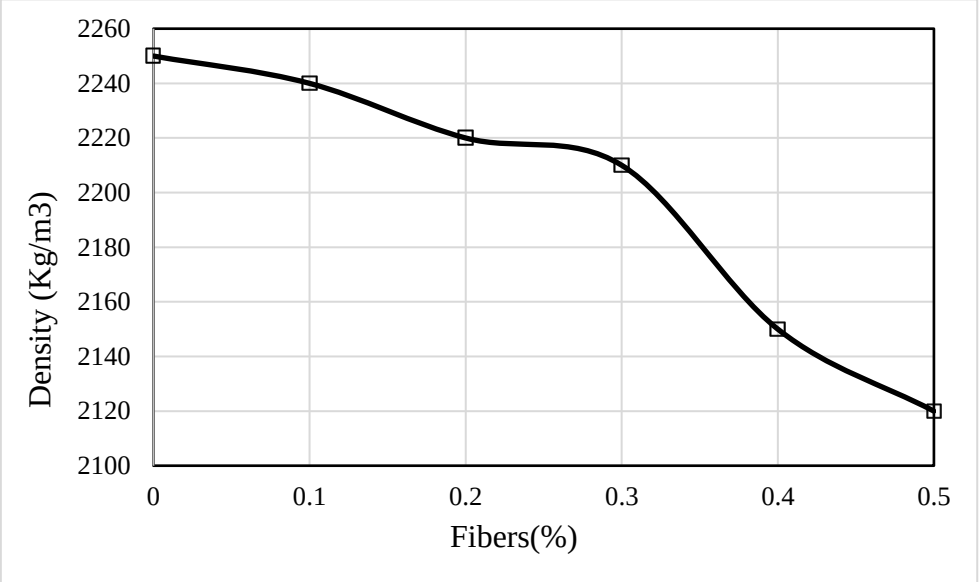


Figure IV 1: Effect of Sisal fibers on density

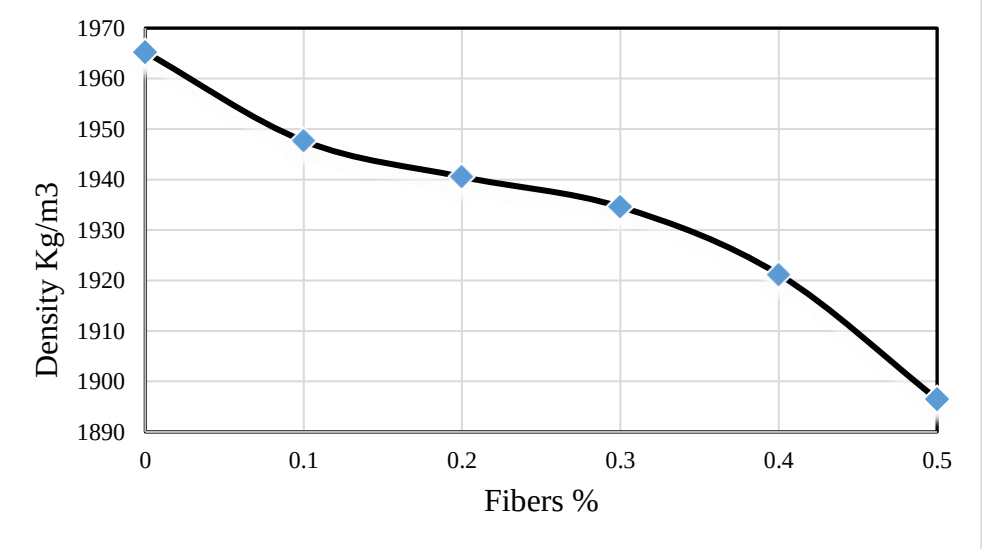


Figure IV 2: Effect of Alfa fibers on density

IV.2.2 Capillary absorption test

Knowing the absorption capacity is important, it provides a general idea of the presence and significance of voids. When a volume of soil is subjected to stress, the material compresses, resulting in a decrease in the void ratio[9]. Generally, the lower the water absorption of a block, the better its mechanical performance[48]. In the case of Sisal fibers, the bar charts in Figures IV.3 and 4.4 reveal that the absorption coefficient is notably impacted by the addition of Sisal fibers and cement. Initially, the blocks made solely from soil and BW (without cement and fibers) exhibit

extremely low water resistance causes them to start disintegrating upon exposure to moisture as shown in Figure IV.5. However, with the addition of fibers, the blocks retained partial integrity, suggesting that sisal fibers help reduce the water sensitivity of CEB. This implies that sisal fibers enhance the water resistance of the blocks. These observations indicate that using fibers alone to reinforce CEB blocks is not enough to ensure their resistance to moisture over time; a chemical stabilizer is needed to enhance adhesion among soil particles. Secondly, in cement-stabilized, fiber-reinforced CEB, it was noted that, at a constant cement content, the absorption coefficient increased with increasing fiber content. Compared to unreinforced blocks, the absorption coefficient of blocks reinforced with 0.5% fiber showed an increase in absorption by 81%, 71%, and 7% when stabilized with 5%, 7%, and 9% cement, respectively. The findings correspond with results reported in earlier research[73][109]. The authors noted that incorporating fibers resulted in higher water absorption in laterite bricks. Ghavami et al [93], reported that plant fibers contributed to the formation of voids and created channels among soil particles. At the same time, it was observed that absorption decreased as cement content increased, as demonstrated in Figure IV.4 The addition of cement contributed to reducing the absorption rate by improving interparticle bonding, thereby decreasing porosity and minimizing the presence of flocculated soil components[110]. It is important to emphasize the impact of compaction stress on water absorption, as compaction changes the soil density, mechanical strength, permeability, and porosity**.** Additionally, this material is classified as having low capillarity according to NF XP 13-901[14].

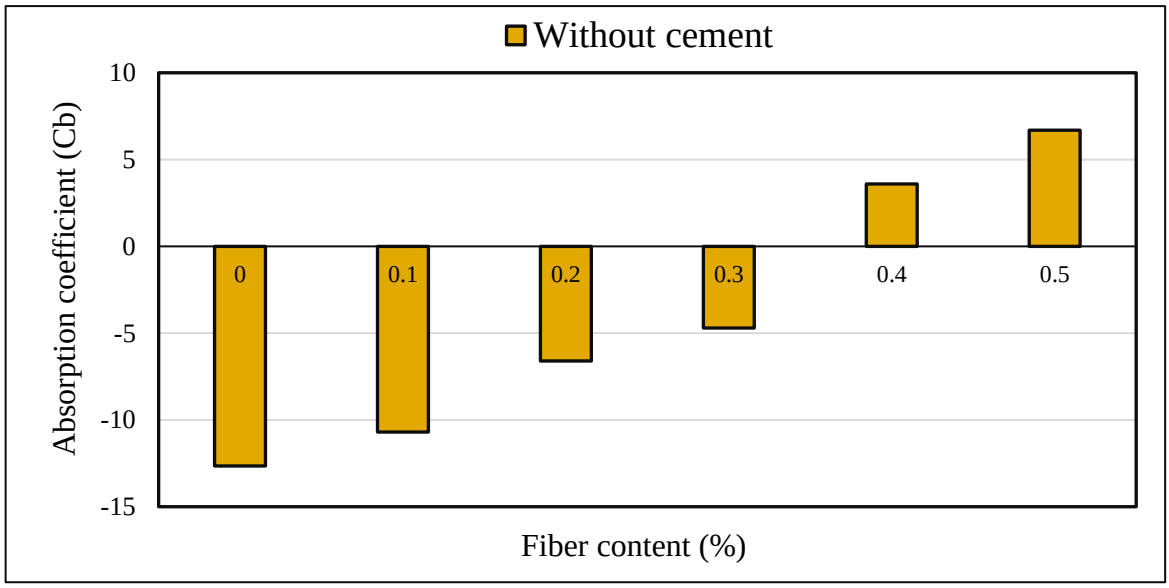


Figure IV 3: Effect of Sisal fibers on the capillary absorption of unstabilized CEB

