الجمهورية الجزائرية الديمقراطية الشعبية
People's Democratic Republic of Algeria
وزارة التعليم العالي والبحث العلمي
Ministry of Higher Education and Scientific Research

جامعـــة زيـــان عـاشـــور بالـجـلـفــــة
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كـــلــــيـــــة الـــعـــلـــوم و الــتــكــنـــولـــوجـيـــا
Faculty of Science and Technology

Department: Civil Engineering

Order N°: . …. / 2024
Defense authorization N° …………./**2024**

DOCTORAL THESIS

3rd Cycle Doctoral (D-LMD)

Presented by

FERDOUS BEZAOU

With a view to obtaining the doctoral diploma in 3rd Cycle Doctoral (D-LMD)

Branch: Civil Engineering

Specialty:

Topic

Valorization of fired bricks waste and dune sand in adobe stabilization

Supported, on17 /09 / 2024, before the jury composed of:

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Djelfa University, FST - 2024

DEDICATION

To my super hero, my dad who passed away, wherever you are, you may be gone … but you will never be forgotten …

To my dear mother, to the person who I love the most … even though my words will never do enough in thanking you for the great contribution you made in my life, I want you to know I'm deeply grateful for you, you have supported me and encouraged me my entire life. You are my everything…

To my loving family, your constant encouragement and belief in me fueled my determination to see this thesis through

Sincerely yours Ferdous Bezaou

ACKNOWLEDGMENTS

First and foremost, I would like to thank God for granting me the health, strength, and patience to overcome this challenge.

I would like to express my sincere gratitude to my supervisor, **Professor Salim GUETTALA** from the University of Djelfa, for his unwavering availability, invaluable guidance, and insightful advice throughout this work.

I would like to express my gratitude to **Dr. Ouarda IZEMMOUREN** from University of Biskra, my co-supervisor. Her willingness to share her knowledge and experience, as well as her encouragement and guidance throughout this work, have been invaluable to me.

I extend my warm thanks to **Dr. Taha-Hocine DOUARA**, from the University of Djelfa, who honored me by being a member of the thesis defense committee.

I also want to thank **Dr. Naas ALLOUT**, from Djelfa University, and **Professor Bachir TAALLAH** from Biskra University, for agreeing to be members of the thesis committee.

I also extend my thanks to Dr. **Taha-Hocine DOUARA**, Head of the Civil Engineering department university of Djelfa, and **Dr. Issam ABDESSELAM**, Head of the Civil Engineering department university of Biskra, for their assistance and encouragement.

I would also like to thank all the members of the **civil engineering laboratory** for their advice, support and invaluable help throughout my work.

I would like to express my sincere gratitude to the General Manager of the Center of **Technological Studies and Services for the Materials Industry** (CETIM) in Boumerdès, Algeria, for his availability and collaboration in carrying out the XRD tests.

Abstract

The primary motivators behind the renewed focus on employing locally available materials, recycling industrial waste, and utilizing their characteristics for adobe bricks are cost-effective building materials, thermally efficient, consuming less energy and reducing environmental emissions. In light of this, this study examines how the physical characteristics, thermal conductivity and mechanical behavior of quicklime-stabilized adobe bricks are affected when dune sand (DS) and crushed fired brick waste (CB) are combined. The durability including total and capillary absorption, swelling, erosion, abrasion, drying-wetting, sulfuric attack of adobe bricks was also studied. In this context, three types of sand and waste from fired bricks with proportions (10%, 20%, 30%, 40%, and 50%) by weight of the dry mixture were employed. The fired brick waste was combined with the dune sand to formulate the mixtures M1(30%CB+10DS%), M2(25CB%+15DS%), and M3(20CB%+20DS%).

According to the data, SEM technique confirmed that the use of CB and DS in the adobe bricks preparation procedure resulted in a reduction of voids in the matrix, thereby improving the characteristics, especially their physical characteristics. Additionally, there was an improvement in the apparent density when the M1 combination was included. This resulted in an increase in the speed at which ultrasonic waves propagated. Similarly, the M3 combination helped to reduce the T_A and C_b. With regard to the M1 combination, it increased the compressive and flexural strength of adobe bricks by 71.75% and 52.23%, respectively, as compared to the RB. Significant increases in elasticity modulus were observed in compression and flexion. The combination of CB and DS slightly increased the thermal conductivity. Conversely, the M1 blend exhibited enhanced resistance against abrasion and erosion. Meanwhile, the M3 mixture showed improvements in swelling, wetting-drying resistance, and resistance to external sulfate attack.

Keywords: Adobe bricks; Crushed fired brick waste; Dune sand; Mechanical characteristics; Thermal conductivity; durability.

الملخص

إن الدوافع الرئيسية وراء التركيز المتجدد في استخدام المواد المتاحة محليًا مثل إعادة تدوير النفايات الصناعية والاستفادة من خصائصها في صناعة الطوب الطيني، حيث تعتبر هاته المواد، مواد بناء فعالة من حيث التكلفة وفعالة كذلك من حيث الكفاءة الحرارية، كما أنها تستهلك طاقة أقل خلال انتاجها وتقلل من الانبعاثات البيئية الضارة. في ضوء ذلك، يرتكز هذا البحث على دراسة طريقة تأثر الخصائص الفيزيائية والتوصيل الحراري والسلوك الميكانيكي للطوب الطيني المعالج بالجير الحي عند دمج رمل الكثبان الرملية (DS) ومخلفات مسحوق الطوب المحروق (CB) كما تمت دراسة الديمومة بما في ذلك الامتصاص الكلي، الشعيري، الانتفاخ، التآكل، الكشط، التجفيف-الترطيب والوسط الكبريتي للطوب الطيني. في هذا السياق، تم استخدام ثلاثة أنواع من الرمل وكذا مخلفات الطوب المحروق بنسب (10%، 20%، 30%، 40%، و50%) من وزن الخليط الجاف. حيث تم دمج نفايات الطوب المحروق مع رمل الكثبان لإنتاج ثلاثة خلائط هي :M1 (30%CB+10DS%) M2, (25CB%+15DS%)و M3 (20CB%+20DS%)

ووفقًا للبيانات، أكدت تقنية SEM أن استخدام CB وDS في إجراء تحضير الطوب الطيني أدى إلى تقليل الفراغات في المصفوفة، وبالتالي تحسين الخصائص، وخاصةً خصائصها الفيزيائية. وبالإضافة إلى ذلك، كان هناك تحسن في الكثافة الظاهرية عند الخليط M1. نتج عن ذلك زيادة في سرعة انتشار الموجات فوق الصوتية. وبالمثل، ساعد الخليط M3 على تقليل TA وCb. وفيما يتعلق بالخليط M1، فقد زادت من قوة الانضغاط وقوة الانحناء للطوب الطيني بنسبة 71.75% و52.23% على التوالي، مقارنةً بـــ RB. ولوحظت زيادات كبيرة في معامل المرونة في الانضغاط والانحناء. أدى الدمج بين CB وDS إلى زيادة طفيفة في التوصيل الحراري. وعلى العكس من ذلك، أظهر الخليط M1 مقاومة معززة ضد التآكل والكشط. وفي الوقت نفسه، أظهر الخليط M3 تحسينات في الانتفاخ ومقاومة الترطيب والتجفيف ومقاومة وسط الكبريت الخارجي.

الكلمات المفتاحية: الطوب؛ مخلفات مسحوق الطوب المحروق؛ رمل الكثبان الرملية؛ الخصائص الميكانيكية؛ التوصيل الحراري؛ الديمومة.

RESUME

les principales motivations sous-tendent à l'utilisation de matériaux disponibles localement, le recyclage des déchets industriels et l'utilisation de leurs caractéristiques pour les briques d'adobe qui sont des matériaux de construction rentables, thermiquement efficaces, consommant moins d'énergie et réduisant les émissions dans l'environnement. Dans ce contexte, cette étude examine comment les caractéristiques physiques, la conductivité thermique et le comportement mécanique des briques d'adobe stabilisées à la chaux vive sont affectés par la combinaison de sable de dune (DS) et de déchets de briques cuites concassées (CB).

La durabilité, comprenant l'absorption totale et capillaire, le gonflement, l'érosion, l'abrasion, le séchage-mouillage et l'attaque sulfurique des briques d'adobe a également été étudiée. Dans ce contexte, trois types de sable et de déchets de briques cuites dans des proportions (10 %, 20 %, 30 %, 40 % et 50 %) en poids du mélange sec ont été utilisés. Les déchets de briques cuites ont été combinés avec le sable de dune pour formuler les mélanges M1(30%CB+10DS%), M2(25CB%+15DS%), et M3(20CB%+20DS%).

La technique SEM a confirmé que l'utilisation de CB et DS dans la procédure de préparation des briques d'adobe a permis de réduire les vides dans la matrice, améliorant ainsi les caractéristiques, notamment physiques. En outre, la densité apparente s'est améliorée lorsque la combinaison M1 a été incluse. Cela s'est traduit par une augmentation de la vitesse de propagation des ondes ultrasonores. De même, la combinaison M3 a permis de réduire le TA et le Cb. En ce qui concerne la combinaison M1, elle a augmenté la résistance à la compression et à la flexion des briques d'adobe de 71,75 % et 52,23 %, respectivement, par rapport à la RB. Des augmentations significatives du module d'élasticité ont été observées en compression et en flexion. La combinaison de CB et de DS a légèrement augmenté la conductivité thermique. Inversement, le mélange M1 a montré une meilleure résistance à l'abrasion et à l'érosion. Le mélange M3 a quant à lui amélioré le gonflement, la résistance au mouillage et au séchage, ainsi que la résistance à l'attaque externe par les sulfates.

Mots-clés: Briques Adobe; Déchets de briques cuites concassées; Sable de dune; Caractéristiques mécaniques; Conductivité thermique; Durabilité.

Greek symbols and Nomenclature

Greek symbols

LOI: Loss on ignition.

WL: The liquidity limit

PI: Plasticity index

WP: Plasticity limit

λ: Thermal conductivity

PI: Plasticity index

ρ: Bulk density

F: The force

I: The moment of inertia

E: Elastic modulus

R_c: The compressive strength

S:The surface area

F_f: The flexural strength

T_A: The total absorption

C_b: The capillary absorption

Ca: Abrasion coefficient

Nomenclature

RB:	Reference block
CB:	Crushed brick
DS:	Dune sand
CS:	Crushed sand
RS:	River sand
BCS:	Block based on soil stabilised by lime and crushed sand
B10CS:	Block based on soil stabilised by lime and 10% crushed sand
B20CS:	Block based on soil stabilised by lime and 20% crushed sand
B30CS:	Block based on soil stabilised by lime and 30% crushed sand
B40CS:	Block based on soil stabilised by lime and 40% crushed sand

B50CS: Block based on soil stabilised by lime and 50% crushed sand

BRS: Block based on a soil stabilised by lime and river sand

B10RS: Block based on a soil stabilised by lime and 10% river sand

B20RS: Block based on a soil stabilised by lime and 20% river sand

B30RS: Block based on a soil stabilised by lime and 30% river sand

B40DS: Block based on soil stabilised by lime and 40 %dune sand

B50DS: Block based on soil stabilised by lime and 50% dune sand

B20DS: Block based on soil stabilised by lime and 20% dune sand

BCB: Block based on a soil stabilised by lime and crushed brick waste

B10CB: Block based on a soil stabilised by lime and 10 % crushed brick waste

B20CB: Block based on a soil stabilised by lime and 20 % crushed brick waste

B30CB: Block based on a soil stabilised by lime and 30 % crushed brick waste

B40CB: Block based on a soil stabilised by lime and 40 % crushed brick waste

B50CB: Block based on a soil stabilised by lime and 50 % crushed brick waste

M1: Brick based on a soil stabilised by lime and 30 % crushed brick waste and 10% dune sand

M2: Brick based on a soil stabilised by lime and 25 % crushed brick waste and 15% dune sand

M3: Brick based on a soil stabilised by lime and 20 % crushed brick waste and 20% dune sand

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Chapter IV: Influence of the combination of brick waste and dune sand on the durability of adobe

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GENERAL INTRODUCTION

GENERAL INTRODUCTION

1 Research background

In recent decades, there has been a significant resurgence of interest in the use of earth as a sustainable building material. Approximately 15% of architectural works listed as UNESCO World Heritage sites are built using earth [1], [2]. Currently, bio-sourced materials are emerging as a promising alternative to conventional building materials.

Adobe has attracted considerable attention as a widely used alternative building material derived from the earth, and improving its mechanical strength and inherent durability characteristics has remained a key focus of research. Adobe offers numerous advantages, including reduced energy consumption, accelerated construction processes, abundant availability of local materials, significant thermal and acoustic insulation, fire resistance, and environmental sustainability.

Several studies have described these advantages, as demonstrated by Pittet et al. [3], in his comparative study among different construction technologies (earth, concrete, fired brick, and stone). They also indicated that the use of adobe and cob as building materials significantly reduces energy consumption and thus CO_2 emissions. According to Shukla et al.[4], building and maintaining an adobe house saves 370 GJ of energy per year compared to conventional materials and reduces CO_2 emissions by 101 tons per year.

Adobe presents inherent limitations, including low strength, susceptibility to water, and durability issues. Therefore, the practice of stabilizing adobe with cement, lime, gypsum, and bitumen is widely accepted. The performance of adobe bricks is also influenced by soil properties and particle size distribution. In-depth research and soil standards suggest that optimal soil fractions should fall within the following ranges: sand and gravel not exceeds 75%, silt and clay not exceeds 30% [5], [6]. If the soil does not contain enough sand, sand must be added to adapt it for making adobe bricks.

Several studies have used natural sands to correct the earth such as crushed sand, river sand and dune sand [6], [7],[8]. However, the demand for natural aggregates is increasingly becoming an issue due to the diminishing supply of natural deposits and associated environmental impacts. Furthermore, authors in numerous studies have used construction and demolition waste as recycled coarse aggregates for the production of mud bricks [10–14].

It has been revealed that the production of fired bricks generates significant quantities of waste, at different stages of the manufacturing process. This waste can also result from non-compliant and damaged bricks. It has been revealed that these brick wastes may be recycled and recovered because this would significantly contribute to partly solving of waste storage, reducing environmental pollution, and preserving natural resources. In this regard, several previous researches have indicated that the addition of waste brick from building construction and demolition wastes to mud bricks increases their capacity absorption. To minimize this absorption, it is highly recommended to combine crushed fired brick waste with dune sand as partial soil substitutes when producing adobe.

2 Aims of the thesis

By employing local resources, recycling industrial waste (crushed fired brick waste), and taking advantage of their qualities for adobe bricks, this study aims to lower the amount of energy required in rural areas with dry and semi-arid climates. In order to accomplish this goal, our first steps were figuring out the ideal time for the adobe bricks to curing and adjusting the amount of lime added to the soil according to its dry compressive strength. Then, in order to investigate the effects of different sands, with different shapes and origins as well as the dosage of sand on the mechanical strengths, the total and capillary absorption of adobe bricks, the mixture (soil + sand) was replaced with various types of sand; including dune sand (DS), crushed sand (CS), river sand (RS), as well as crushed fired brick waste used as sand (CB). Subsequently, studies were conducted on the combined impact of dune sand and crushed fired brick waste on the physical characteristics and mechanical behavior of quicklime-stabilized adobe bricks'. In addition, the study examined the thermal conductivity of adobe bricks. The durability of bricks containing crushed brick and dune sand was also assessed using a range of accelerated laboratory tests, such as capillary absorption, total absorption, erosion, abrasion, swelling, wetting-drying cycles, and external sulfate attacks.

3 Structure of the thesis

The thesis is structured into four chapters:

The first chapter is dedicated to the literature review, starting with an overview of the techniques for using earth in construction and a discussion on the types of clay and methods of stabilization. It then delves into previous studies conducted on the impact of industrial waste on the physical-mechanical, thermal, and durability properties of raw earth bricks. Additionally, the chapter provides insights from past research on the stabilization of raw earth bricks using various types of natural sands, along with a summary of fired brick production and their use in stabilizing raw earth bricks.

The second chapter focuses on the identification and characterization of the materials used in this study, including soil, various types of sand, lime, and waste from fired bricks. It also presents the mixtures used, the curing method, and the experimental testing procedures employed in this research.

The third chapter presents the analysis of the results obtained regarding the effects of incorporating various types of natural sands and brick waste on mechanical strength and water absorption. Additionally, it examines the impact of combining fired brick waste and dune sand on compressive strength, flexural strength, mechanical behavior, ultrasonic wave propagation velocity, and thermal conductivity.

The fourth chapter examines the results of the analysis regarding the effects of the combined use of fired brick waste and dune sand on the durability of adobe bricks, including total absorption, capillary absorption, erosion, abrasion, swelling, drying and wetting cycles, as well as exposure to external sulfates.

The manuscript of thesis concludes with a comprehensive summary of the primary findings concerning the viability of adobe bricks through the substitution of natural sands with a combined of fired brick waste and dune sand, accompanied by recommendations for further research.