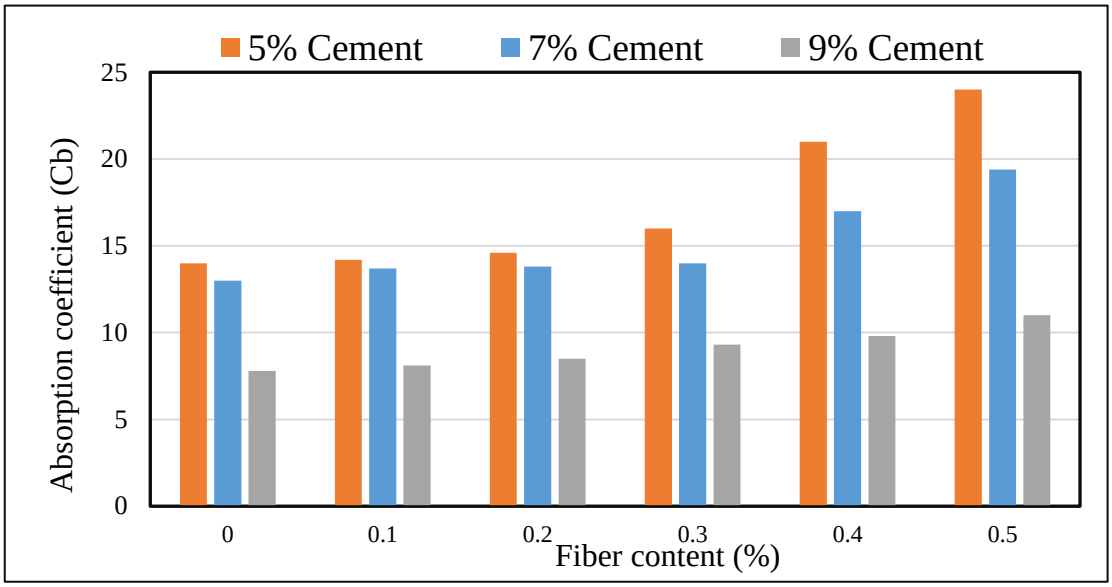


Figure IV 4: Effect of Sisal fibers and cement on the capillary absorption of stabilized CEB

Figure IV 5: Appearance of blocks after water immersion

Regarding Alfa fibers, the impact of fiber content on the absorption rate coefficient (Cb) is illustrated in Figure IV.6. The analysis reveals that as fiber content increases, Cb also rises. Compared to the reference block, the block with 0.5% fibers exhibited a 40% increase in Cb. This effect is mainly due to the presence of vegetal fibers, which generate voids and interconnected channels within the material, as illustrated in Figure IV.7, where visible pores and voids are observed. Additionally, the hydrophilic nature of Alfa fibers contributes to this increase, as they absorb and retain water. These findings align with previous studies[73], [93], [111], [112]. Moreover, despite the rise in Cb, the water absorption rate remained within the acceptable limits set by the NF XP 13–901, stipulating a required minimum Cb value of 2.

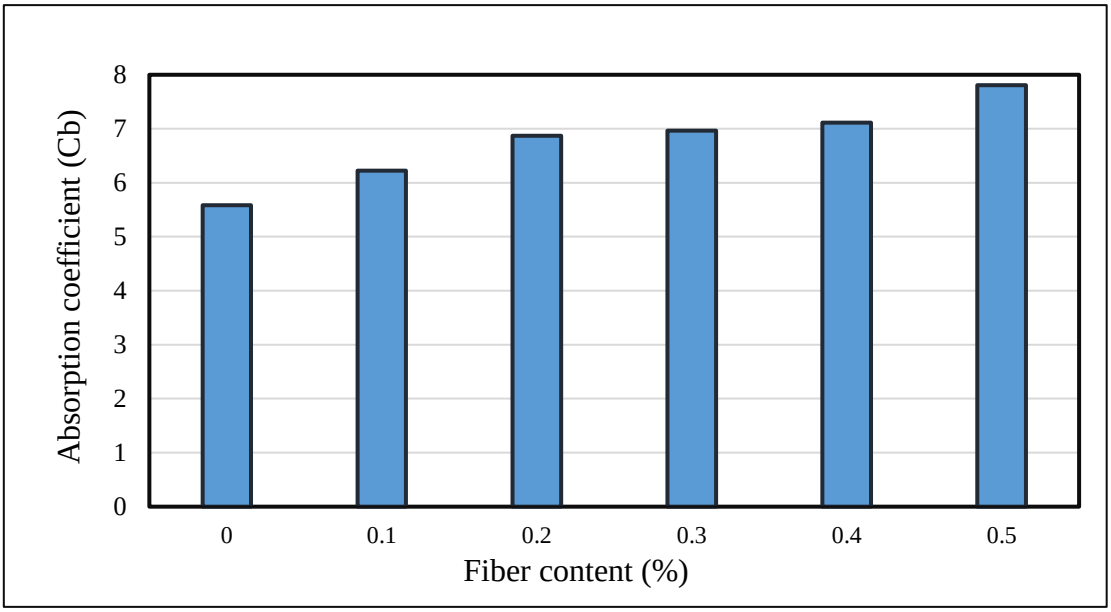


Figure IV 6: Effect of Alfa fibers on the capillary absorption of stabilized CEB

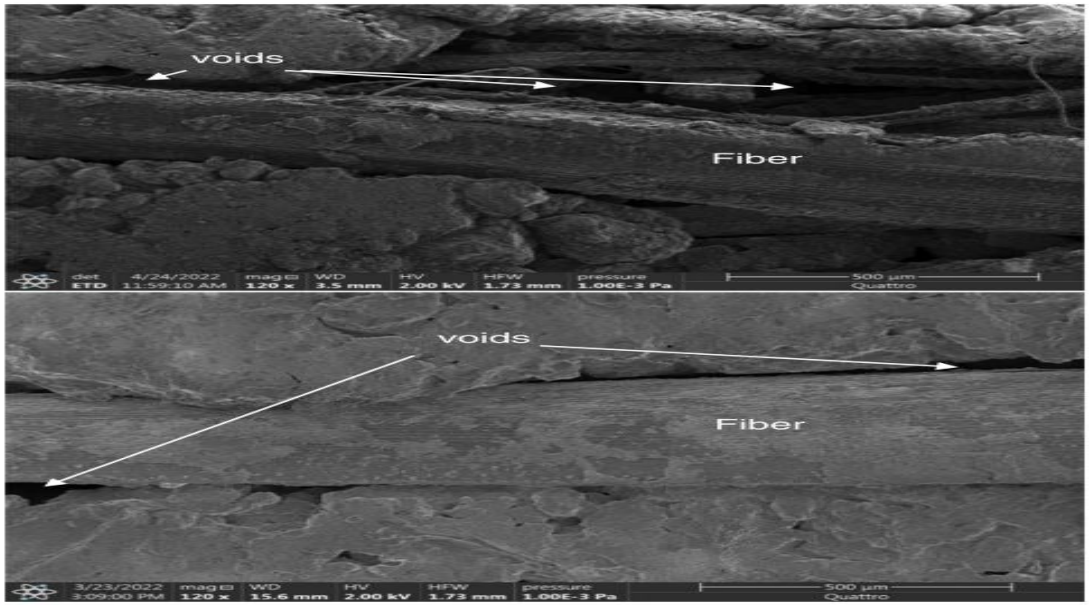


Figure IV 7: Voids created by Alfa fibers

IV.2.3 Thermal properties

Figure IV.8 presents the impact of Sisal fiber addition on the thermal properties of cement-stabilized and fiber-reinforced samples. In fiber-reinforced CEB, thermal conductivity progressively decreased with increasing Sisal fiber content. For instance, incorporating 0.5% fibers led to a 15% reduction in thermal conductivity compared to unreinforced CEB. This decline can be explained by the increased porosity from fiber inclusion, which created additional voids and an open skeletal structure. Similar trends have been observed in previous studies [76], [92], [113], [114].

For cement-stabilized fiber-reinforced CEB, an increase in fiber content led to a reduction in thermal conductivity. Specifically, adding 0.5% fiber resulted in a 17%, 19%, and 21% for cement contents of 5%, 7%, and 9%, respectively. The same principle explaining the decrease in thermal conductivity for fiber-reinforced CEB also applies to cement-stabilized fiber-reinforced CEB. Conversely, at a constant fiber content, thermal performance improved with higher cement content. Similar trends were observed by Zakham et al. [115], where thermal conductivity increased from 0.189 to 0.24, 0.3, and 0.351 W/m·K as the control block was stabilized with 5%, 7%, and 9% cement, respectively. This rise in thermal conductivity was mainly attributed to the hydration reaction between soil and cement minerals, resulting in strengthened interparticle bonds, minimized porosity, and improved the overall rigidity of the CEB material. [116].

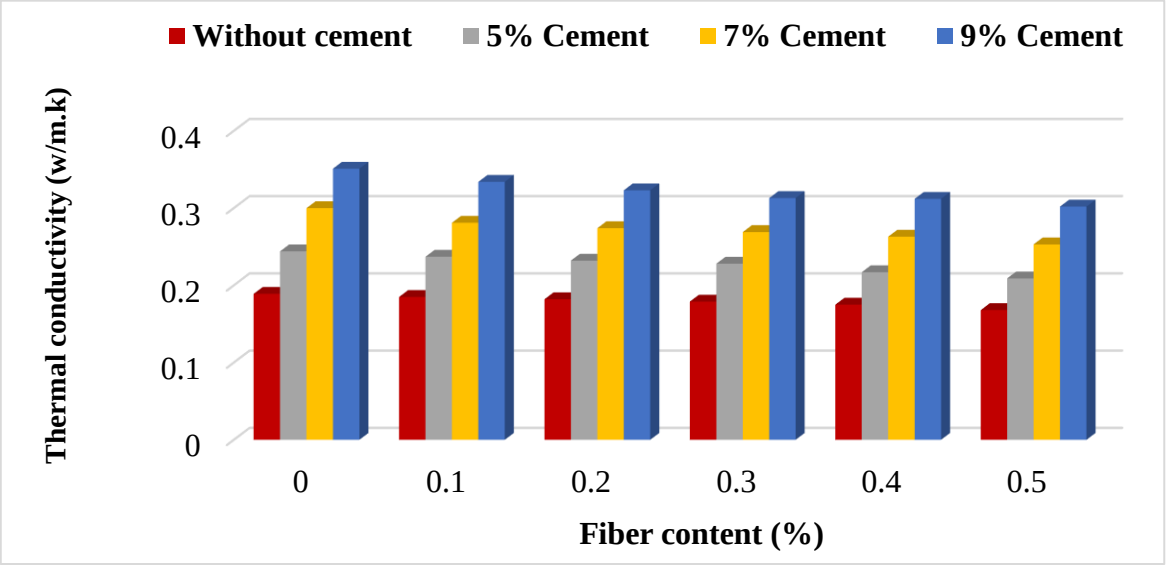


Figure IV 8: Variation of thermal conductivity of CEB for Sisal fibers

Concerning Alfa fibers, their incorporation was evaluated for their impact on heat transfer potential by measuring the thermal conductivity coefficient. As illustrated in Figure IV.17, increasing the fiber content led to a reduction in thermal conductivity. Specifically, the value dropped from 0.753 W/m·K in the unreinforced reference CEB to 0.654 W/m·K in the CEB containing 0.5% fibers, marking a 13% decrease. This reduction is mainly due to the insulating nature of Alfa fibers, which introduces additional air pockets within the material, thereby limiting heat transfer.

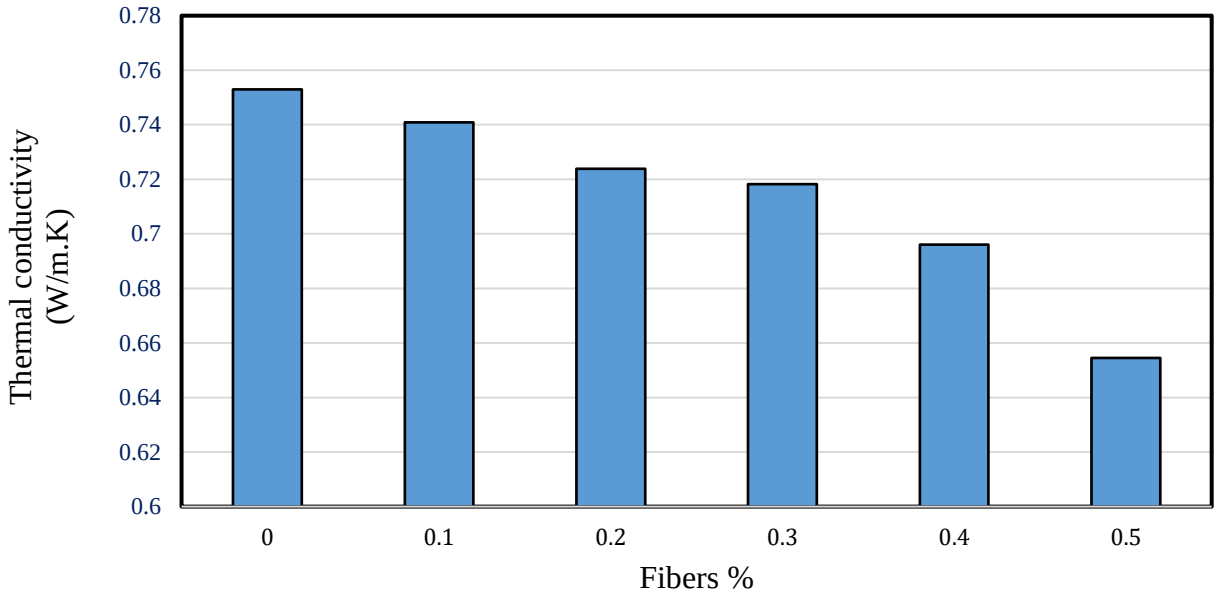


Figure IV 9: Variation of thermal conductivity of CEB for Alfa fibers

IV.3. Effect of fiber content on mechanical properties

IV.3.1. Dry compressive strength

Figure IV.6 presents the 28-day dry compressive strength of the various blocks produced. The results indicate that adding cement and fibers enhanced the strength, though fiber-reinforced blocks and cement-stabilized blocks exhibited distinct behaviors. Initially, the compressive strength of fiber-reinforced CEB consistently improved with the increase in fiber content. Specifically, the compressive strength rose from 2 MPA to 5 MPA when fibers were incorporated at a rate 0.5%, marking a 150% improvement compared to the unreinforced sample. This behavior is largely due to the fibers, which helped carry part of the applied load, resulting in increased friction between soil particles. The interaction between the fibers and soil strengthened the contact forces among the particles, enhancing the material's properties. Studies have shown that fibers, when combined with soils, introduce additional cohesion to the composite, thereby enhancing the

performance of earth-based materials. [117]. Additionally, it is important to note that a minimum strength of 2 MPa is recommended for CEB, as stated in [118]. This requirement was already met by the fiber-reinforced CEB in this study. Furthermore, the strength achieved in this work exceeded that reported in other studies. [92], which can likely be attributed to the specific soil type and the quality of the fibers used.