Chapter I

Bibliographic Review

I .1 Introduction

Currently, as concerns about environmental degradation and energy consumption associated with industrialized materials grow; earthen construction is once again garnering attention as a sustainable building material. However, the inherent flaws of natural earth, such as low strength and susceptibility to water, impede its acceptance in modern construction society. Additionally, the lack of design standards for raw earth bricks limits its dissemination [13]. Furthermore, raw earth construction techniques are still evolving today thanks to the various stabilization processes that exist. The chemical and physical processes involved in these techniques have been widely used to prevent or mitigate the existing shortcomings. The adopted chemical methods consist of adding lime or cement or both to the mixture. In recent years, numerous researches has focused to valorize different industrial waste in confection the earth bricks

I.2 Earth construction

The history of earthen construction goes back some ten thousand years, with clay as the main material. Today, around two-thirds of the world's population lives in houses built entirely or partly from unbaked clay. These earthen constructions can be found on every continent of our planet.

Figure I.1: Earthen architecture worldwide [15].

Algeria is home to a large number of historically significant kosour, or earthen buildings, which are an integral part of the nation's legacy. The provincial hospital in Adrar, Algeria, was created by architect Michel Loix in 1943 and is a notable example of earthen public architecture in the area [16].

Earth is a tried-and-true natural building material that may be used to produce modern, environmentally friendly structures when paired with contemporary methods. Approximately 50% of people on the planet currently reside in earthen homes. While the majority of earthen buildings are located in less developed countries, developed nations such as Germany, France, and the UK also exhibit this type of building; in the UK alone, there are over 500,000 earthen residences [17]. The use of earth building techniques has increased significantly in Iran, the United States, Europe, and the Middle East. Growing interest in sustainable construction methods is the main driver of this expansion [17].

I.3 Techniques for the Use of earth in construction

The technique of building with raw earth is an ancient method widely recognized worldwide, as it was the first construction material used by humans. According to H. Houben et H. Guillaud.[5], there are twelve distinct techniques for implementing raw earth construction, each utilizing a specific type of earth with a unique formulation. In fact, the five most commonly used construction methods are adobe, cob, wattle and daub, rammed earth, and compressed earth bricks.

I.3.1 Rammed earth

Rammed earth is a method of working with soil that has been and continues to be employed worldwide (Morocco, France, Denmark, etc.). Initially, a mold is constructed, which is then filled with damp clayey soil. This soil is subsequently compacted layer by layer using a rammer.

I.3.2 Wattle and daub

Wattle and daub is a construction system involving stacked earth, a technique that entails shaping forms directly without the use of a mold, utilizing the plasticity of moist soils.

I.3.3 Compressed earth blocks (CEB)

The compressed earth block represents a modern evolution of the molded adobe block, appearing as small parallelepipedic masonry elements. This technique involves compressing dry earth using a press, thereby reinforcing the mechanical properties of the blocks and increasing their resistance to water damage. The dimensions vary depending on the types of presses and molds adapted for use.

I.3.4 Cob

Cob, an ancient method of earth construction, has been employed globally for millennia, across diverse climates. Wet earth blocks are manipulated by hand or foot until they form uniform walls. Typically, various fibers are added to the earth mixture for reinforcement.

I.3.5 Adobe

Adobe is the name given to the first prefabricated construction materials that humans used thousands of years ago all throughout the world. These were called molded mud bricks. It is a building material made of a mixture of clay, sand, chopped straw, and other fibers. Adobe is mostly composed of clay, with up to 30% fine fraction. It has a sandy texture and is wetted down to a semi-firm consistency (15 to 30% water content). Each component of the combination adds to its unique qualities; for example, clay binds the particles together, while sand lessens the possibility of microcracks in the clay bricks. To create tiny masonry units, this mixture is manually poured into wooden molds. The molds are then taken out, and the mixture is allowed to dry on the ground. From China and Eastern Europe to Africa, Latin America, and the United States of America, adobe construction has been performed all over the world.

- **Advantages and disadvantages of using adobe**

The table I.1 shows some of the advantages and disadvantages of using adobe

Table I.1: Advantages and disadvantages of using adobe.

Advantages	Disadvantages
✓ Abundance of materials: The materials used to make adobe - sand, clay, and straw - are often readily available in many regions, making this method of construction cost-effective and environmentally friendly. ✓ Thermal insulation: Adobe possesses natural thermal insulation properties, which can help maintain a comfortable indoor temperature in various climates. ✓ Moisture regulation: Due to its natural composition, adobe can help regulate moisture inside buildings, which can be beneficial for the comfort and health of occupants.	✓ Water sensitivity: adobe can be sensitive to water and may deteriorate if exposed to prolonged wet conditions or flooding. ✓ Maintenance: adobe structures often require regular maintenance to prevent deterioration due to erosion or weathering. ✓ Construction time: adobe construction can take longer than other modern construction methods due to the drying process of bricks and walls. ✓ Risk of cracking: Adobe structures may be prone to cracking due to expansion and contraction caused by temperature and humidity fluctuations.

Figure I.2:Cob house in Devon, UK [18].

Figure I.3: Contemporary house made of rammed earth ,China.

Figure I.4: Building with compressed earth blocks (CEB), India [19].

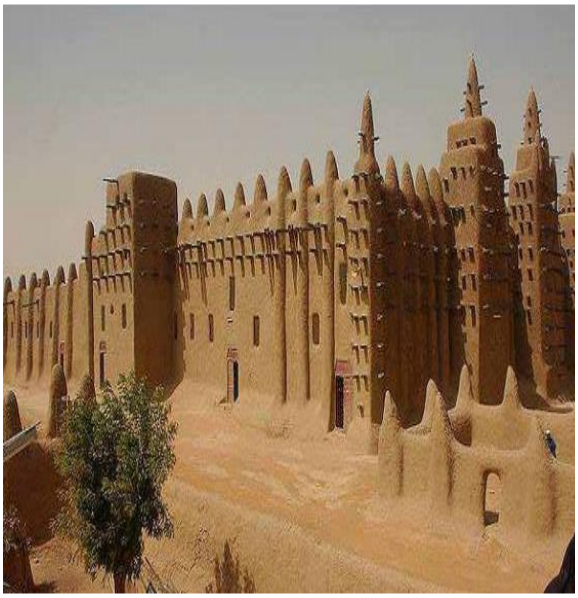


Figure I.5: Djenné adobe mosque [20].

I.6 Clay reminder

Tiny clay particles, measuring less than 0.002 mm (2 µm), are what define them their distinct physical characteristics and chemical makeup set them apart from other soil constituents. They are classified chemically as hydrated aluminosilicates, which are produced when coarse particles from main rock minerals leach. Clay particles often have a lamellar structure and are flat and elongated in shape. When compared to coarse particles, which are often angular or spherical, their specific surface area is significantly larger. For this reason, clays are recognized for their propensity to expand and contract in reaction to their surroundings.

I.6. 1Clay

A common definition for the term "clay" does not exist. The definition of the term varies depending on the topic of study and includes two concepts: one connected to mineralogy and the other to particle size [21].

Any small-sized mineral is considered clay by geologists and soil scientists; the upper limit is typically defined as 2 or 4 microns, depending on the situation [7],[8]. Clay is a basic material that ceramicists define as a plastic paste that hardens after firing when combined with water.

A soil is considered clay to a civil engineer if a sizable portion of its minerals are clay, as these have an impact on the soil's behavior. This kind of soil is very water-sensitive, cohesive, fine, plastic, and electrochemically active. The impacts of clay on soil qualities are more pronounced the higher the proportion of clay, particularly when there is a substantial amount of water present. The characteristics of the clay mostly dictate the mixture's overall behavior when its mass in the soil surpasses 50% [23].

I. 6.2 Clay families

Although there are many other kinds of clay, the following three clay mineral types are the most prevalent:

I.6.2.1Kaolinite

This mineral has two layers of **T-O**. There is nothing in the interfoliar area, and every layer is neutral. At 7.2 Ångströms, the structural unit is thick. The oxygen atoms at the base of the **T** layer and the hydrogen atoms of the hydroxyl group in the **O** layer of the following layer form hydrogen bonds that connect the layers (Figure I.6). This clay has no ability to inflate; its structure is stable and water can only be adsorbed around the particles.

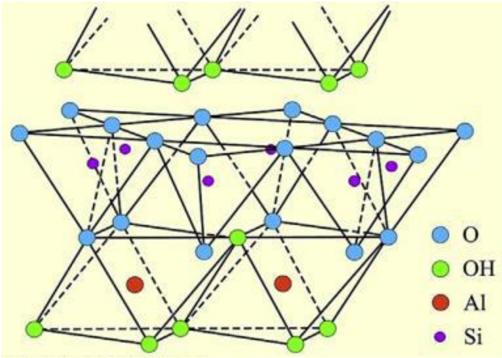


Figure I. 6: Schematic diagram of the structure of kaolinite [1].

I.6.2.2Illite

Illite is a member of the **T-O-T** family of phyllosilicates, in which aluminum atoms take the place of silicon atoms in the tetrahedra. High negative charge resulting from this substitution is mostly offset by K^+ ions forming robust ionic connections (Figure I.7). Illite is relatively impermeable to water due to these strong connections, which also limit the capacity of the material to absorb water molecules between its layers.

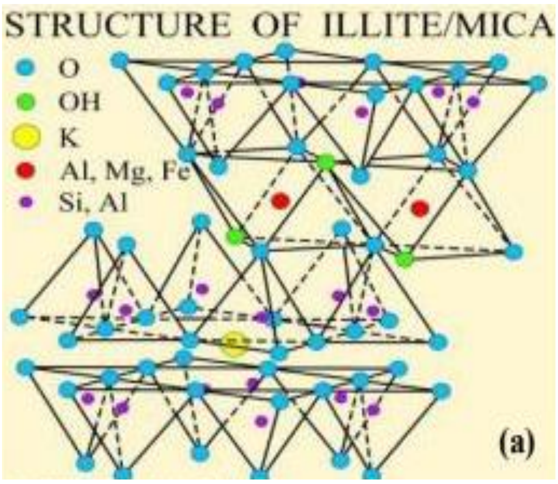


Figure I.7: Schematic diagram of the structure of Illite [1].

I.6.2.3Montmorillonite

Similar to illite, smectites have some of its basic structure's ions changed. Iron or magnesium atoms can take the place of aluminum atoms. These minerals can contain either calcium or sodium as compensatory cations (Figure I.8). Because of the significantly weaker interfoliar connections that are produced, water can move between the various layers and interact with these compensatory ions. This results in swelling of the soil, a feature common to smectite clays [24, 25].

Figure I.8: Schematic diagram of the structure of Montmorillonite[26].

I.7. Techniques for stabilizing earthen materials

Generally speaking, there are three fundamental types of stabilization: mechanical stabilization, physical stabilization, and chemical stabilization.

I.7.1 Mechanical stabilization

Mechanical stabilization refers to the process of stabilizing soil by compacting it. This is an essential part of the process. This compaction is carried out to reduce porosity by eliminating trapped air. Ideal compaction properties are determined using the normal Proctor test. The results of this test, such as the optimum water content to achieve the maximum dry density of the soil, are used in stabilization studies and in the field during construction.

The analysis carried out by [7] shows an increase in mechanical strength as a function of compaction stress until an optimum of 17.5 MPa is reached, which corresponds to the best strength. Above this value, a decrease in strength is observed, as illustrated in Figure I.9.

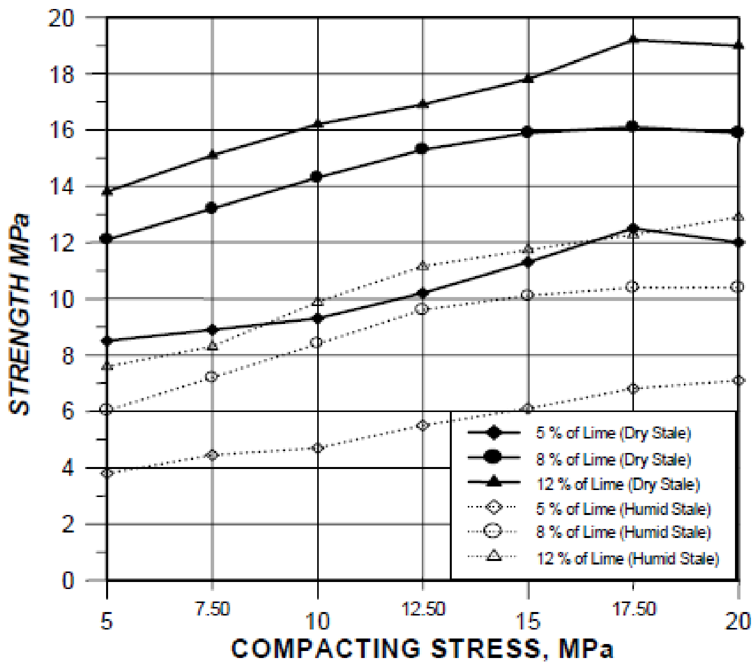


Figure I.9 : Influence of compaction stress and lime content on mechanical strength [7].

I.7.2 Physical stabilization

Physical stabilization can be achieved in two different ways. The first involves modifying the properties of the soil by improving the characteristics of the material through granulometric corrections. In this case, the intervention is made directly on the texture of the soil, and the mixture obtained can lead either to a reduction in the plasticity of the base material by adding sand, or to giving it certain cohesion by adding fines. The second method involves incorporating plant or industrial fibers into clay soils; there by reinforcing the structure of the material to prevent it from cracking when the clay shrinks as the soil dries.

Bouhicha et al. [27], proposed that when the quantity and length of plant fibers in soil increased, the shrinkage in both linear and volumetric terms reduced. However, Millogo et al. [28], found that including short kenaf fibers helped to slow down the spread of cracks in earth blocks.

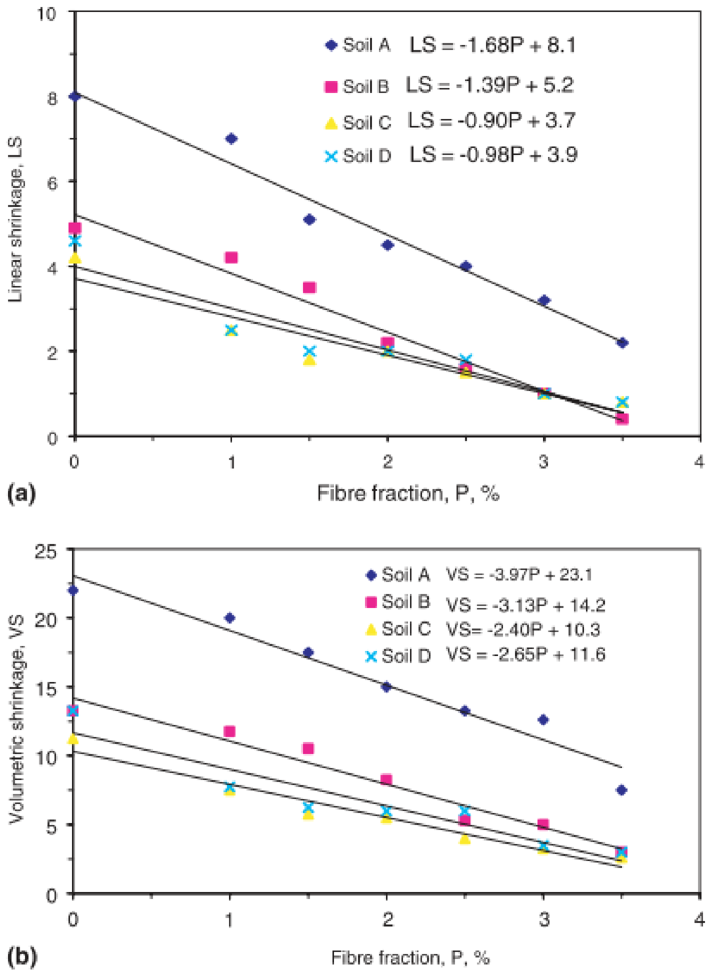


Figure I.10: Variations in linear and volumetric shrinkage with fiber fraction [29].

I.7.3 Chemical stabilizers

Chemical stabilization involves adding other materials or chemical products to the soil that modify its properties, based primarily on a physico-chemical reaction between the particles and the added material or product, or by creating a matrix that binds or coats the particles. The physico-chemical reaction can lead to the formation of a new material (pozzolanic reaction between clay and lime, for example). The chemical stabilizers generally used are cement, lime, bitumen or resins.

I.7.3.1. Cement

Cement stabilization is a technique developed since the beginning of the 20th century for public works, in particular road and runway construction. It involves adding hydrated cement to the soil, which forms a mortar of pure hydrated cement and also reacts with the sandy fraction of the soil. However, cement can react with clays in three phases: hydration, development of hydration and interpretation of cement gels and degraded clay agglomerates. The dosage of cement depends on the texture and structure of the soil, generally between 5 and 12%. Cement stabilization modifies the plasticity of the material, improving its resistance and durability, but remains costly and polluting, and cement-stabilized soils cannot be reused.