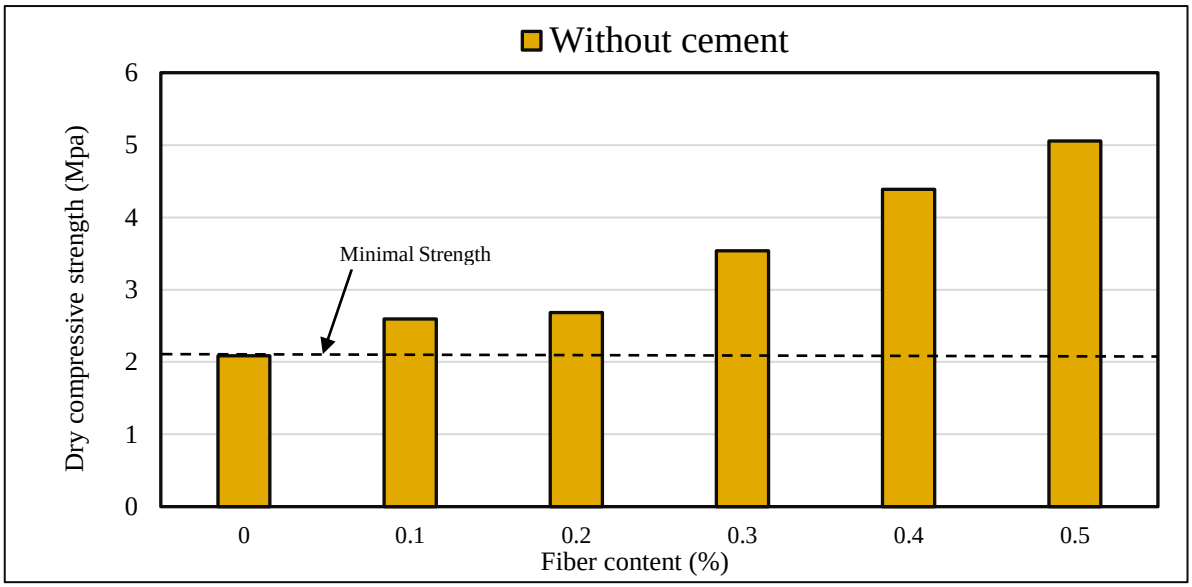


Figure IV 10: Variation of dry compressive strength of CEB without cement for Sisal fiber

Then, the strength of cement-stabilized fiber-reinforced blocks reached its peak at an optimal fiber content, after which a decline in strength was observed. The impact of fibers was more pronounced at lower cement contents, while the sensitivity of strength decreased as the cement content increased. Across all cement concentrations, the optimal fiber content was identified as 0.2%, with the strengths beyond this point remaining relatively consistent. Notably, a maximum strength of nearly 8 MPa was achieved, demonstrating the potential to achieve high strength with reduced cement content, which is an environmentally friendly approach to minimizing cement use.

In cement stabilization, strength primarily develops due to the interaction between cement and water, which generates rigid hydrates that fill voids and hold particles together. Additionally, pozzolanic reactions take place between clay minerals and calcium hydroxide ($Ca(OH)_2$), a byproduct of cement hydration.[119], [120]. In the literature, researchers attributed the reduction in strength of cement-stabilized fiber-reinforced CEB beyond the optimal fiber content to the full mobilization of fiber-matrix interactions. Moreover, the excess fibers created additional voids within the composite, leading to a decline in strength.[72], [73].

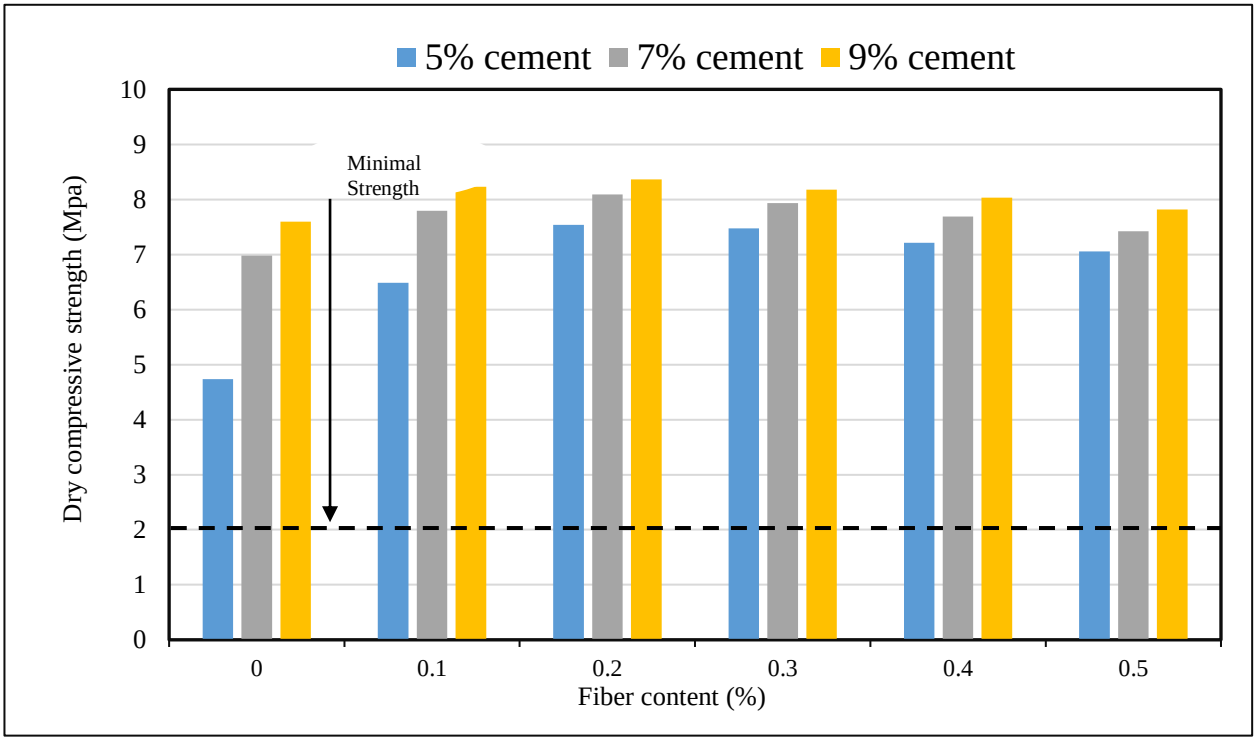


Figure IV 11: Variation of dry compressive strength of CEB with cement for Sisal fiber

As for Alfa fibers, the relationship between compressive strength and fiber content is illustrated in Figure IV.12. As observed, compressive strength improves with increasing fiber content. Specifically, it rises from 3.91 MPa in the control block to 8.26 MPa in the block reinforced with 0.5% fibers, representing a 111.25% enhancement. This behavior can be attributed to the mechanical interaction between the fibers and the soil matrix, furthermore, the fibers enhance cohesion within the composite by restricting the relative displacement of soil particles in the clay-brick mixture, thereby mitigating lateral deformation and improving structural stability. These results are consistent with previous studies that have demonstrated the reinforcing effect of fibers in improving the mechanical performance of earthen materials.[92], [112], [121]–[123].

The influence of fiber reinforcement on the stress-strain behavior of CEB is illustrated in Figure IV.13. The results indicate that the curve's shape evolves as fiber content increases, leading to two key observations. To begin with, a higher fiber content significantly enhances the compressive strength of CEB. Additionally, an analysis of the initial section of the stress-strain curves reveals that an increased fiber dosage reduces the modulus of elasticity. This suggests that fiber reinforcement strengthens CEB by restricting lateral deformation while simultaneously improving ductility due to the flexible nature of plant fibers. These findings are consistent with previous studies[92][111], which reported a 16% increase in compressive strength with the addition of 0.4% Hibiscus cannabinus fibers and 0.2% sisal fibers.