I.7.3.2 lime

Lime is mainly composed of calcium oxide (CaO) with contents of approximately 88 ± 4% quicklime (CaO) and 10 ± 3% hydrated lime ($Ca(OH)_2$) and less than 3% calcite ($CaCO_3$). The presence of hydrated lime and calcite results from the reactivity of quicklime to air during storage. Hydrated lime (HCL) contains approximately 90% hydrated lime and 7% calcite, according to X-ray diffraction and thermo-gravimetric analyses [30].

The addition of lime causes an increase in the quantity of Ca^{2+} and OH^- ions in solution in the soil. These ions react with the constituents of the material, modifying their characteristics through various physic-chemical processes. Classically, a distinction is made between short-term and long-term actions[19].

The addition of lime to a clay soil triggers four main reactions: cation exchange, flocculation-agglomeration, the pozzolanic reaction and the carbonation reaction.

A. Cation exchange

The addition of lime to a clay soil immediately leads to changes in its properties. When lime is in the presence of water, it releases Ca^{+2} ions, which raises the pH of the soil. This causes a cation exchange between the metal ions bound to the clay particles and the Ca^{+2} ions released by the lime. The valency and size of the ions play an important role in this reaction, with higher valency ions replacing lower valency ones more easily, and larger ions being more likely to be replaced. A rough hierarchy of cation replacement capacities can be drawn up, in ascending order depending on the type of clay, the cations to be replaced and the concentration of ions in the water: $Li^+ < Na^+ < H^+ < K^+ < NH^{4+} < Mg^{+2} < Ca^{+2} < Al^{+3}$[32]. This cation exchange reaction is responsible for reducing the plasticity of clay soils treated with lime, although it has little impact on kaolinite-rich soils due to the absence of interleafs where cations could be inserted. On the other hand, for soils rich in smectites such as montmorillonite, the cation exchange reaction contributes significantly to reducing their plasticity.

B. Flocculation-agglomeration

After the cation exchange reaction, the clay particles are surrounded by a diffuse double layer that can be modified by ion exchange with calcium. This changes the electric charge density around the clay particles, which attract each other and form flakes. This phenomenon is known as flocculation. Flocculation can change the texture of the clay particles, causing them to form larger particles [33]. This results in a reduction in the plasticity and an increase in the bearing capacity of the clay soil. Particle agglomeration is caused by the attraction between the remaining negatively charged soil particles and the positively charged surface particles. This process is influenced by cation exchange or particle flocculation [28].

C.Pozzolanic reaction

According to Prusinski and Bhattacharja [34], the pozzolanic reaction (Figure I.11) is a secondary process of soil stabilization that works with lime, cement, and soil systems alike. The silicates and aluminates in the clay combine with calcium hydroxide in the soil water to generate cementing materials or binders, which are composed of calcium silicates and/or aluminate hydrates [35]. The silica and alumina contained in clay particles are more soluble and reactive in the high pH environment of a calcium-stabilized system [36, 37]. The combination of the soil particles is the result of hydrated gels formed by the reaction between the dissolved dissociated Ca^{++} ions and the dissolved SiO_2 and Al_2O_3 from the surface of the clay particle [35].

$$Ca^{+2} + 2(OH)^{--} + SiO_2 \rightarrow CSH \qquad (I.1)$$
$$Ca^{+2} + 2(OH)^{--} + Al_2O_3 \rightarrow CAH \qquad (I.2)$$

The primary part of the reaction will begins a few days after the lime is mixed [38], It usually takes from one to five year to complete [35].

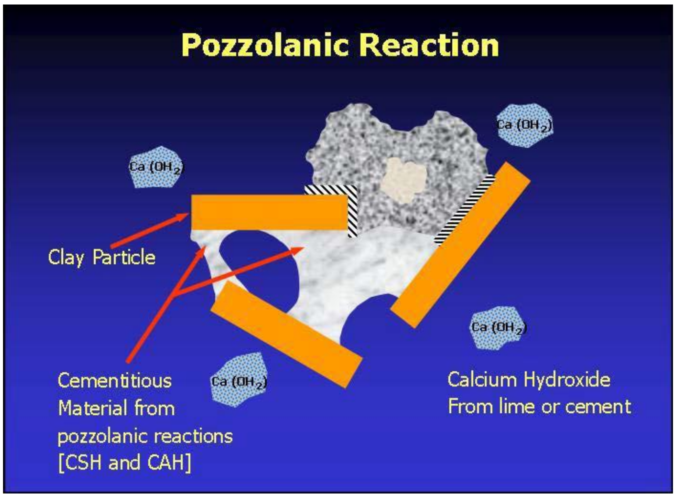


Figure I.11: Pozzolanic reaction [36].

D. Carbonation (formation of calcite)

A fourth reaction can take place with lime. This is the formation of calcite in contact with CO_2. In the treatment of clay soils, the calcite crystals formed have very poor binding properties and interfere with stabilization because their development inhibits the pozzolanic reaction. On the other hand, this carbonation is sought after when stabilizing calcareous materials such as chalk. Calcite crystals block the porosity of these materials.

$$CaO + CO_2 \rightarrow CaCO_3 \qquad (I.3)$$

$CaCO_3$ increases the flexibility of the soil and binds to lime to stop it from reacting with pozzolanic materials. Therefore, adding too much lime to the soil does not yield positive outcomes [30].

I.8 The influence of adding lime on the mechanical properties of the stabilized material

A number of studies investigating the effect of lime addition on the compressive strength of different soils have been carried out in geotechnical studies. The addition of lime increases compressive strength by promoting the creation of hydrated gel. Various factors play a role in mechanical efficiency, including the composition of the clay minerals, the amount of lime added, the maturation time and the surrounding temperature [24].

According to Roux et al.[39], kaolinite gives a greater increase in mechanical strength than illite and montmorillonite, although its reaction is less active than that of montmorillonite.
Al-Mukhtar et al.[40], explained the increase in strength over time in relation to the increased consumption of lime. After 7 days, lime consumption is minimal regardless of the tested dosage

variation (see Figure I.12). At 90 days, with a lime dosage of 20%, approximately 18% of the lime is consumed. The slow consumption of lime highlights the sluggishness of the pozzolanic reaction induced by lime.

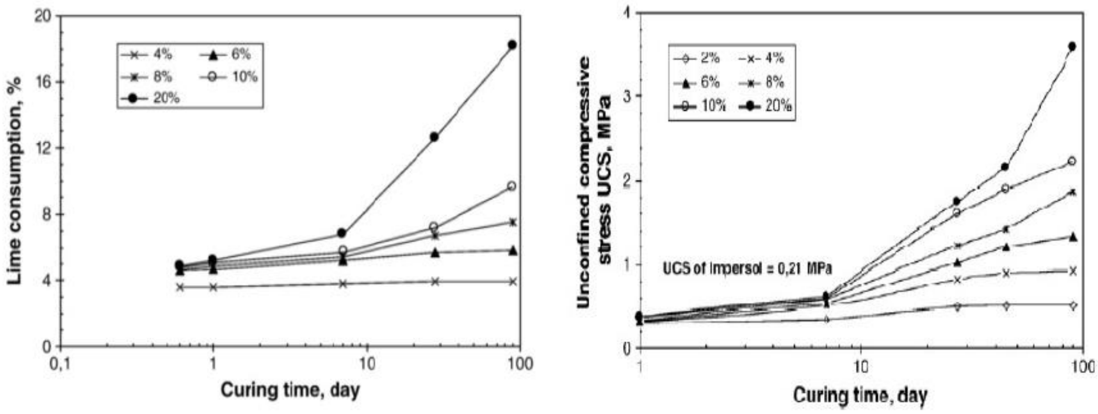


Figure I.12:Compressive strength and lime consumption of a soil as a function of lime content and curing time [40].

Increasing the curing temperature of lime-stabilised soils accelerates pozzolanic reactions [40]. After 90 days, 6% lime content doubles the compressive strength of a soil when the temperature is raised from 20°C to 50°C.

However, Millogo et al.[41], found that the compressive strength of adobe bricks (Figure I.13) increased with increasing lime addition, whereas higher lime contents above 10% of the mix weight had no beneficial effect on strength. These findings are supported by the microstructure (Figure I.13).

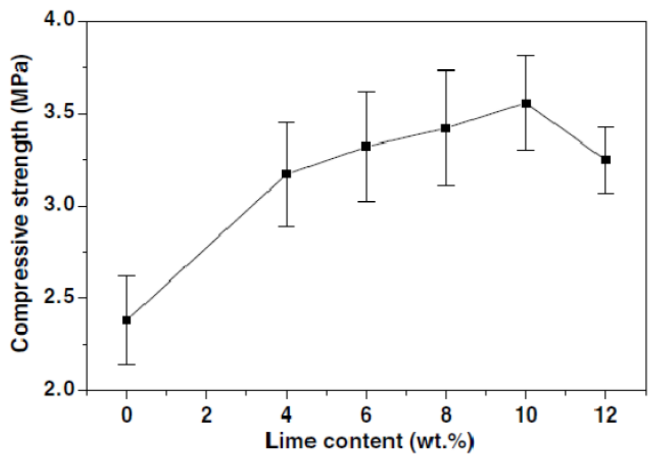


Figure I.13: Changes in compressive strength of adobe bricks as a function of lime content [42].

When the lime content was increased to 6%, the free silica disappeared and the bond between the particles was developed, leading to the appearance of a homogeneous microstructure. In this case, isolated particles without relief (Figure I.14e), identified as CSH, and were developed. As the lime content exceeded 12%, portlandite and calcite, which show such bright domains (Figure I.14 f) H zone, were largely formed. Excessive carbonation resulted in the appearance of a heterogeneous microstructure.

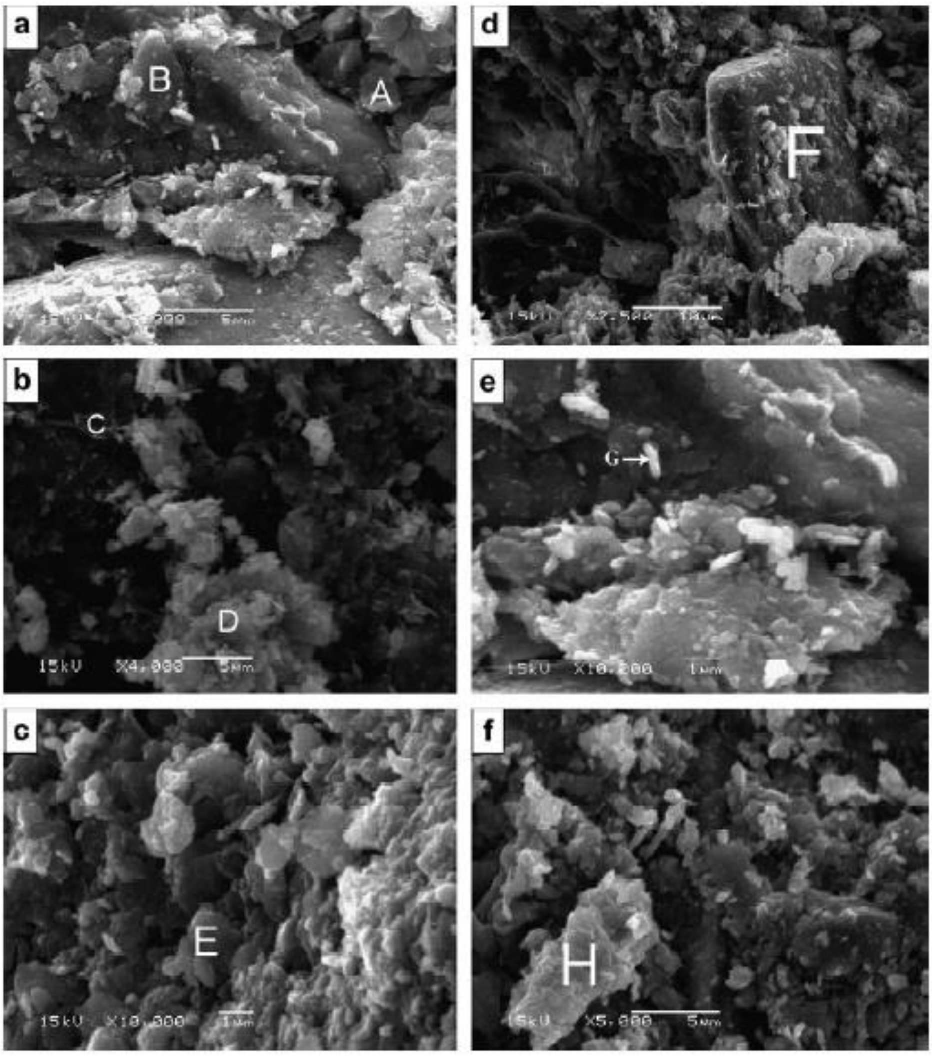


Figure I.14:SEM micrographs of adobe bricks: **(a)** 0% lime, **(b)** 4% lime, **(c)** 6% lime, (d and **(e)** 10% lime and **(f)** 12% lime [42].

I.9 Stabilization of unfired earth bricks with natural sand.

Sand and gravel are natural resources typically employed to adjust grain size, as each earth construction method necessitates a specific grain composition. In this regard, Houben and Guillard.[5], proposed that soil intended for adobe production should comprise sand and gravel

(55-75)%, silt (10-28)%, and clay (15-18)%. However, Standard NTE E.080 [6] advises clay proportions of (10-20)%, silt (15-25)%, and sand (55-70)%. Delgado and Guerrero.[43], brings together various standards and recommendations for the granular zone adopted for different earth construction techniques, as illustrated in Figure I.15.

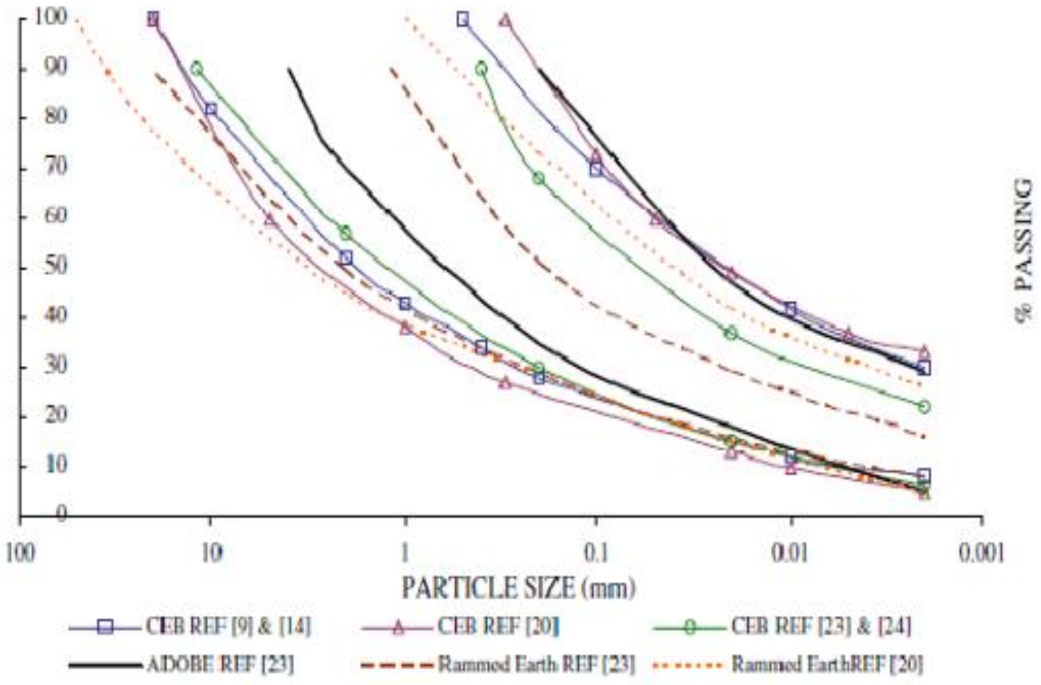


Figure I.15: Granular zones adopted for different earth construction techniques [43].

Izemmouren and Guettala. [8], Izemmouren et all.[44], investigated the compressed earth block stabilization that was carried out by particle size correction using two types of crushed sand and 5% of cement. The findings indicated that the mechanical strengths improved when the sand content increased. This content reached an optimum value of 30% when testing the durability.

Bachar et al. [9], reported that the addition of 30% of dune sand (DS) and 12% of cement to the soil in the stabilization of compressed earth blocks allowed improving their dry compressive strength and tensile strength, as indicated in Figure I.16 In addition, this composition assures maximum dry density of 1750kg/m^3 (Figure I.17).