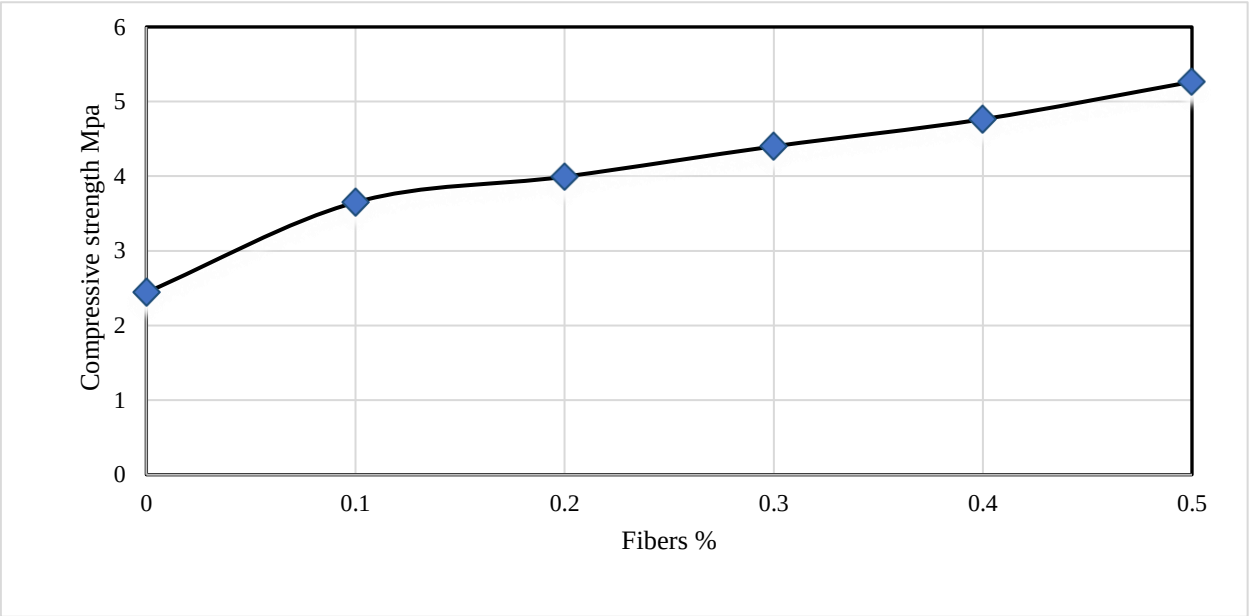


Figure IV 12: Variation of dry compressive strength of CEB for Alfa fiber

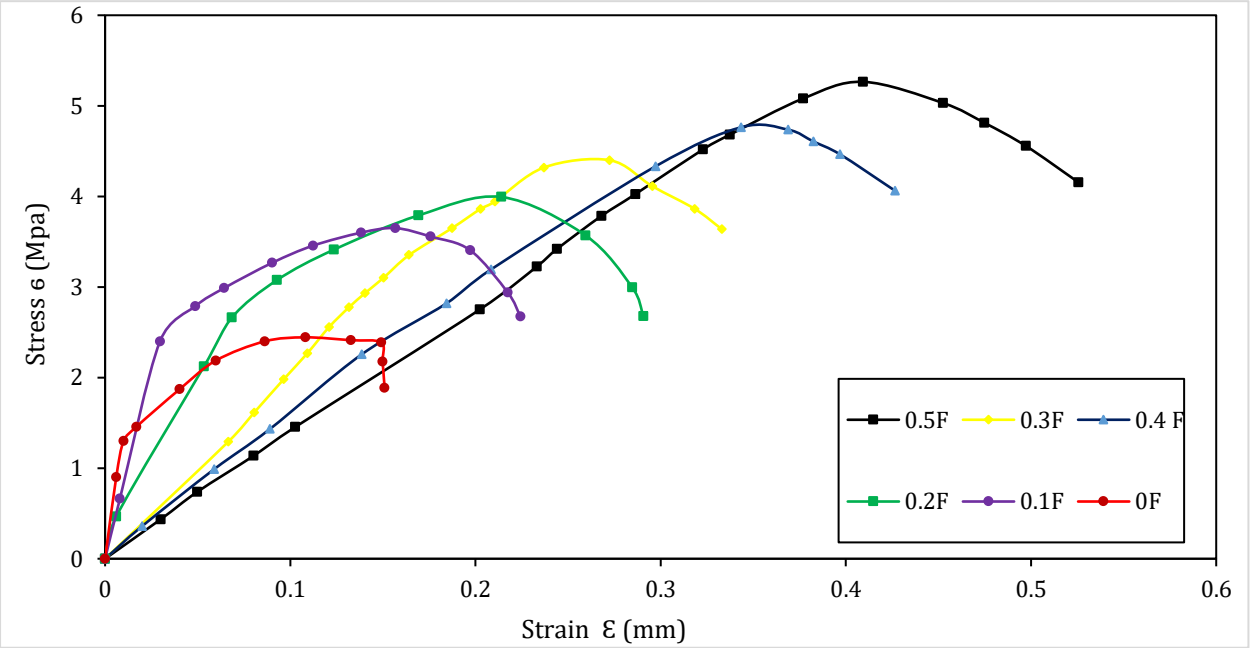


Figure IV 13: Effect of Alfa fibers on the stress-strain curves

IV.3.2. Wet compressive strength

To evaluate the performance of CEB under severe conditions, a wet compressive strength test was conducted. Additionally, several researchers have regarded this factor as an indicator of durability [124]. The test involved measuring the compressive strength following a 2-hour immersion of CEB in water. The finding for Sisal fibers, presented in Figure IV.14, revealed two distinct behaviors:

(i) Fiber-reinforced blocks either partially or completely disintegrated upon immersion, rendering 0074heir strength negligible. (ii) Cement-stabilized fiber-reinforced blocks retained their integrity and exhibited enhanced consolidation.

Building on these findings and the previously discussed dry strength results, fiber-reinforced blocks can be utilized in earth construction, provided they are coated with an impermeable material to prevent water infiltration.

From Figure IV.14, it is also evident that wet compressive strength increased with higher cement content. As previously discussed, this improvement was attributed to the reactions between clay and cement. These findings are consistent with those observed by Reddy et al. [43]. Furthermore, the analysis revealed that strength decreased as Sisal fiber content increased, likely due to the relatively weak bond between Sisal fibers and the matrix [105]. However, even with this reduction, the strength values achieved with 7% and 9% cement content met the minimum requirement of 2 MPa. In contrast, for 5% cement content, the Sisal fiber percentage should not exceed 0.3%. Nevertheless, incorporating higher fiber percentages may be feasible if the CEB is coated with an impermeable material to prevent water infiltration.

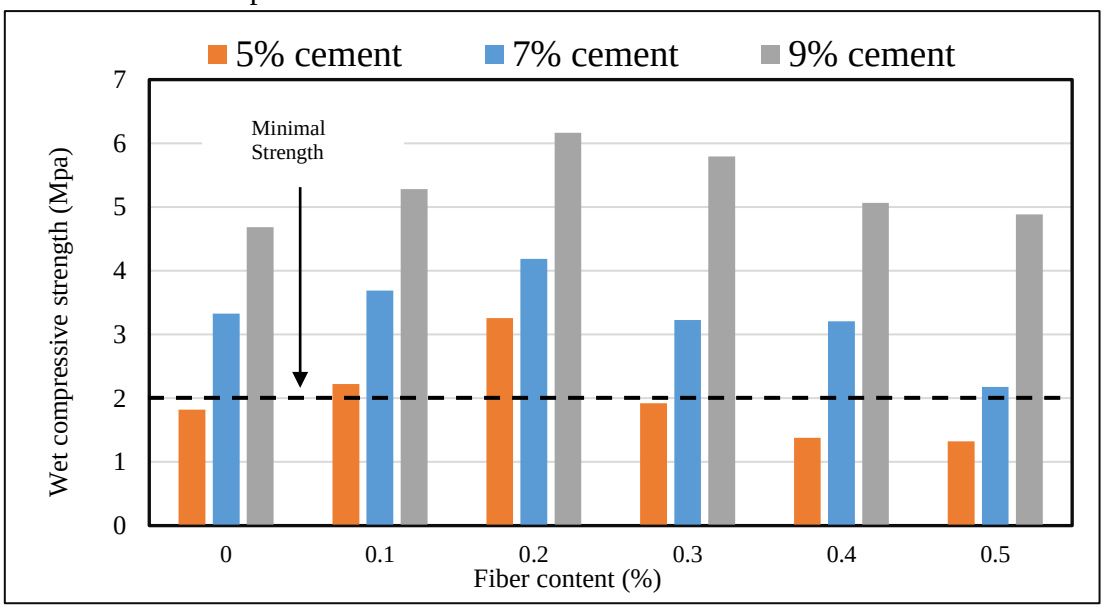


Figure IV 14: Variation of wet compressive strength of CEB with cement.

IV.3.3. Tensile strength

Figure IV.15 illustrates the impact of Sisal fiber incorporation on tensile strength. The findings reveal a consistent increase in tensile strength for both cement-stabilized and fiber-reinforced cement-stabilized CEB as fiber content rose. The rise in tensile strength with higher cement content is due to the hydration reaction, as previously discussed. The influence of fibers was more pronounced in tensile strength compared to compressive strength. This can be attributed to the directional variations in the material's behavior. The intense compaction applied during CEB production results in the formation of horizontal layers that align at a right angle to the compaction force. This phenomenon has also been highlighted by other researchers when analyzing pavement materials subjected to high compaction in a specific direction [125]. The obtained results were aligned with those documented by Millogo et al. [92]. Their study indicated that fibers under tensile stress enhanced the interconnection between the matrix and the fibers. Similarly, another study [126] revealed that incorporating 1% hay fibers effectively enhanced the tensile resistance strength of fiber-reinforced clays. Figure IV. 16 illustrates the impact of Alfa fiber incorporation on tensile strength. The results indicate a consistent increase in tensile strength as fiber content increases. Adding 0.5% fibers enhanced the tensile strength of CEB by 79% compared to the control sample. A similar explanation can be applied to justify this improvement, as observed with Sisal fibers. Some previous research studies have reported the opposite effect [45], [105], [127], [128]This decline has been attributed to the heterogeneous distribution of fibers with the CEB [105] and an insufficient fiber content [128]. Furthermore, during the test, it was observed that in fiber-reinforced CEB, the fractured specimen remained partially connected, whereas, in unreinforced CEB, the two parts of the specimen were completely separated (Figure. IV.17). This indicates that the inclusion of fibers enhanced the material's energy absorption capacity, thereby improving its ductility compared to unreinforced CEB. These findings are consistent with those observed in previous studies [129], [130] . On the other hand, some researchers have indicated that the addition of natural aggregates or fibers led to a reduction in tensile strength[45], [105], [127], [131], [132] This decline was attributed to factors such as fiber distribution, the heterogeneity of CEB. [105], and an insufficient amount of fiber in the mix [132].