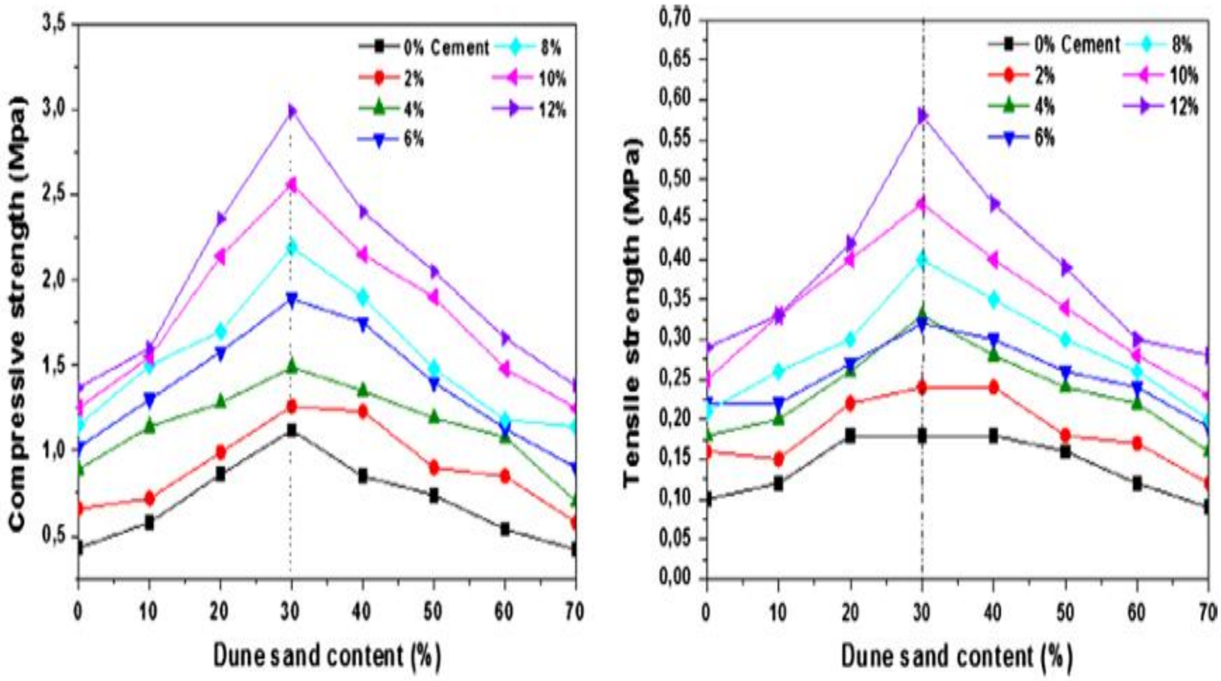


Figure I.16: Variation in compressive strength and tensile strength as a function of cement content for different percentage of sand [9].

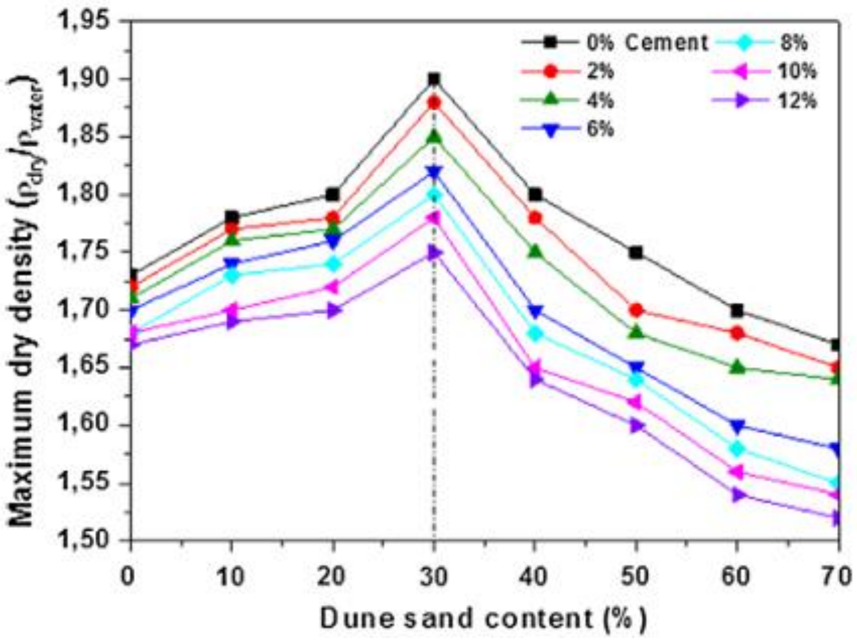


Figure I.17:Variation in compressive strength and tensile strength as a function of cement content for different percentage of sand [9].

In their study on the impact of date palm waste on the mechanical properties and durability of adobe bricks [45], Zaidi et al.[46], observed that the particle size distribution of the soil used was outside the recommended range. After adding 10% and 20% of crushed sand to correct this soil, it remained outside the recommended range but was very close to the lower limit. However, when the soil was corrected with 30% sand content, it entered the recommended range, as illustrated in Figure I.18.

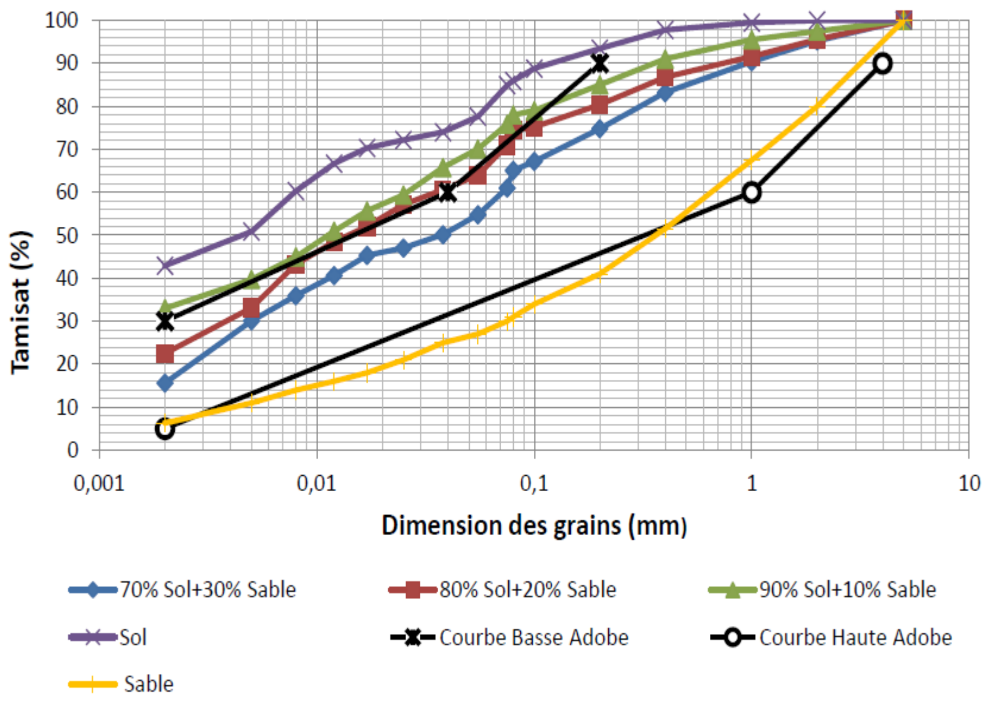


Figure I.18: Particle size distribution of soil with different content of sand [46].

I.10 Effect of industrial waste on the physico-mechanical and thermal properties of unfired bricks

Industrial waste has been integrated into the production of earth bricks in three forms: aggregates, powder, and fibers. Table I.2 summarizes previous research on the use of various industrial waste additives in stabilizing earth bricks. Information reported includes, type and amount of binder and additive used, specimen size and age of curing, strengths, density and thermal conductivity data.

I.10.1 Effects of industrial waste on the compressive and flexural strength of unfired earth blocks

Table I.2 indicated that the majority of studies demonstrated a correlation between increasing additive percentage and higher compressive strength and flexural strength. However, certain additives, including alumina filler waste and soda ash, and crumb rubber, exhibited a decline in strength as the volume of waste increased. Miqueleiz et al.[47], demonstrated that the inclusion of alumina filler waste resulted in a decrease in compressive strength due to diminished cohesion between particles, consequently forming an additional internal open structure within the samples. The data in Table I.2 clearly shows that ceramic waste exhibited the highest value of compressive strength at 33.60 MPa.Conversely, soda ash displayed the lowest compressive strength, measured at 1.71 MPa.

A study conducted by Seco et al. [10], explored the partial use of concrete and ceramic waste to replace a portion of clay soil in the production of mud bricks. The findings suggest that concrete waste can substitute for up to 50% of the clay, whereas ceramic waste is limited to a maximum replacement of 30%. Bricks manufactured by mixing concrete waste with clay exhibited lower mechanical strength compared to those made with ceramic waste and clay.

I.10.2Effect of industrial waste on unfired brick density

The density of samples blended with waste generally increases when waste materials are utilized in powdered form (Table I.2). The authors (Miqueleiz et al. [28], Vinai et al. [30], Oti et al [49]), explain this increase in density by the larger quantities of CSH gel are produced in the lime-activated granulated blast furnace slag system, resulting in the bonding of sufficient calcite, quartz, alumina, and Wollastonite crystals with the CSH gel formed during the hydration process. The authors (Siddiqua et al.[50], Huynh et al.[51], Vinai et al.[48]) confirm that the reduction in the porosity of earth bricks, regarding mineral additives, is attributed to the formation of CSH gel resulting from the pozzolanic reaction between the additives and the binders. However, when using the indusial waste as fiber in production of earth bricks, the fibers in contact with the soil were displaced, resulting in an increase in sample porosity and a decrease in sample density [52].

Table I.2: Overview of research on Industrial waste additives for production of unfired earth blocks.

Ref.	Industrial waste	Content (wt%, vol%) and fibre length (mm)	Technical	Stabiliser	Test Age	Sample Size (cm)	Max. Compressive strength (CS), Flexural strength (FS) (MPa))	Density (kg/m³)	Min. Thermal conductivity (W/mK)
[53]	Granulated blast furnace slag	5, 5.5, 11, 12%	Adobe	cement	28 days	21,5×10. 25 ×6.5 10.2 ×10.2 ×3.5	CS : 7.40	1790–1800	0.37
[54]	Salvaged steel fibre	1.7, 2, 2.7 vol% 20, 35, 50 mm	Adobe	cement	7, 14, 21, and 28 days	21.5×10. 5 ×5.5	CS: 11.60 FS: 2.60	undefined	undefined
[47]	Alumina filler (AF) and Coal ash (CA)	AF:16.1, 32.2, 47.82%, CA:7%	Adobe	cement and lime	28 days	12.5×6×4	CS : 16	1540–1840	undefined
[55]	Soda ash	4.38, 4.56, 4.74, 4.92 l of water	Adobe	undefined	7 days	20×22.5× 7.5	CS : 1.71	1160–1410	undefined
[48]	Bottom ash	75, 60, 52.5 vol%	earth compressed bricks	cement	7, 21, 28 and 45 days	14×14×9	CS : 27	1200–1600	undefined
[49]	Brick Dust	5, 10, 15, 20%	adobe and mortar	quick lime	3, 7, 14, 28 and 56 days	ø5×10	CS : 2.10	undefined	undefined
[56]	Molybdenum tailing	55, 60, 65, 70, 75%	Adobe	cement	3, 7 and 28 days	16×4×4	CS: 27.35 FS: 7 .56	undefined	undefined
[57]	Polyethylene terephthalate	0.2, 0.4, 0.6, 0.8, 1.0%, 54 mm	compressed earth blocks	cement	7, 21, and 28 days	19.1×20. 3 ×12.1	CS: 5.55	undefined	undefined
[58]	Ceramic waste	50, 75, 100%	compressed earth block	cement	7 days and 28 days	10×5×4	CS :33.60	1703.33–1774.89	undefined
[59]	Crumb rubber	5, 10, 15%	Adobe	undefined	undefined	16×4×4	CS: 2.52 FS: 0.16	undefined	undefined
[59]	Polyurethane	5, 10, 15%	Adobe	undefined	undefined	16×4×4	CS: 2.62 FS : 0.17	undefined	undefined
[60]	Marble dust (MD) and Polymer fibre PF)	MD-10, 20% PF-0.5, 1, 1.5, 0.2%	Adobe	lime and calcined gypsum	07 and 28 day	5×5×5 and 4 ×4×16	CS :3.47 FS :1.43	undefined	undefined

[61]	Iron mine spoil	30, 40, 50%	compressed earth block	cement and lime	7, 15, 30, 60 days and 6 months	23×11×7.5	CS: 6.00 FS: 1,12	2050	undefined
[62]	Magnesium oxide	3, 6, 9, 12, 15, 18%	Adobe	Lime	1, 7, 28, 56 and 90 days	Ø 6.5×7.5	CS :9.90	2000–1890	undefined
[10]	Ceramic waste	30%	Adobe	cement and lime	1, 7, 14, 21 and 28 days.	Ø 6.5 ×7.5 and 22.5×11×6	CS :12.65	undefined	undefined
[10]	Concrete waste	50%	Adobe	cement and lime	1, 7, 14, 21 and 28 days	Ø 6.5 ×7.5 and 22.5 ×11×6	CS :12.75	undefined	undefined
[63]	Bottom ash	6, 12, 18%	rammed earth	cement	7, 14, 28, 45 and 60 days	Ø 15×30	CS : 2.5	1800–1850	undefined
[63]	Polyethylene terephthalate	1, 3, 7%	compressed earth bricks	undefined	2 days	undefined	CS : 1 .55	undefined	undefined
[51]	Fly ash	10, 15, 20%	Adobe	cement	28 days	8×8×18	CS : 6.03	undefined	0.78
[64]	Crumb rubber	5, 10, 20%	rammed earth	cement	28 days	15×15×15	CS : 10	2064	undefined
[11]	Recycled aggregate	15%	compressed earth blocks	cement, and lime	28 days	29.5×14×9 and 14.5×14×9	CS: 5.40 FS: 1.19	1740_1810	0.61
[52]	Glass fibre reinforced polymer	2.5, 5.0, 7.5 and 10%	Adobe	undefined	35 days	30×15×8 and 60×8.5 ×3.5	CS : 2.05	1524_1565	0.68
[65]	Polyethylene terephthalate	1, 3, 7, 15 and 20%	Adobe	undefined	28 days	16×4×4	CS : 4 .5	1440–1710	undefined
[66]	Expanded polystyrene beads	0, 40, 45, 50, 55, 60 and 65%	Adobe	Lime	7 days	4x4x16	CS: 1.4 FS : 1.43	1505.43-568.51	0.195
[67]	waste concrete powder	0, 5, 10, 15, and 20%	compressed earth block	cement	7, 14, 28, and 90 days	25.4 × 12.7 × 7.6 and 5 × 10	CS: 10.95 FS : 1.9	undefined	1.09
[68]	fine recycled concrete aggregate	0,10 and 20%	compressed earth blocks	cement	2 days	12 ×6 ×4	CS: 13.72 FS : 1.15	undefined	0,353
[69]	municipal solid waste incinerator bottom ash	7, 14,21 and 28%	compressed earth blocks	cement	28 days	24 ×11.5 x9	CS: 9 FS : 0.85	1883 - 2081	undefined

I.10.3Effect of industrial waste on thermal conductivity of unfired earth bricks

The selected articles rarely explored thermal properties. However, out of the total of nine articles (Table I.2), thermal conductivity was measured. The review papers indicate that density, void volume, and thermal conductivity are correlated. Thermal conductivity decreases with decreasing density, but it exhibits an inverse relationship with the void volume of the samples.

Layachi et al.[66], have been studies the effect of the incorporation of different contents of Expanded polystyrene beads EPS (0, 40, 45, 50, 55, 60, 65% by volume) on the thermal properties of lightweight earth blocks. It has been revealed that the incorporating EPS bead into raw earth greatly improves its ability to regulate temperature. Findings revealed that as the EPS content increased from 40% to 65%, thermal conductivity, thermal effusivity, and volumetric heat capacity decreased by approximately 19.26%, 24.66%, and 29.78%.

Bogas et al. [11], utilized 15% recycled fine aggregates from construction debris as a partial substitute for clay in producing stabilized compressed earth blocks. It has been observed that the average dry thermal conductivity ranged from 0.61 to 0.65 W/m°C, increasing by up to 80% in humid conditions. The thermal conductivity of compressed earth blocks tended to be lower than that of lightweight concrete with equivalent dry density.

I.11 Effect of industrial waste on the durability of unfired earth bricks

There are various durability indicators used to assess unfired earth bricks. Most previous studies have focused on water absorption as the primary criterion to evaluate their moisture resistance.

Seco et al.[10], employed a combination of concrete waste (50 wt%) and ceramic remnants (30 wt %) to replace the soil in the confection of unfired earth bricks. The earth bricks were fabricated using soil sourced from northern Spain, with four additives: ground granulated blast furnace slag, Portland cement, calcareous hydrated lime, and natural hydrated limeas binding agents. The ideal binder proportion for both the mixer was 2% calcareous hydrated lime and 8% ground granulated blast furnace slag. Regarding the water absorption rate, there was minimal differentiation observed between the two brick blends. However, the decline in water resistance was slightly more pronounced in the concrete waste samples compared to the ceramic waste samples. The water absorption rate ranged from 5.90% to 19.20% for ceramic waste and from 9% to 16.90% for concrete waste.

Bogas et al.[11], investigated the capillary absorption of compressed earth blocks (CEB) produced with partial incorporation of recycled aggregate (RA). The recycled aggregate was used to correct the grade composition of the selected soil and was 15% of the soil weight. Les (CEB) stabilized with 8% cement (CEBC) and stabilized with 4% cement and 4% lime (CEBCL). As a result, it was determined that the CEBCL blocks exhibited greater absorption compared to CEBC. Specifically, the percentage mass absorption values after 48 hours corresponded to percentage volume absorptions of 25.2% for CEBC and 29.2% for CEBCL show the Figure I.19 this is due to the higher void rate presented by cement-lime mixtures. It can be inferred that the porosity of cement-stabilized mixtures exhibits less interconnectivity compared to cement-lime mixtures [70].

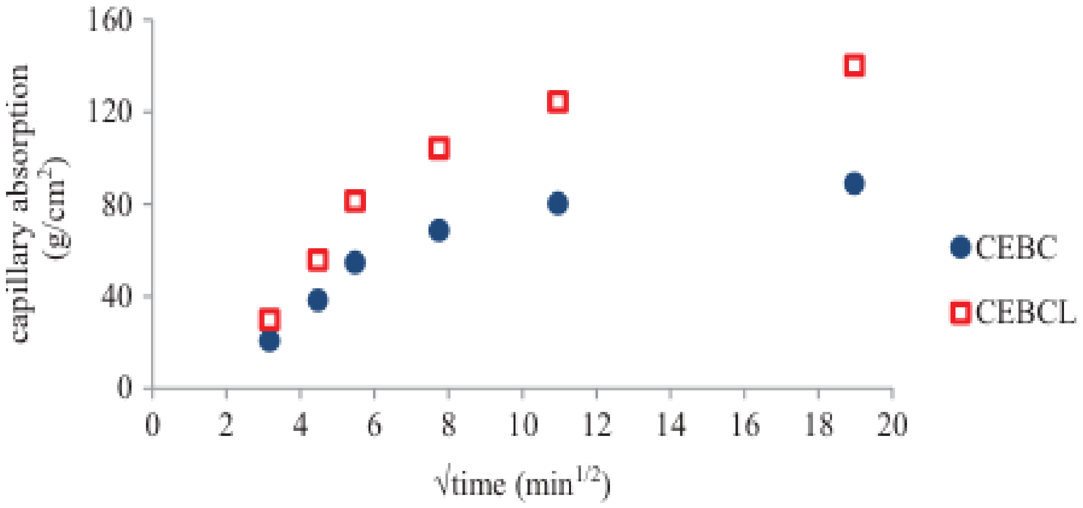


Figure I.19:Capillary absorption for CEBC et CEBCL [11].

Aninda and Islam [67], investigated the viability of incorporating waste concrete powder (WCP) with cement for the production of cement-stabilized compressed earth blocks (CSEB). To determine the ideal proportion of stabilizers, they explored fifteen different combinations of cement and WCP. These combinations included three levels of cement content (4%, 6%, and 8% by weight of dry soil) and five levels of WCP content (0%, 5%, 10%, 15%, and 20% by weight of dry soil).

The findings indicate that as the content of waste ceramic powder (WCP) increases, the water absorption of the cement-stabilized compressed earth blocks (CSEB) decreases (FigureI.20). For instance, CSEB samples without WCP stabilization display an initial water absorption rate of approximately 12–13%. However, with a 20% replacement of WCP, the water absorption rate decreases to a range of 10.5–11.5%. This reduction in water absorption can be attributed to the ongoing curing process. The moisture present during curing aids in the formation of hydration products, which subsequently fill the pores within the material. As a result, a denser microstructure develops, accompanied by a decrease in pore size.

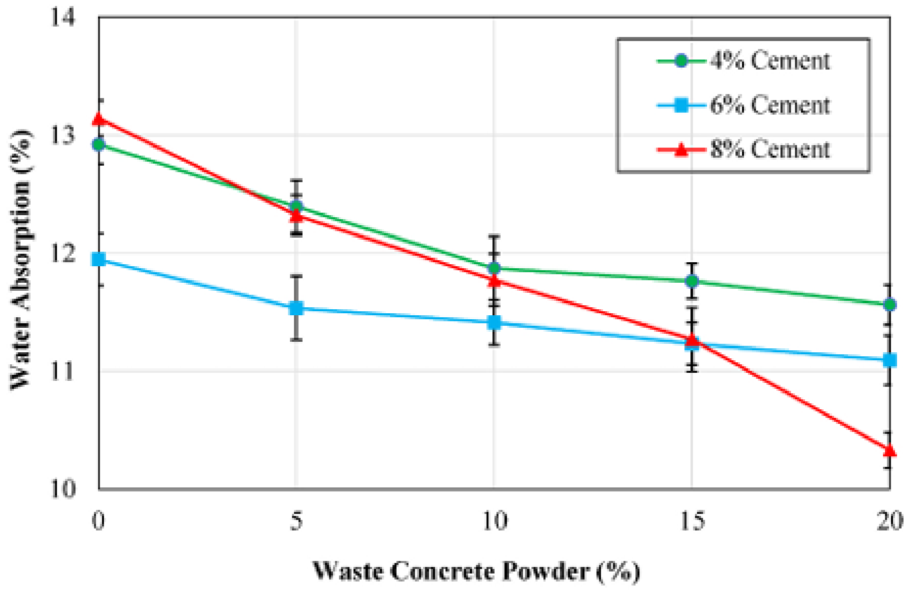


Figure I.20:Water absorption as function of WCP contents [67].

Latha et al. [69], valorized the incinerator bottom ash derived from municipal solid waste (MSWIBA) with the aim of producing compressed stabilized earth blocks (CEBs). Compressed stabilized earth blocks are prepared with 6–12% cement and 10–40% MSWIBA.

The authors noted a progressive increased in water absorption when MSWIBA was utilized as a substitute for sand in the mixes. Water absorption values varied from 9.1% to 13.7% for combinations M10 and M40. With the addition of 7% and 28% MSWIBA to the mixes, water absorption increased by 30% and 95%, respectively, compared to the control mix. According to the authors, this increase in water absorption could be attributed to the heightened water absorption capacity of the ash employed. Moreover, it may also be linked to the increased void content within the blocks as the quantity of ash was elevated.

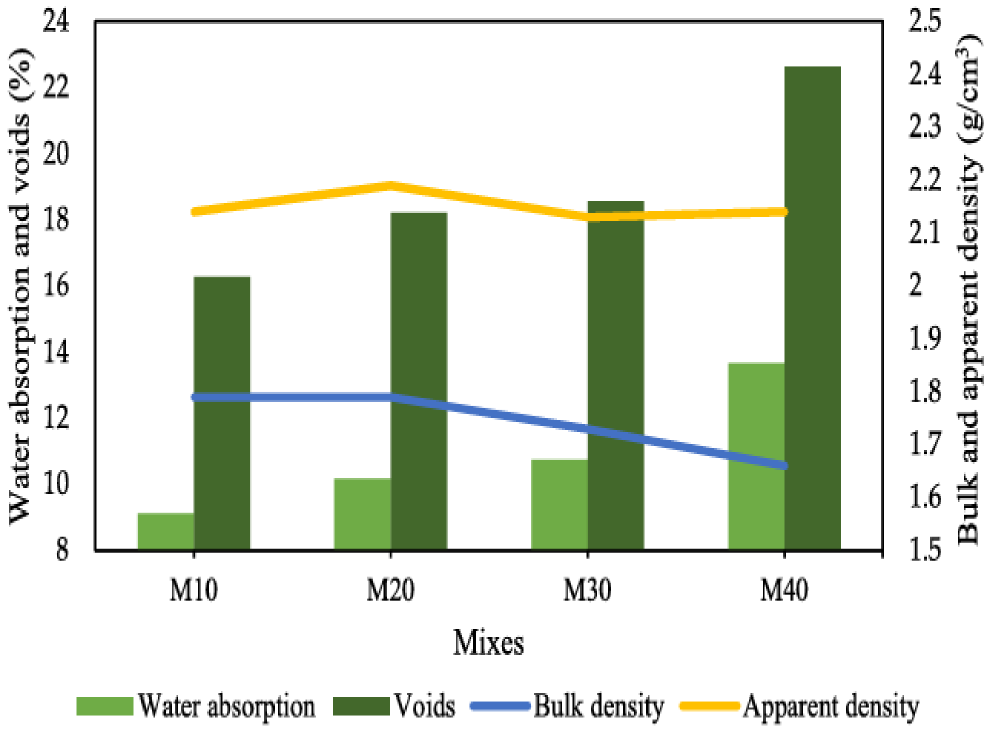


Figure I.21: Water absorption, density and voids of MSWIBA mixes [69].

Regarding other durability indicators for unfired earth brick, such as drying-wetting tests, freeze-thaw cycles, sulfate attack, erosion, and abrasion, there has been limited research on the impact of industrial waste on the durability of these bricks.

Akinwumi et al.[63], assessed the feasibility of producing compressed earth bricks (CEB) using a combination of earth and varying proportions (0%, 1%, 3% and 7%) of shredded plastic waste of producing compressed earth bricks (CEB) using a combination of soil and varying proportions (0%, 1%, 3%, and 7%) of shredded waste plastic. The findings revealed that as the percentage of shredded waste plastic content increased, the erosion rate of the CEB also increased. Specifically, for CEB containing 1% of shredded waste plastic particles smaller than 6.3 mm, the erosion rate spiked by 50% compared to CEB without any shredded waste plastic. This underscores the significance of the erosion rate as a measure of CEB durability.

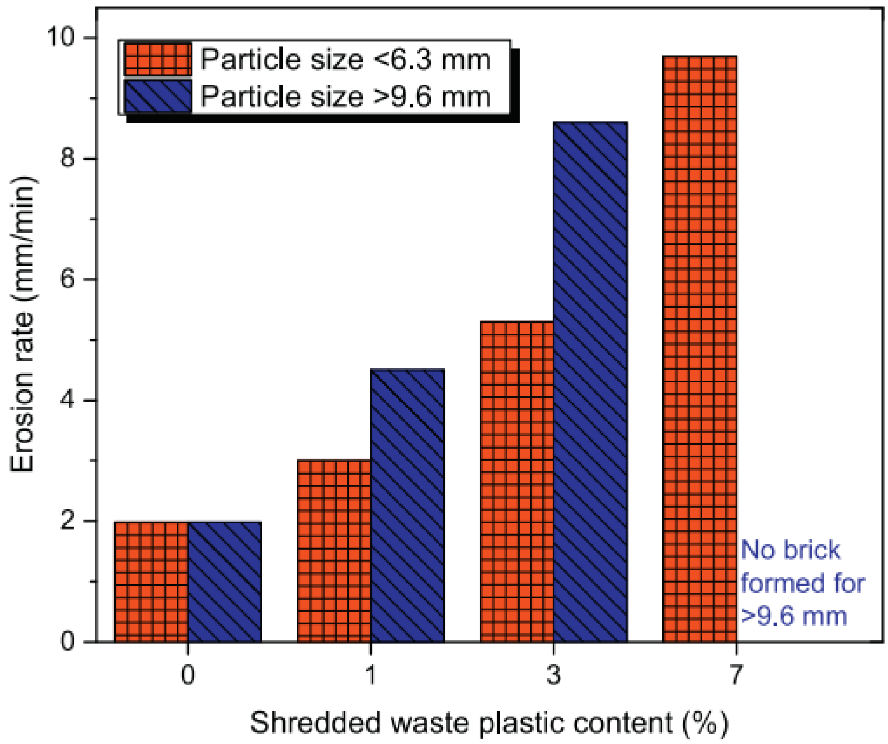


Figure I.22: Variation of erosion rate with shredded waste plastic [63].

Miqueleiz et al.[47], presented the results of a study investigating the use of alumina filler wastes and coal ash waste in the production of unfired bricks stabilized with Portland cement and lime. At the end of the freezing/thawing cycle, fractures were observed in the alumina filler (AF) waste samples, persisting from the beginning to the end of the cycles. These fractures were notably prominent in the sample containing 60% AF waste. However, no instances of spalling or delamination were noted during the entire testing period.

Raj et al.[71], conducted a study on coal ash stabilized rammed earth, focusing on utilizing industrial waste for a sustainable construction approach. They performed a spray erosion test on cube specimens and measured the pitting depth. The average pitting depths obtained for M3 (18% bottom ash, 12% fly ash, 3% cement) and M4 (18% bottom ash, 12% fly ash, 6% cement) are presented in Table I.3, The pitting depths observed for both cases were less than 10 mm, which falls well within the recommended limit according to IS 1725 [72].

Figure I.23: Spray erosion test [47].

Table I.3: Pitting depth obtained in weathering test [47].

Mix	Pitting depth (mm)
M3	5
M4	3

I. 12 Production of fired bricks and solid waste

The brick is a construction material made of raw clay (often mixed with sand) that is shaped, dried (either in the sun or fired in a kiln), and then fired at an appropriate temperature the sintering temperature. The clay particles begin to melt and fuse together to form a stony mass. After firing, the brick retains a certain level of porosity, which gives it specific properties and distinguishes it from other construction materials.

I.12.1 Clay excavation and stockpiling

Clay is mined from natural clay quarries and stored in heaps, flattened using a bulldozer. The clay is organized into layers, each consisting of different types of clay sourced from various sections of the quarry.

I.12.2 Preparing the clay

During this phase, water, sand, and other additives, including recycled or secondary-sourced materials, are blended with the clay. Color pigments may be introduced to alter the fired hue of the clay brick, while certain additives aid in the firing process or enhance the durability of the final product.

I.12.3 Shaping the clay into bricks

The two most prevalent types of bricks are named according to their formation process. Extruded bricks are created by passing clay through a vacuum chamber and extrusion dies, shaping the clay under pressure. The resulting rectangular columns are then cut into individual bricks using wire-cutting techniques.

On the other hand, soft mud bricks are crafted from a particularly soft clay mixture with higher water content. These bricks are either pressed or thrown into molds and subsequently removed onto a tray. While traditionally done by hand in the past, modern soft mud machines are capable of producing tens of thousands of molded bricks per hour.

I.12.4 Drying the bricks

After being shaped through extrusion or soft mud molding, the bricks need to undergo a drying process before firing. They are stacked and transported to the dryer, where moisture is removed from the soft, or "green," bricks. The duration of drying varies, typically taking anywhere from four to 45 hours, depending on the specific product. Once the moisture content of the clay drops to below 2%, the brick is considered dry and ready for firing.

I.12.5 The firing process

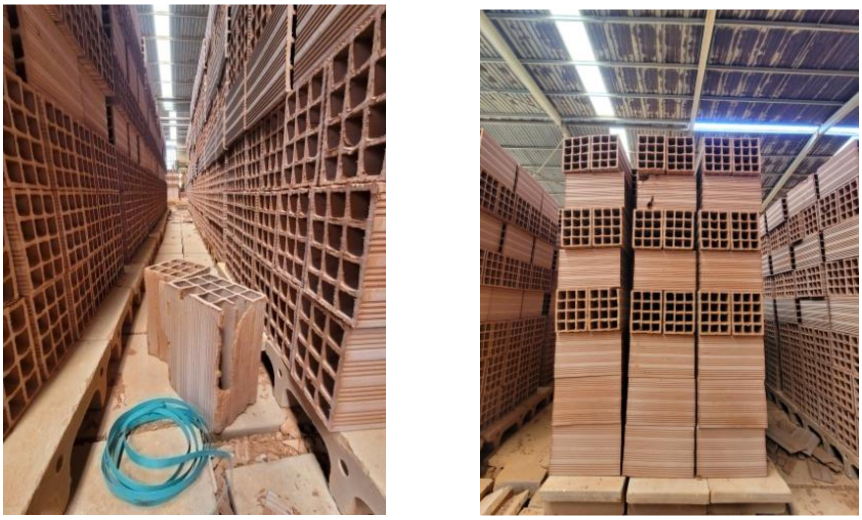
The dried bricks are conveyed to large-scale industrial kilns, where they undergo firing at temperatures ranging from 1000 to 1100 degrees Celsius. This intense heat is crucial for imparting durability, strength, and fire resistance to the clay, characteristics that contribute to the widespread popularity of bricks as a building material. The temperature, the rate of temperature increase, and the kiln atmosphere all play vital roles in determining the final properties of the brick. These variables are meticulously monitored to guarantee the uniform quality of each brick.

I.12 .6 Packaging and delivery

After the fired products have cooled, they undergo a thorough quality inspection before being packed and prepared for shipment. Any product that fails to meet the quality standards during inspection will be sorted out and recycled.