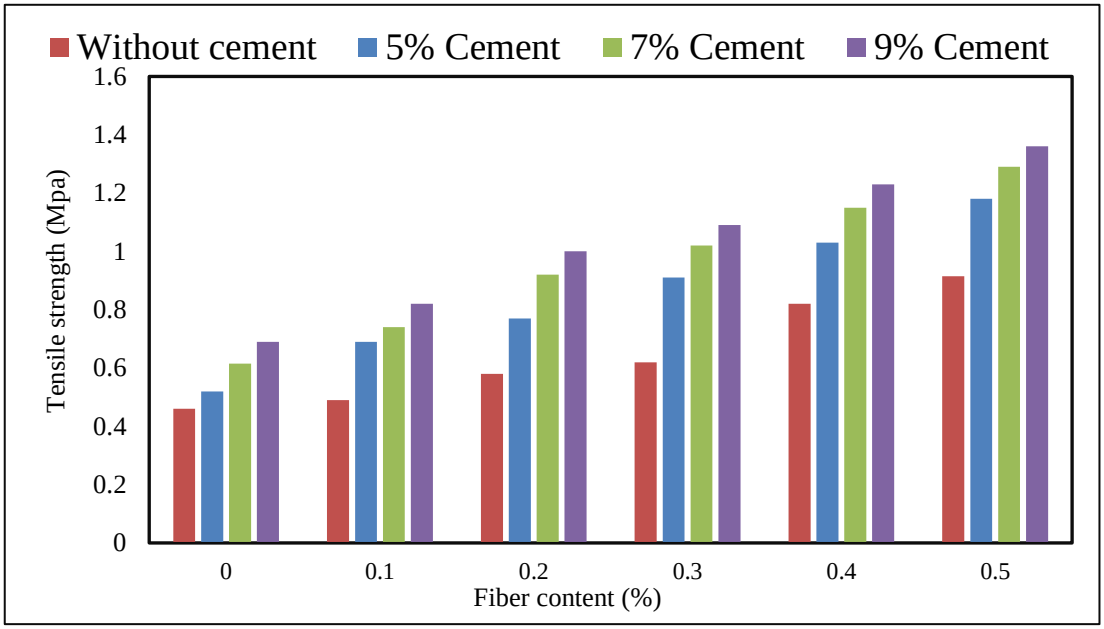


Figure IV 15: Variation of dry tensile strength of CEB for Sisal fibers

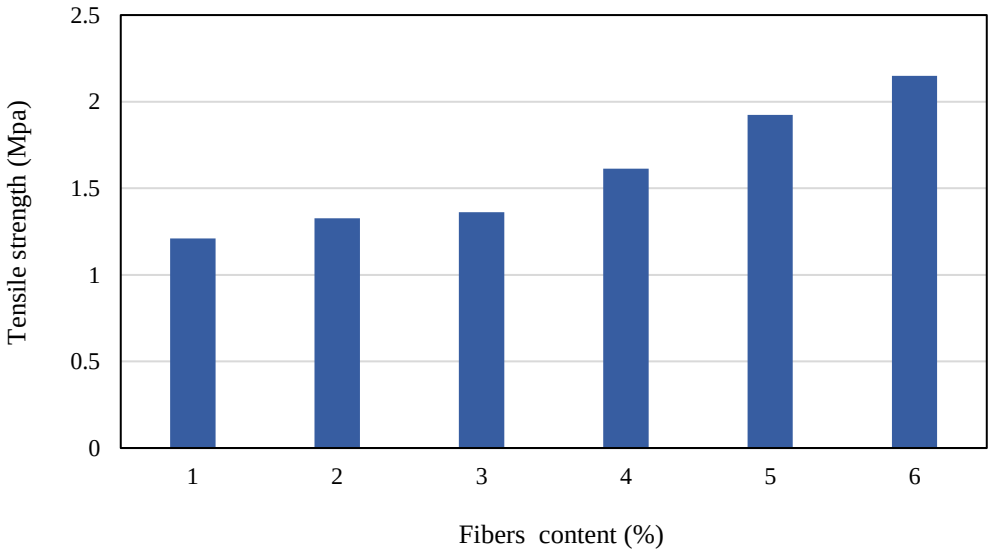


Figure IV 16: Variation of dry tensile strength of CEB for Alfa fibers

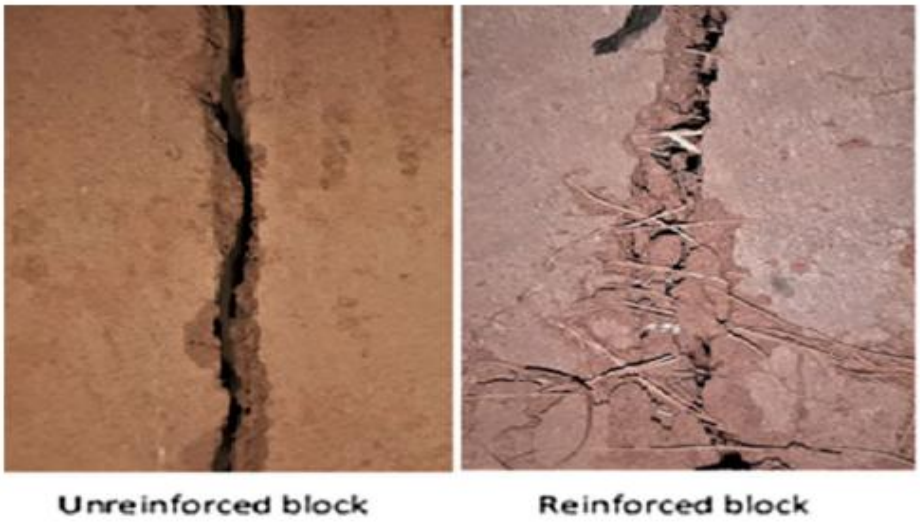


Figure IV 17: Tensile failure of soil blocks

IV.4. Abrasion resistance test

The abrasion resistance test shows the erosion of CEB samples due to the abrasive impact of wind-driven sand, aiming to replicate conditions found in dry, arid regions. The abrasion coefficient (Ca) measures the material's resistance to abrasive forces. In this test, contact forces detach particles from the specimens, which then act as abrasives, causing further material loss. Figures IV.18 and IV.19 presents the abrasion test results for fiber-reinforced unstabilized CEB and fiber-reinforced cement stabilized, respectively. The findings indicate that incorporating fibers into CEB led to an increase in the abrasion coefficient. When compared to unreinforced CEB, the abrasion coefficient was higher by 232%, 239%, 184%, 43%, and 20% for samples containing 0.5%, 0.4%, 0.3%, 0.2%, and 0.1% fiber, accordingly. The enhancement in abrasion resistance is attributed to the addition of fibers, which created additional cohesion through strong bonding with soil particles and uniform distribution within the soil matrix[117], [133]. In fiber-reinforced, cement stabilized blocks, the abrasion coefficient increased in those containing 0.1% fiber and stabilized with 5% and 7% cement. Conversely, with 9% cement addition, the abrasion coefficient(Ca) consistently decreased as fiber content rose. Thus, for a given fiber content, the abrasion coefficient (Ca) increased as the fiber content increased. Comparable findings have been observed in numerous studies[92], [132]–[135]. Notably, the abrasion coefficient for fiber-reinforced CEB was significantly lower than that of cement-stabilized blocks, as the strong bond formed through hydration improved abrasion resistance. Moreover, all abrasion coefficient values exceeded the minimum recommended level of 2 cm^2/g, as outlined by NF XP 13-901.

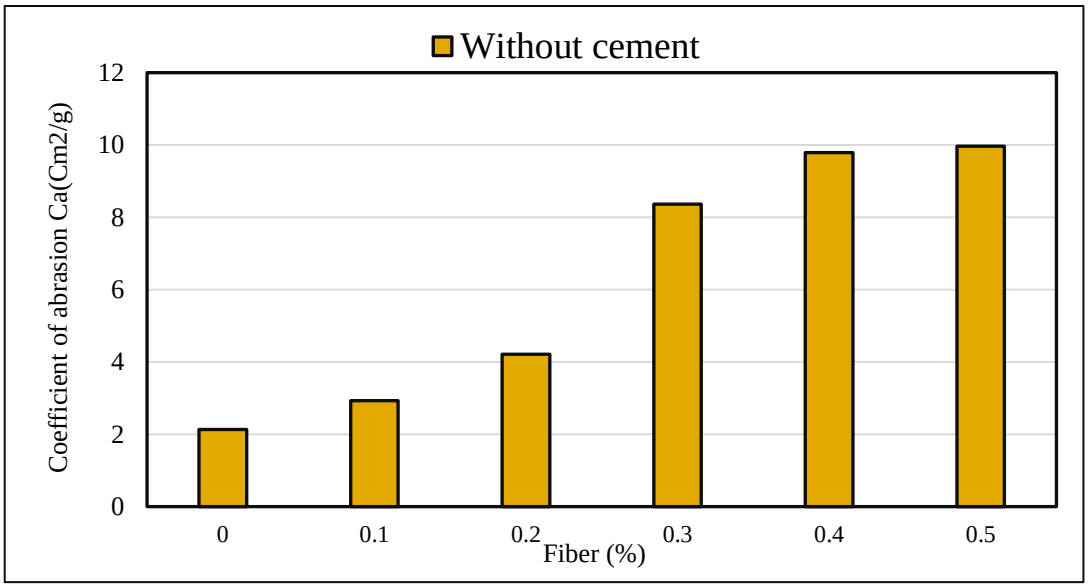


Figure IV 18: Abrasion coefficients of fiber-reinforced, unstabilized CEB

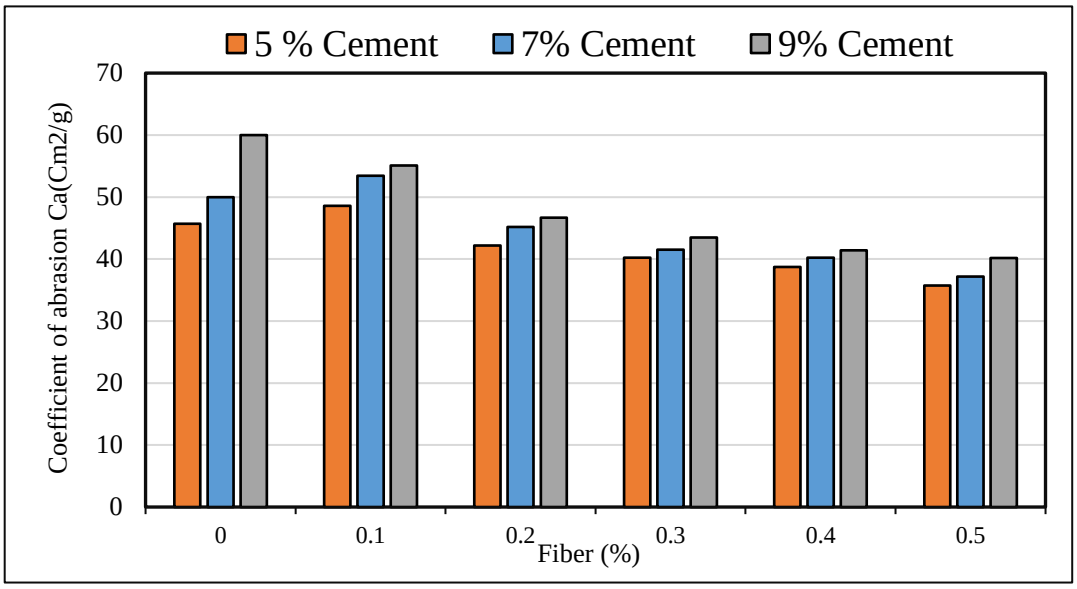


Figure IV19: Abrasion coefficients of fiber-reinforced, stabilized CEB

IV.5. Conclusion

This chapter enabled us to explore the potential for improving the thermomechanical properties of compacted earth by incorporating sisal or Alfa fibers. A chemical stabilizer, such as cement, is utilized to achieve better stabilization of CEB.

Based on the findings of this experimental study, the main conclusions can be summarized as follows:

- The maximum amount of brick waste incorporated into CEB should not exceed 20% to ensure compliance with the minimum plasticity requirements.
- Incorporating Sisal or Alfa fibers reduces the weight of CEB due to the variation in unit weight between the clay and the fibers. At 0.5% content of Sisal or Alfa fibers, the density decreased by 5.7% and 3.5%, respectively.
- Sisal fiber-reinforced CEB blocks exhibit low resistance to water, although their sensitivity decreases as fiber content increases. On the other hand, cement-stabilized Sisal or Alfa fiber-reinforced blocks demonstrate improved water resistance. The capillary absorption of CEB increases with higher fiber.
- The results indicated a consistent decrease in thermal conductivity as the Sisal fibers content increased. For instance, at a 0.5% fiber addition, the thermal conductivity coefficient dropped by 15% and 21% for uncemented and cemented CEB, respectively. A similar result was observed for Alfa fibers. Their incorporation into CEB also enhances its thermal insulating properties.
- The dry compressive strength at 28 days of Sisal fiber-reinforced CEB showed a steady increase with higher fiber content in the mix, with a 0.5% fiber addition leading to a 150% strength improvement. However, in cement-stabilized, fiber-reinforced CEB, the strength peaked at an optimal fiber content of 0.2%, followed by a decline beyond this threshold. In the same way, the integration of Alfa fibers into CEB significantly enhances its mechanical properties. At 0.5% fiber content, compressive strength improved significantly, increasing by 111.25% relative to the unreinforced CEB.
- The 28-day wet compressive strength showed that fiber-reinforced blocks either partially or fully disintegrated after water immersion, whereas blocks exhibited significantly greater resistance when stabilized through the combined effect of cement and fibers.
- The tensile strength consistently increased with the rise in both cement content and Sisal or Alfa fiber content in the mix.