I.13 Fired brick waste

Just like in any industrial activity, factories involved in the production of fired clay materials generate various types of waste. However, the majority of these waste products are classified as non-hazardous and do not pose environmental harm, but this may not be the case if the quantity of these wastes is significant. In Algeria, a considerable number of factories and brickworks produce waste during their operations, largely attributed to the significant proportion of non-compliant or damaged bricks, accounting for 10 to 15% of their total output [73]. Figure I.24 present different fired bricks waste in brickworks.



(a) storage of bricks at brickyards

(b)loading and unloading bricks into trucks

Figure I.24: Different fired bricks waste in brickworks.

I.13.1 Use of fired brick waste in the stabilization of earth blocks

In recent years, there has been a shift in the research focus concerning crushed bricks waste (CBW) in earth mixtures. These studies have integrating CBW as fine and coarse aggregates into earth bricks. In this regard Oti et al.[49], used waste brick dust with ground granulated blast furnace Slag (ME1, ME2, ME3 et ME4) as a partial substitute for soil in the production of mud bricks, at different replacement levels. The incorporation of these wastes up to a percentage of 20% contributed to improving the compressive strength (Figure I.25). Furthermore, this led to an increase in the water absorption (Figure I.26), linear expansion, and weight loss of bricks exposed to multiple freeze/thaw cycles, with variations depending on the proportion of brick dust in the mixture.

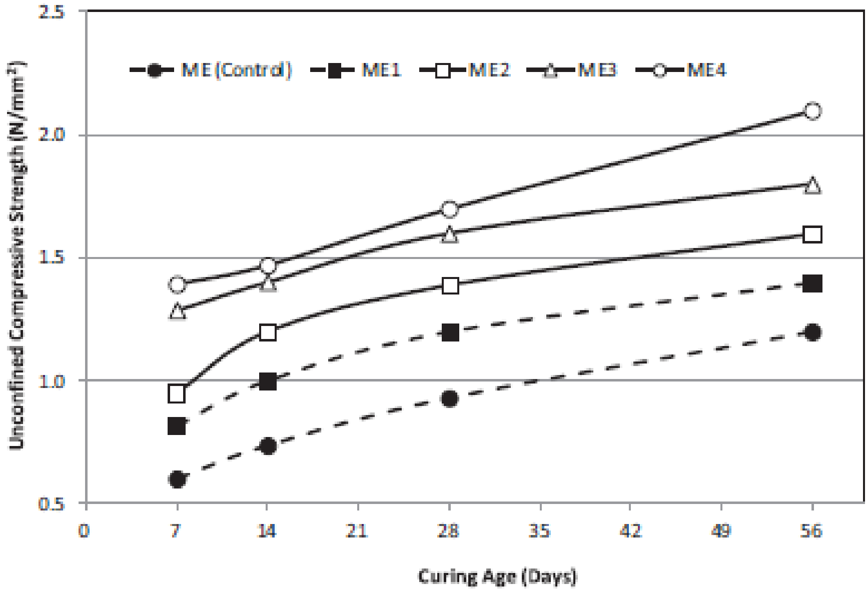


Figure I.25: Unconfined compressive strength development of the stabilized compressed earth blocks [49].

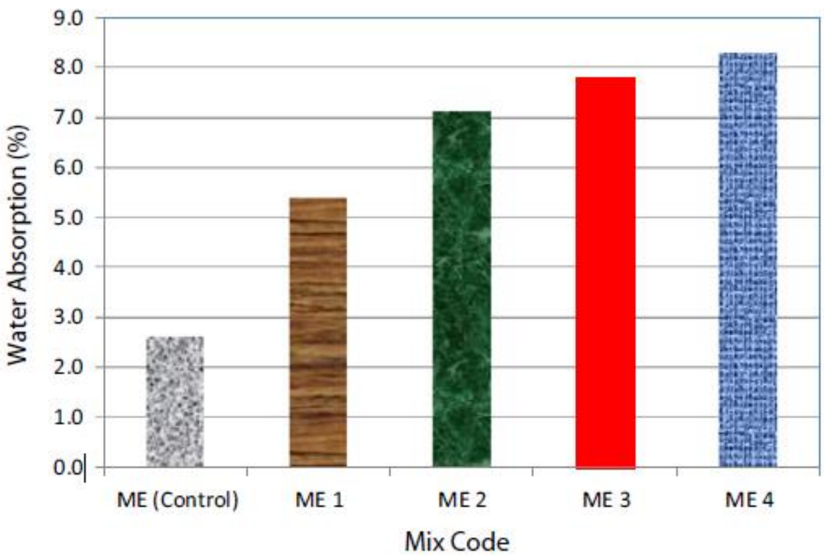


Figure I.26: Water absorption of the stabilized compressed earth blocks [49].

Another study conducted by Joshi et al.[12], on substituting soil with crushed demolished brick masonry in preparation of stabilized adobe blocks (SAB).The soil is replaced by various percentages of fired brick waste (0%, 20%, 40%, 60%, 80%, and 100%) to study the physical characteristics of adobe bricks. It was then found that an improvement in the physical properties of adobe bricks manufactured by replacing between 60 and 80% of natural soil with crushed brick waste show Table I.4.

Table I.4: Physical properties of stabilized adobe blocks (SAB)[12].

Series–(% replacement of DBMW)	Dry density (g/cc)	Wet density (g/cc)	IRA (kg/ m^2/min)	Water absorption (%)	Wet Comp. strength (MPa)		Wet flexural strength (MPa)		Avg. weight loss after 12 cycles (g)*	Expansion on saturation# (%)
					7 day	28 day	7 day	28 day		
Series A (0%)	1.67	1.94	2.34	10.49	2.16	3.04	0.29	0.33	0.47	0.06
Series B (20%)	1.62	1.85	1.80	10.86	2.28	3.36	0.33	0.39	0.42	0.18
Series C (40%)	1.77	1.93	1.42	9.91	3.04	4.34	0.38	0.44	0.38	0.05
Series D (60%)	1.81	1.97	1.26	9.49	3.57	5.23	0.56	0.63	0.36	0.04
Series Z (70%)	1.81	1.94	0.91	6.51	4.48	5.37	1.23	1.34	0.37	0.05
Series E (80%)	1.76	1.94	0.96	8.60	4.35	5.15	0.93	0.98	0.39	0.05
Series F (100%)	1.65	1.83	2.00	11.10	3.63	3.80	0.64	0.70	0.44	0.04

Similarly, Kasinikota and Tripura [13], examined the mechanical properties and durability of compressed earth blocks utilizing crushed brick waste as a substitute for both the soil-sand mixture and sand. Then, they found the addition of 24% crushed brick waste into soil-sand mixture with particle size 0/4.75 mm increases the dry and wet compressive strength show figure I.25etfigure I.26.The average dry and wet compressive strengths achieved ranged from 8.20 to 9.57 MPa and 7.16 to 8.43 MPa, respectively, corresponding to crushed brick waste contents of 0% to 24%.According to the authors, this increase can be attributed to the pozzolanic effect of crushed brick waste and improved particle size distribution.

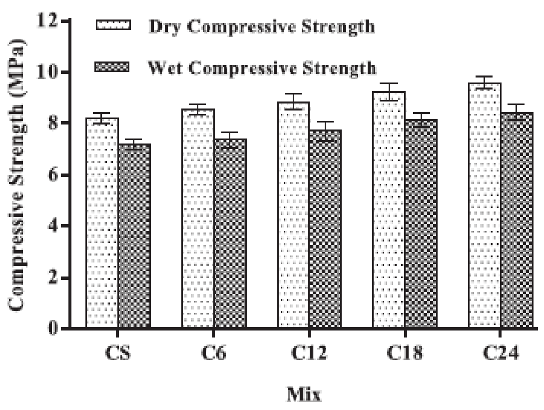


Figure I.27: Dry and wet compressive strength of bocks [13].

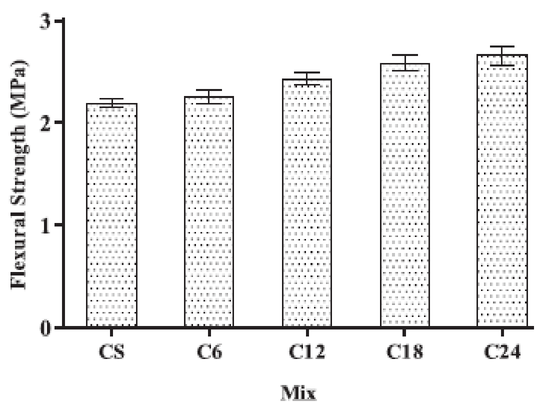
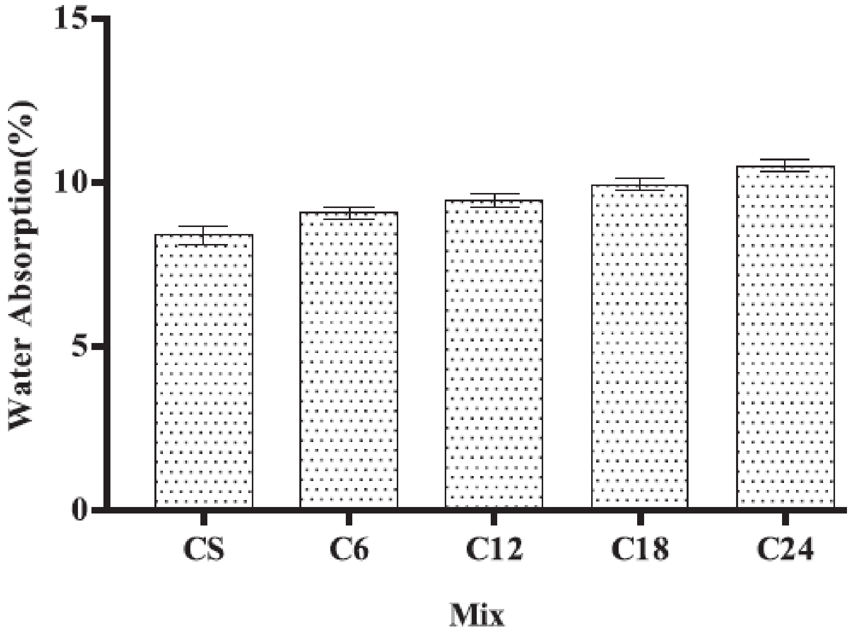


Figure I.28: Flexural strength of bocks [13].

However, adding crushed bricks have a negative effect on the water absorption of the blocks. As the dosage of crushed brick waste increases from 0% to 24%, the water absorption of blocks also increases, ranging from 8.41% to 10.52%, as illustrated in Figure I.29.



FigureI.29:Water absorption of blocks [13].

Rajurkar et al. [74], created cement-stabilized Compressed Earth Bricks (CEB) by incorporating different proportions of demolition waste, including crushed brick and mortar, to substitute natural sand and enhance the block's strength characteristics. Optimal outcomes were achieved when replacing 40–45% of the soil. The author suggests that demolition waste can be efficiently employed in such construction projects as a replacement for natural sand, thereby curbing the extraction of natural resources. Furthermore, recycling and repurposing this material emerge as an ideal approach to waste management [75].

In the stady of Kongkajun et al.[76], compressed earth blocks stabilized with cement were manufactured by substituting laterite with waste from local clay bricks (CBW) and soft sludge from fiber (SS), ranging from 10% to 50% by weight. The findings indicated that all bricks incorporating by-products surpassed industry standards in compressive strength, with the highest strength achieved at 10% replacement with clay brick waste. However, they displayed higher rates of water absorption.

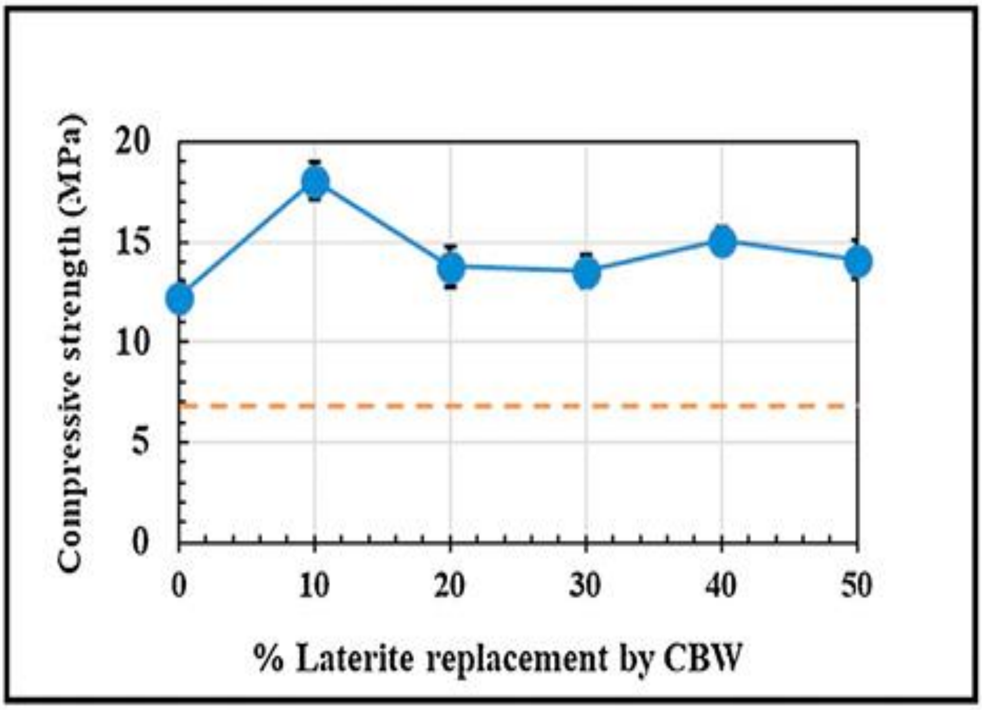


Figure I.30: Compressive strength of the CEB versus % laterite replacement by CBW[76].

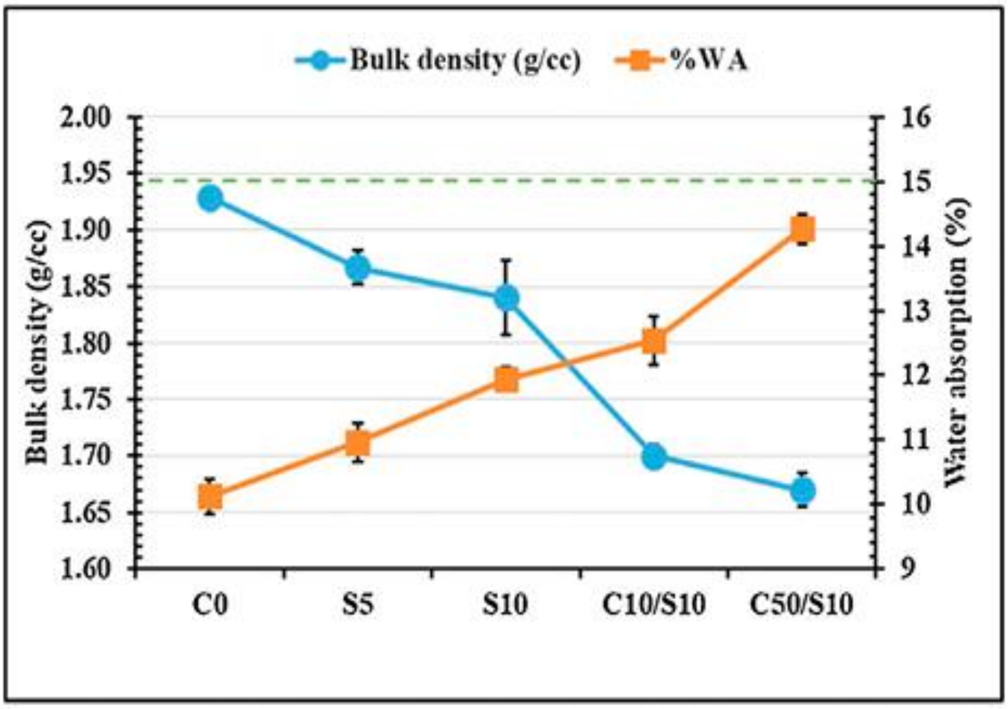


Figure I.31: Bulk density and percentage of water absorption (%WA) of the soil-cement bricks versus % laterite replacement by CBW [76].

I.14 Conclusion

This chapter initially reviewed the general context of earthen construction. The entirety of the physico-mechanical processes generated by the addition of lime to the soil was presented. Then, the effect of stabilizing unfired earth bricks with sand was analyzed in previous studies. These studies show that the soil suitable for making unfired earth bricks needs to be corrected with sand if the soil lacks sufficient sand content. Furthermore, these previous studies demonstrate that each type of soil has an optimal amount of sand that corresponds to it.