- The findings revealed that the abrasion coefficient consistently decreased with higher Sisal fiber content in cemented blocks. However, for uncemented blocks, it increased as fiber content rose.

General conclusion and further works

General conclusion

Sustainable earth construction has been practiced for centuries, as evidenced by traditional housing found across various regions of the world. Its popularity stems from its economic advantages and ease of use. However, with the rise of industrial construction materials like steel and concrete, raw earth was largely abandoned and forgotten. In recent years, it has regained interest in both developing and industrialized countries as a sustainable alternative. Bricks, in both raw and fired forms, have also been used in construction for centuries and continue to be a fundamental component of modern building practices. Although fired bricks are widely used over traditional earthen bricks, their production requires a significant amount of energy. In developing countries like Algeria, the heavy dependence on fired bricks for affordable housing has led to unsustainable development. As concerns about environmental degradation and energy-intensive construction materials continue to grow, earth-based construction is once again gaining attention for its sustainability and low environmental impact. Among modern earth-building techniques, the compressed earth block (CEB) is a relatively recent innovation. It represents an advancement of the traditional adobe block, offering more consistent dimensions, improved density, higher compressive strength, and better water resistance. The reinforcement of construction materials with natural fibers has been utilized for centuries in architecture and engineering. Over the years, numerous studies have explored the use of plant-based fibers as reinforcement in construction materials, particularly in developing countries where such fibers are widely available, cost-effective, and require minimal processing. This research focuses on enhancing the performance of CEB and developing new local construction materials by utilizing abundant natural resources such as soil, Sisal or Alfa fibers, and brick waste. To reduce the susceptibility of CEB to water, cement was used as a binder. Hence, the objective of this research is to examine the thermomechanical characteristics and physical properties of Sisal or Alfa fiber-reinforced compressed earth blocks for their potential use as a sustainable construction material. The application of the studied material in housing construction relies on its capability to satisfy building standards, particularly concerning suitable thermomechanical and physical properties, as well as durability. The key findings of this research can be outlined as follows:

The results indicated that the maximum proportion of brick waste in CEB should be limited to 20% to meet the minimum plasticity requirements. Additionally, incorporating sisal or Alfa fibers reduces the weight of CEB due to the difference in unit weight between the fibers and clay, with a 0.5% Sisal or Alfa fibers addition leading to a 5.7 % and 3.5% decrease in density, respectively. Furthermore, fiber-reinforced CEB blocks exhibited low water resistance, although their sensitivity to moisture decreased with higher fiber content, necessitating external protection to prevent water infiltration. Moreover, compared to unreinforced blocks, the absorption coefficient of blocks with 0.5% of Sisal fiber content increased by 81%, 71%, and 7% for those containing 5%, 7%, and 9% cement, respectively. Similarly, the capillary absorption of CEB increased with higher Alfa content, with a 40% rise in Ca for blocks incorporating 0.5% fibers. This increase is attributed to the porous structure and elongated shape of the fibers, which enhance water permeability. As a result, blocks stabilized through the combined effect of cement and fibers meet the requirements of the NF XP 13–901 standards. In addition, thermal conductivity consistently decreased as fiber content increased, enhancing the material's insulation properties. For instance, with the addition of 0.5% of Sisal fibers, the thermal conductivity coefficient was reduced by 15% and 21% for uncemented and cemented blocks, respectively. A similar result was observed for Alfa fibers. Their incorporation into CEB also enhances its thermal insulating properties, leading to lower energy consumption for heating and cooling in residential buildings. At 28 days, dry compressive strength of Sisal fiber-reinforced CEB consistently improved as the fiber dosage increased in the composition, with a 150% strength enhancement observed at 0.5% fiber addition. However, in cement-stabilized fiber-reinforced CEB, the compressive strength peaked at a fiber content of 0.2%, followed by a decline at higher concentrations. This reduction in strength is attributed to the increased porosity introduced by the fibers compared to unreinforced blocks. In the same way, the integration of Alfa fibers into CEB significantly enhances its mechanical properties. At a 0.5% fiber content, compressive strength increased by 111.25% relative to the unreinforced CEB. Moreover, under extreme conditions (saturated state), Sisal fiber-reinforced blocks either fully or partially disintegrated after immersion in water, whereas blocks stabilized with both cement and fibers exhibited significantly higher resistance. Additionally, CEB stabilized with 7% and 9% cement successfully met the minimum required strength of 2 MPa, irrespective of fiber content. However, for 5% cement content, limiting sisal fiber incorporation to 0.3% is recommended to achieve optimal performance. Also, the tensile strength consistently increased with the rise in cement content and Sisal or Alfa fiber content in the mix. Equally important, the abrasion test results indicated that the abrasion coefficient consistently decreased with higher fiber content in cemented blocks, whereas it increased in uncemented blocks. Nevertheless, the abrasion

coefficient values for both fiber-reinforced and cement-stabilized fiber-reinforced CEB still comply with the minimum requirements of NF XP 13–901 standards.

From these findings, stabilizing CEB with a combination of Sisal or Alfa fibers and cement proved effective in enhancing the insulating properties of CEB-based walls. Although fibers remain a viable reinforcement material for CEB, ensuring protection against water infiltration remains crucial.

Finally, this research presents a novel environmental strategy by integrating brick waste (BW) into CEB production, fostering sustainability in construction materials.

Further Works

- Simulation and modeling of the performance of building walls constructed with CEB incorporating crushed brick and soil
- Improvement of the adhesion between Sisal or Alfa fibers and a stabilized compressed earth and waste matrix.
- Investigation of the full-scale dynamic behavior of walls constructed using compressed earth blocks reinforced with both Alfa and Sisal fibers.
- Investigation of the durability of CEB reinforced with fibers in aggressive environments.

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List of publications and communications

International publications:

- **Yacine Labiad.,** Abdelaziz Meddah., Beddar Miloud (2022)
  Physical and mechanical behavior of cement-stabilized compressed earth blocks reinforced by sisal fibers DOI: 10.1016/j.matpr.2021.12.446

- **Yacine Labiad.,** Abdelaziz Meddah., Beddar Miloud (2023)
  Performance of sisal fiber-reinforced cement-stabilized compressed-earth blocks incorporating recycled brick waste DOI: 10.1007/s41062-023-01078-w
- **Yacine Labiad**., Abdelaziz Meddah., Beddar Miloud., Lysandros Pantelidis (2023)
  Study on characterization, mechanical, and thermal properties of Alfa fiber–reinforced compressed earth blocks incorporating crushed brick waste DOI: 10.1007/s12517-023-11695-5

International Conference Papers

- **Yacine Labiad.,** Abdelaziz Meddah., Beddar Miloud (2021)" Mechanical and physical behavior of compressed earth blocks reinforced by sisal fibers " Polymer & Mediterranean Fiber International Conference 2021Algeria (pmfic 2021).
- **Yacine Labiad.,** Abdelaziz Meddah., Beddar Miloud (2021) " Physical and mechanical properties of compressed earth block containing sisal fibers" 2ndINTERNATION SYMPOSIUM ON CONSTRUCTION MANAGEMENT AND CIVIL ENGINEERING "ISCMCE 2021"10-11 November 2021, University 20 Aout 1955-Skikda, Algeria.