Diverse studies on the integration of industrial waste into the making of unfired earth bricks to enhance their physico-mechanical characteristics and durability were collected and analyzed. It has been verified that construction and demolition waste can be repurposed in the form of recycled concrete, ceramics, crushed fired bricks, and mixed aggregates to replace natural aggregates in the development of environmentally friendly building materials. Further, the authors confirm that aggregates from fired brick waste have high absorption compared to earth.

To the best of our knowledge, no prior study has been conducted on the combination of fired brick waste and dune sand in the stabilization of adobe bricks.

Indeed, within the scope of this research, a study is being conducted to comprehend the effect of the combination of fired brick waste and dune sand on the physico-mechanical, thermal properties, and durability of adobe bricks.

Chapter II

Materials and experimental methods

II.1Introduction

The selection of materials used in making adobe bricks requires an understanding of their various physical, chemical, mineralogical, physico-chemical, and mechanical characteristics that can predict the quality of adobe bricks based on their intended use. The nature of soil, the binders used as stabilizers and the type of the sands employed are fundamental parameters that influence the behavior of bricks. Therefore, to properly study the properties of adobe bricks, we must consider the characteristics of their constituents.

In this chapter, we first present the characteristics of the materials used, followed by an overview of the formulations. Secondly, we describe the various experimental methods used for testing the mechanical strengths and durability of adobe bricks.

II.2 Materials

II.2.1 Soil

II.2.1.1Origin

The soil used in this study was collected from the southern region of Algeria, at a depth between 0.50 and 1.00 m below the surface, as shown in Figure II.1.

Figure II.1: Soil used in this study.

II.2.1.2 Physical characteristics of soil

a) Apparent and Specific densities

The apparent and specific densities of the studied soil are shown in Table II.1.

Table II.1: Physical characteristics of the soil.

Atterberg limits			Apparent density (kg/m^3)	Specific density (kg/m^3)
WL (%)	WP (%)	PI (%)	1185	2670
43	17	26		

b) Particle size distribution

The evaluation of the sizes of the different particles constituting the soil and their distribution were investigated using the wet sieving method for the coarse fraction, in accordance with Standard NF P 94-056 [77], and the sedimentation technique for the fine fraction, in accordance with Standard NF P 94-057 [69], as clearly illustrated in Figure II.2.

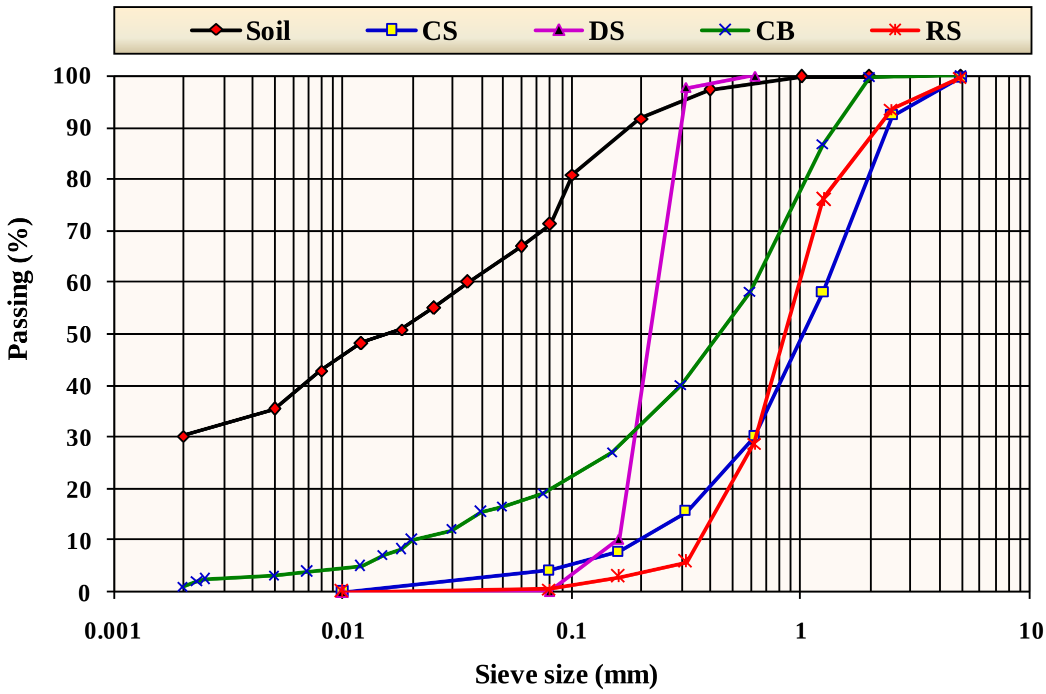


Figure II.2: Particle size distribution of soil, Crushed sand (CS), Dune sand (DS), Crushed fired brick waste (CB) and River sand (RS).

c) Atterberg limits

The Atterberg limits of the studied soil are determined using the procedure outlined in standard NF P 94 -054. The test results are presented in the Table II.1. The results obtained for our soil show that it falls within the transition zone of the liquid limit (31 < WL < 50) and within the transition zone of the plasticity index (16 < IP < 33) according to [43].

II.2.1.3 Chemical and mineralogical analysis of soil

The analyses of chemical and mineralogical compositions of soil are conducted at the laboratory of the Center for Studies and Technological Services in the Construction Materials Industry (CETIM) in Boumerdès, Algeria. The chemical composition analysis was carried out using the X-ray fluorescence spectroscopy (XRF) technique and the results obtained are reported in Table II.2, Moreover, its mineral composition was also investigated using the X-ray diffraction (XRD) approach, and the results obtained are presented in Table II.3, the X-ray diffractogram of the soil is shown in Figure II.3.

Table II.2: Chemical composition of soil (%).

Components	SiO_2	CaO	Al_2O_3	Fe_2O_3	MgO	SO_3	K_2O	Na_2O	P_2O_5	TiO_2	LOI
Soil	35.32	24.11	8.55	3.43	2.38	1.08	1.34	0.61	0.15	0.51	22.52

The chemical analysis of soil revealed a lower presence of sulfur trioxide (SO_3) with a concentration of (1.08%). This concentration must not exceed the recommended limits for soil stabilization which is determined to be 3% [5].

Table II.3: Mineralogical analyses of soil (%).

Components	Calcite	Quartz	Illite	Kaolinite	Orthoclase	Dolomite	Gypsum
Soil	36.5	30	26.5	4	2	1	Trace

Mineralogical analysis shows that the soil contains a high level of calcite (36.5%), as well as significant levels of quartz (30%) and illite (26.5%).

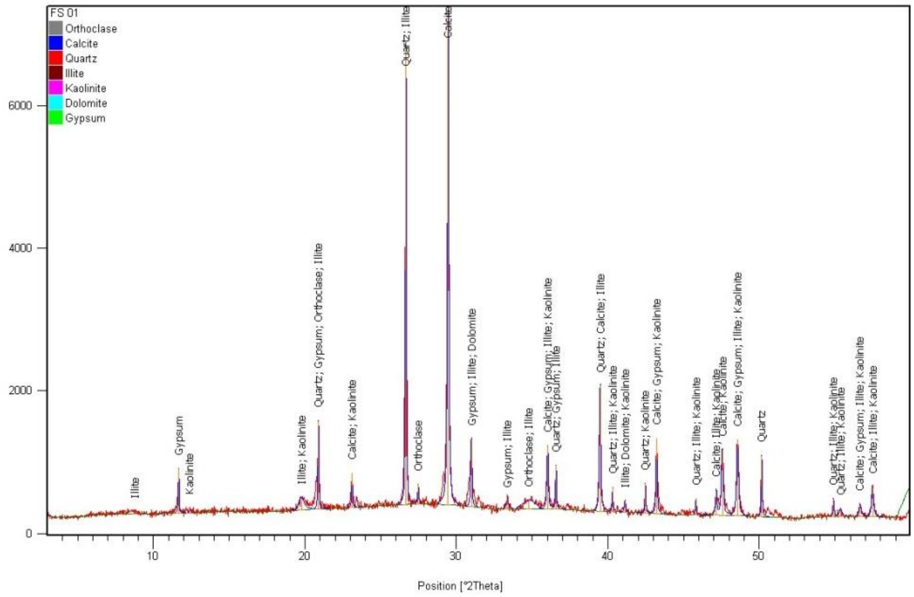


Figure II.3: X-ray diffractogram of soil.

II.2.2. Quicklime

The stabilization of soil in this study was carried out using quicklime (CaO) produced in Hassasna, Wilaya of Saida, Erco unit (see Figure II.4). Its chemical characteristics are listed in Table II.4.

Figure II.4: Quicklime used in this study.

Table II.4: Chemical composition of lime (%).

Components	SiO_2	CaO	Al_2O_3	Fe_2O_3	MgO	SO_3	K_2O	Na_2O
lime	1.37	82.75	10.64	3.26	1.83	0.10	1.34	0.07

II.2.3 Crushed fired brick waste

It was shown that significant losses occur at each stage of the fired brick manufacturing process at the brick factory. These losses mainly occur during the loading, packaging and storage of bricks as shown in Figure II.5. The recovered fired brick waste is then crushed using the Los Angeles apparatus to produce coarse aggregates that are then sieved in order to obtain a homogeneous particle size, as shown in Figure II.5.

Figure II.5: Crushed fired brick waste.

Furthermore, it is useful to remember that the chemical composition and the physical characteristics of its particles of crushed fired brick waste (CB) are presented in Table II.5 and Table II.6, respectively, the particle size curve is shown in Figure II.2, while Figure II.6 presents the scanning electron microscopy (SEM) image and energy-dispersive x-ray (EDX) spectra of CB, Figure II.7 presents the X-ray diffractogram of crushed fired brick waste.

Table II.5: Volume densities of Crushed fired brick waste.

	Apparent density (kg/m^3)	Specific density (kg/m^3)
Crushed fired brick waste	1250	2475

Table II.6: Chemical composition of Crushed fired brick waste (%).

Components	SiO_2	CaO	Al_2O_3	Fe_2O_3	MgO	SO_3	K_2O	Na_2O	P_2O_5	TiO_2	LOI
Crushed fired brick waste	66.29	7.70	12.86	5.20	2.00	1.27	1.82	0.8	0.19	0.64	1.23

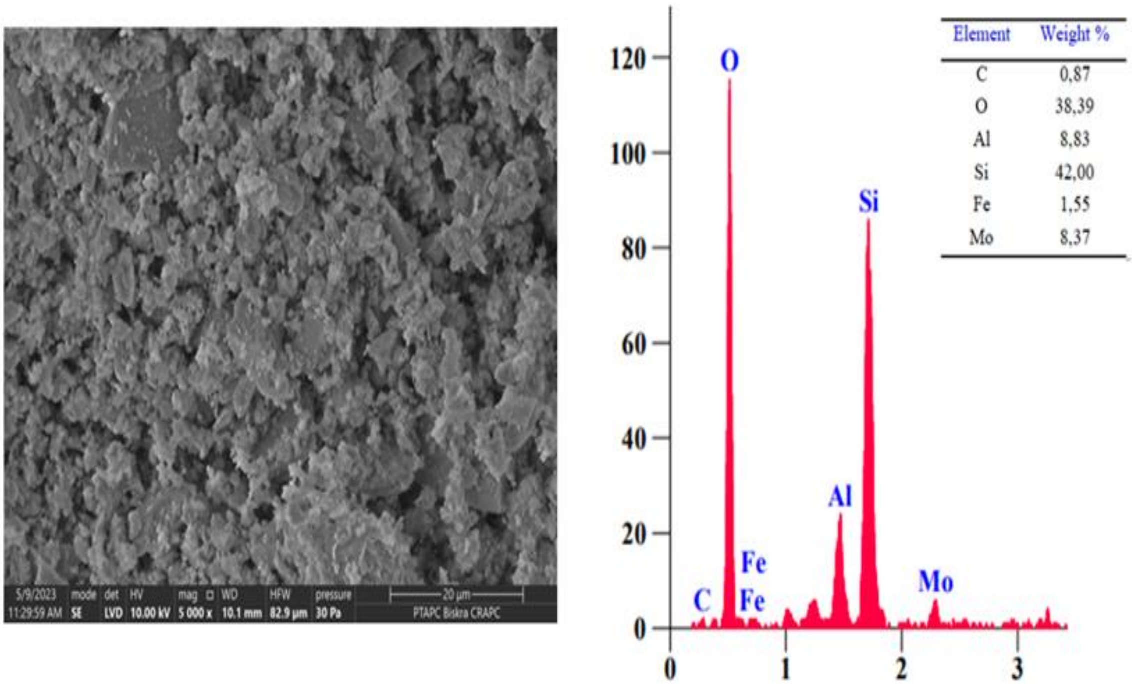


Figure II.6: SEM (G=5000) and EDX of crushed fired brick waste.

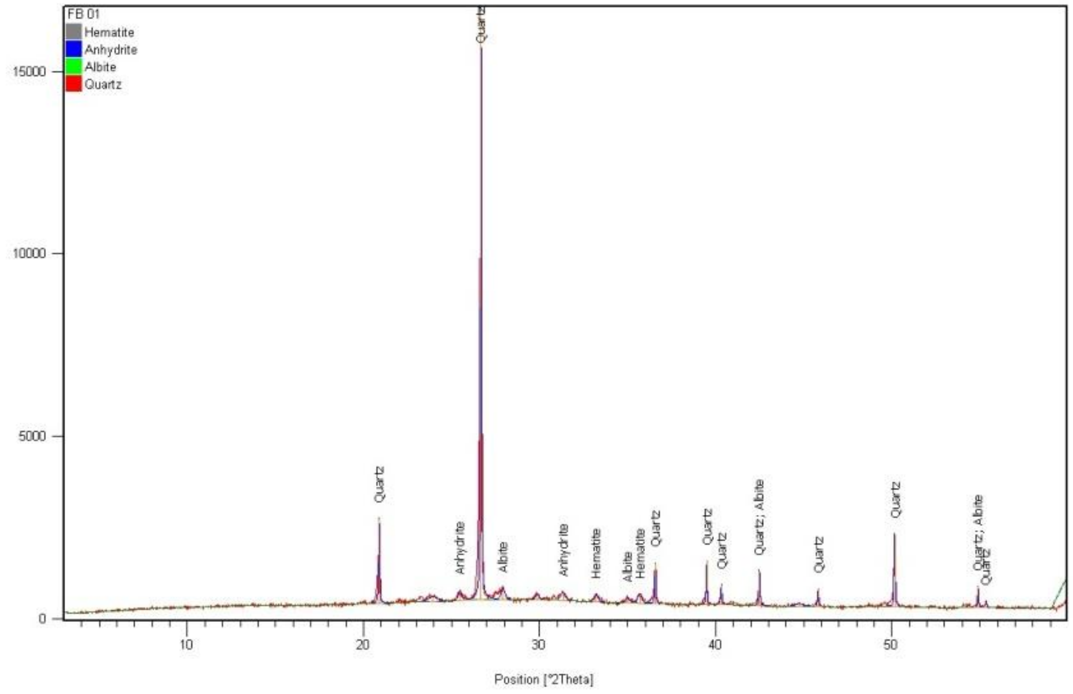


Figure II.7: X-ray diffractogram of crushed fired brick waste.

II.2.4 Sands

In this study, three sand types were used: crushed sand (CS), dune sand (DS) and river sand (RS), as illustrated in Figure II.8. It should be noted that the physical characteristics of the sands used are consistent with AFNOR standards; they are summarized in Table II.7. In addition, the data relating to the particle size analysis of sands are illustrated in Figure II.2, while the SEM and EDX results of dune sand (DS) are illustrated in Figure II.9.

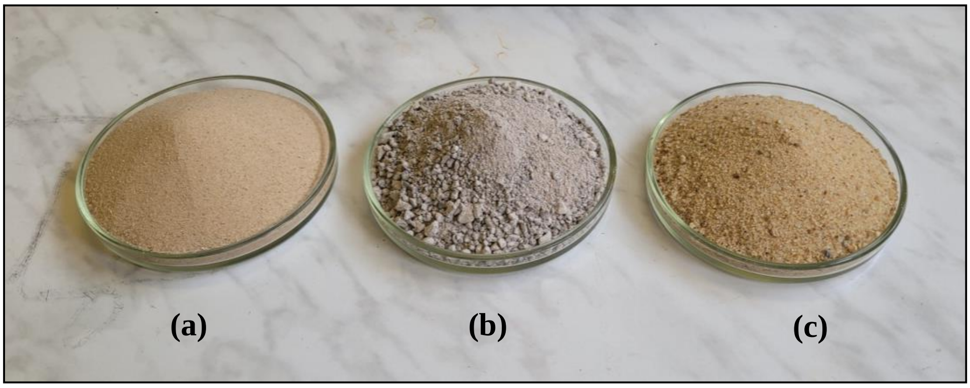


Figure II.8: Sands used in this study: (a) Dune sand, (b) Crushed sand, (c) River sand.

Table II.7: Apparent and specific densities sands used in this study.

	Dune Sand (DS)	Crushed Sand (CS)	River Sand (RS)
Apparent density (kg/m^3)	1442	1632	1729
Specific density (kg/m^3)	2440	2612	2758

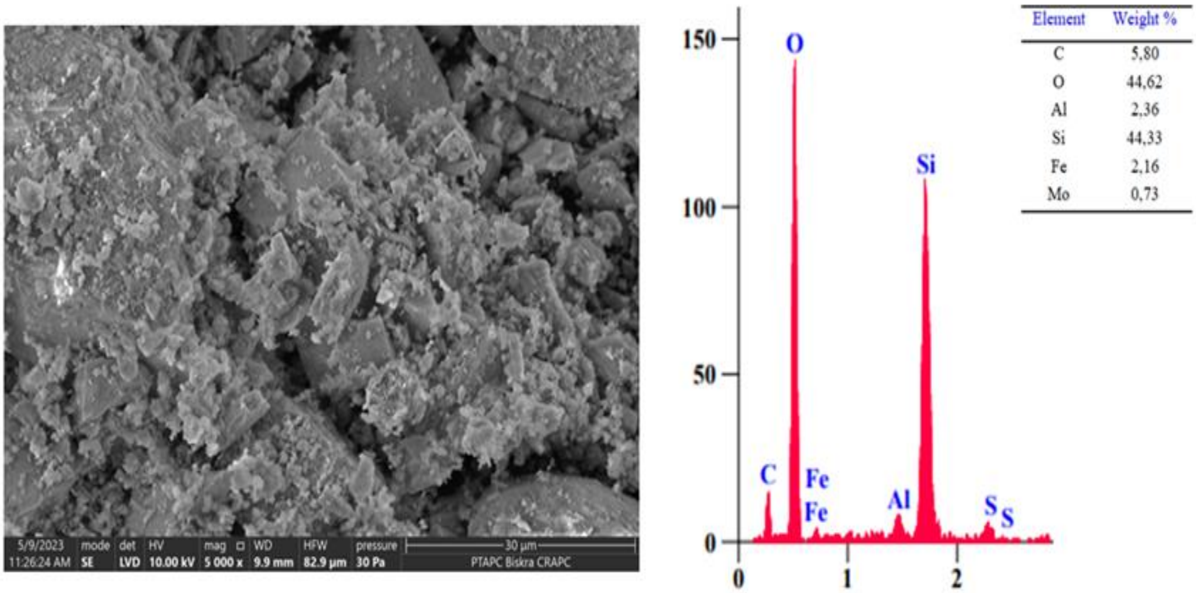


Figure II.9: SEM (G=5000) and EDX of dune sand.

II.2.5 Water

The concoctions' mixing water, or tap water, is obtained from the public network. This water meets quality criteria.

II.3 Mixtures nomenclature and samples preparation

II.3.1 Mixtures nomenclature

In order to carry out the present work, 24 mixtures were prepared to be used in two distinct phases. During the first phase, the mixture (soil+sand) was replaced by different types of sand, including DS, CS, RS, as well as CB used as sand, with mass percentages: 0%(the reference brick (RB)), 10%, 20%, 30%, 40% and 50%. However, in the second phase, the crushed fired brick waste was combined with the dune sand to formulate the mixtures M1, M2, M3. Table II.8 presents the different proportions used in the mixtures prepared for the experiments carried out in this study.

Table II.8: Composition of mixtures with mass percentages.

Mixture	Soil (%)	Crushed brick waste (%)	Dune Sand (%)	Crushed sand (%)	River Sand (%)	Quicklime (%)	Water (%)
RB	90	-	-	-	-	10	32.00
Phase 01							
BCS							
B10CB	80	10	-	-	-	10	30.00
B20CB	70	20	-	-	-	10	30.50
B30CB	60	30	-	-	-	10	30.00
B40CB	50	40	-	-	-	10	31.00
B50CB	40	50	-	-	-	10	31.50
BDS							
B10 DS	80	-	10	-	-	10	29.50
B20 DS	70	-	20	-	-	10	30.00
B30DS	60	-	30	-	-	10	30.50
B40DS	50	-	40	-	-	10	31.00
B50DS	40	-	50	-	-	10	31.50
BCS							
B10CS	80	-	-	10	-	10	30.00
B20CS	70	-	-	20	-	10	30.25
B30CS	60	-	-	30	-	10	30.50
B40CS	50	-	-	40	-	10	30.75
B50CS	40	-	-	50	-	10	31.00
BRS							
B10RS	80	-	-	-	10	10	27.00
B20RS	70	-	-	-	20	10	26.50
B30RS	60	-	-	-	30	10	26.00
B40RS	50	-	-	-	40	10	25.50
B50RS	40	-	-	-	50	10	25.00
Phase 02							
M1	50	30	10	-	-	10	29.00
M2	50	25	15	-	-	10	28.00
M3	50	20	20	-	-	10	27.00

Table II.9: Coding of mixtures.

Code	Designation
RB	Reference block
CB	Crushed brick
DS	Dune sand
CS	Crushed sand
RS	River sund
BCS	Block based on soil stabilised by lime and crushed sand
B10CS	Block based on soil stabilised by lime and 10% crushed sand
B20CS	Block based on soil stabilised by lime and 20% crushed sand
B30CS	Block based on soil stabilised by lime and 30% crushed sand
B40CS	Block based on soil stabilised by lime and 40% crushed sand
B50CS	Block based on soil stabilised by lime and 50% crushed sand
BRS	Block based on a soil stabilised by lime and river sand
B10RS	Block based on a soil stabilised by lime and 10% river sand
B20RS	Block based on a soil stabilised by lime and 20% river sand
B30RS	Block based on a soil stabilised by lime and 30% river sand
B40DS	Block based on soil stabilised by lime and40 %dune sand
B50DS	Block based on soil stabilised by lime and 50% dune sand
B20DS	Block based on soil stabilised by lime and 20% dune sand
BCB	Block based on a soil stabilised by lime and crushed brick waste
B10CB	Block based on a soil stabilised by lime and 10 % crushed brick waste
B20CB	Block based on a soil stabilised by lime and 20 % crushed brick waste
B30CB	Block based on a soil stabilised by lime and 30 % crushed brick waste
B40CB	Block based on a soil stabilised by lime and 40 % crushed brick waste
B50CB	Block based on a soil stabilised by lime and 50 % crushed brick waste
M1	Brick based on a soil stabilised by lime and 30 % crushed brick waste and 10% dune sand
M2	Brick based on a soil stabilised by lime and 25 % crushed brick waste and 15% dune sand
M3	Brick based on a soil stabilised by lime and 20 % crushed brick waste and 20% dune sand

II.3.2 Samples preparation

Cubic samples with dimensions (10×10×10) cm³ and prismatic samples with dimensions (4×4×16) cm³ were carefully prepared, going through several stages:

The first step involved collecting the soil in the form of lumps and then sifting it through a 2mm mesh sieve to obtain a homogeneous texture. The resulting product was then subjected to drying, at a temperature of 65°C for 24 hours, while ensuring that this soil was completely dry.

The second step, various materials such as soil, quicklime and sands were carefully mixed, for a period of 2 minutes, using a mortar mixer, in order to obtain a homogeneous composition and to ensure that all soil and sand grains are covered with quicklime. Then, the amount of water that was previously established in order to achieve a spread diameter of (160 ± 10) mm was slowly added (see Figure II.10), according to the flow table test of Standard BS EN 459-2 [79]. The mixing operation was continued for a period of 2 minutes until a good plasticity composition was obtained, and until the resulting paste was completely homogenized. Then, this paste was manually deposited in the molds, in three identical layers, and carefully compacted. It should be noted that the internal surface of the molds was previously lubricated in order to prevent any fracture of the samples during unmolding. Afterwards, the samples were covered with a plastic film and allowed to air dry for 48 hours. They were subsequently placed in airtight plastic bags [80], and cured in an oven at 65 °C for 7-day, after which they were ready to be tested. Three samples were used on average for each test. All tests were carried out with bricks having dimensions (10×10×10) cm³. However, the flexural test and the evaluation of the mechanical behavior were performed using bricks with dimensions (4×4×16) cm³ (Figure II.10).

Testing on the flow table

Molding of cubic bricks

Figure II.10: Preparation of adobe bricks.

II.4 Mechanical tests

II.4.1 Compressive strength

It is necessary to point out that cubic samples with dimensions of (10×10×10) cm^3 were used for the compressive strength tests, according to the recommendations of Standard NF EN 196-1[77], using a universal hydraulic press. These samples were subjected to the maximum load that caused their fracture. The compressive strength was therefore determined from the following formula:

$$\boldsymbol{R_c} = \frac{F_b}{S} \qquad \text{(II.1)}$$

Here R_c is the compressive strength (MPa), F_b is the maximum load (N) and S is the average surface area (mm^2).

Figure II.11: Compressive strength test.

II.4.2 Flexural strength

The three-point flexural test was carried out on samples with dimensions (4 ×4 ×16) cm^3, according to Standard NF EN 196-1 [81]. The flexural strength was determined from the following expression:

$$\boldsymbol{F_f} = \frac{1.5Fl}{W^3} \qquad \text{(II.2)}$$

Where F_f is the flexural strength (MPa), F is the load applied to the middle of the prism at failure (N), l is the distance between the supports (mm) and W is the depth of the sample (mm).

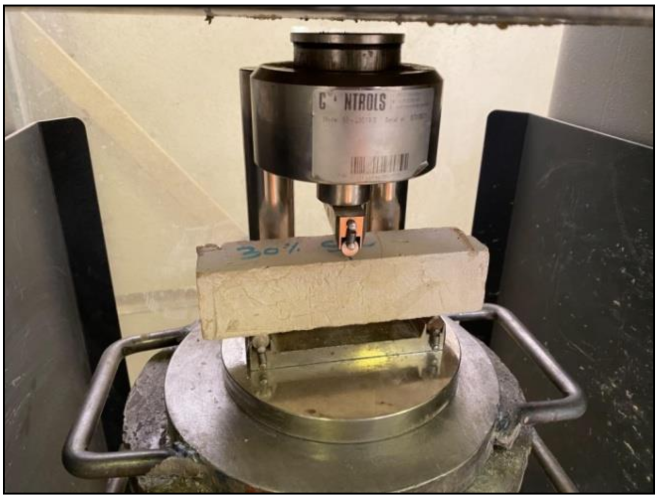


Figure II.12: Flexural strength test.

II.5 Total water absorption

Finding the total absorption capacity (T_A) is the goal of the water absorption test of the samples, according to the protocol of Standard NF EN 12087 [82].This test was carried out by first measuring the dry weight (W_D) of the brick before it was submerged in water for a period of 24 hours. Its wet weight (W_W) was then measured as soon as it was removed from the water. Both values were recorded. The proportional variation in weight (%)between the wet and dry weights (W_W and W_D) was used to calculate the water-absorbed percentage. Total absorption was then evaluated using the expression given below:

$$\boldsymbol{T_A}(\%) = \left(\frac{W_W - W_D}{W_D}\right) \times 100 \qquad \text{(II.3)}$$

Figure II.13: Total water absorption test.

II.6 Capillary water absorption

According to the test guidelines outlined in the French Standard XP P 13-901[83],the capillary absorption coefficient (C_b) was computed. The goal of this test was to submerge the brick facing's surface for ten minutes in a 5 mm-thick layer of water.Next, the water mass gain of the brick was recorded and used to compute the coefficient of water absorption by applying the subsequent formula:

$$\boldsymbol{C_b} = \frac{100.(M_1 - M_0)}{S\sqrt{t}} \tag{II.4}$$

Here C_b is the capillary absorption coefficient ($g/cm^2.min^{1/2}$), M_1 is the weight of the brick immersed in water (g), M_0 is the initial weight of the brick, i.e. before immersion in water (g), t is the duration of immersion (minutes) and finally S is the area of the brick face immersed in water (100 cm^2).

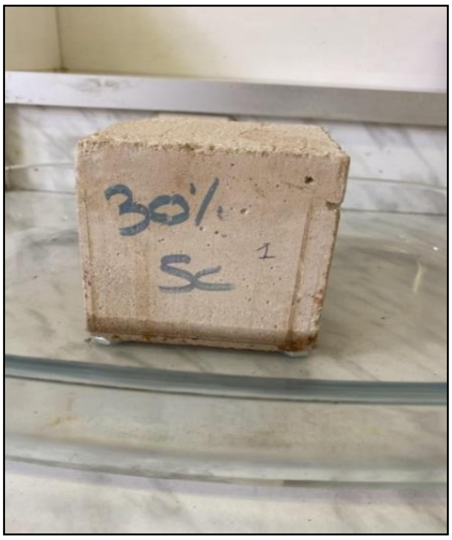


Figure II.14: Capillary water absorption test.

II.7 Apparent density

The apparent density of the prepared adobe was evaluated in accordance with Standard NF EN 1015-10/A1 [84], by applying the expression given below:

$$\boldsymbol{\rho} = \frac{M}{V} \tag{II.5}$$

Note that M represents the dry mass (kg) and V designates the volume (m^3).

II.8 Sound wave propagation speed in adobe bricks

The main objective of this test is to identify the material's porosity by measuring the wave's speed of transmission through it. Then, the results obtained can be utilized to detect any possible presence of heterogeneities and discontinuities within the structures of the prepared adobe bricks. This test was carried out on samples with dimensions (10×10×10) cm³, according to Standard NF EN 12504-4 [85].The wave speed V can therefore be calculated using the formula:

$$\boldsymbol{V} = \frac{L}{t} \tag{II.6}$$

Where L is the distance between the transducers (m) and t is the propagation time (s). It is important to note that the path length of the wave must be greater than or equal to 10 cm.

Figure II.15: Sound wave propagation speed test.

II.9 Thermal conductivity

The conductivity is a physical property that can be estimated in accordance with Standard NF EN 993-15 [86], applying the CT (current transformer) meter. This device uses the transient hot wire approach to operate. A hot wire probe, which consists of a transient temperature sensor and a heating resistor, was used to conduct the tests. Placing the probe between two symmetric bricks that were as smooth as feasible to prevent air contact was done. Every measurement was done at 22 °C, the standard laboratory temperature, and 55% humidity.

II.10 Mechanical characterization

The mechanical characteristics of the prepared adobe were investigated using a testing machine having a load capacity of 100 kN and a loading speed of 0.5 mm/min. The tests, which were carried out in accordance with Standard NF EN 196-1 [81], were performed for the purpose of studying the behavior of the samples under three-point flexural and compression testing.

The flexural strength (FS) was determined by the three-point flexural test using formula (2), while the elastic modulus (E) was found by applying the following expression:

$$\boldsymbol{E} = \frac{FL^3}{48\, I\delta} \qquad \text{(II.7)}$$

Here, E is the modulus of elasticity, F is the force measured by the testing machine, L is the initial height of the samples, I is the moment of inertia of the section at mid-span, and finally δ is the deflection generated by the force F. Regarding the mechanical behavior under compression, the half-test samples resulting from the three-point flexural test were used. The compressive strength (Rc) was determined from relation (II.1).

Figure II.16: Experimental Scene: Mechanical behavior of adobe bricks under compressive.

Figure. II.17: Experimental Scene: Mechanical behavior of adobe bricks under flexural.

II.11 Durability testing

II.11.1 Swelling

The swelling of adobe blocks is measured using the following procedure accordance with the experimental standard XP 13-901[74]:

- Seal two measuring studs on each block with epoxy resin, as shown in the Figure II.18.
- Measure the distance between studs: l_0.
- Place the blocks in a tub of water.
- After 96 hours of immersion, allow the blocks to drain for 10 minutes, then measure the distance between blocks.

The swelling amplitude of each block is given by the following formula:

$$\boldsymbol{\Delta Lg}\left(\frac{\boldsymbol{mm}}{\boldsymbol{m}}\right) = \frac{l1-l0}{l0} \quad \text{(II.8)}$$

Where:

l_0: the distance before immersion;

l_1 : the distance after immersion.

Figure II.18: Swelling test.

II.11.2 Abrasion test

The abrasion resistance of adobe bricks is assessed in accordance with the experimental standard NF XP 13-901[78](Figure II.12). The aim is to test the brick by rubbing it with a metal brush 25 mm wide and with a total mass of 3000g. The brush is moved back and forth across the surface of the brick at a rate of one per second for one minute, giving a total of 60 return strokes. The width of the brush is kept as narrow as possible, and brushing is carried out along the entire length of the brick. From this test, the abrasion coefficient (Ca) of the brick is calculated, representing the loss of material due to the friction of the brick on the abrasion surface. The higher the brick's abrasion coefficient, the better its resistance to abrasion.

$$\boldsymbol{Ca}\left(\frac{\boldsymbol{cm^2}}{\boldsymbol{g}}\right) = \frac{S}{M0-M1} \qquad (II.9)$$

Where:

Ca: Abrasion coefficient of the brick in (cm^2/g);

S: Abrasion surface of the brick in (cm^2);

m_0: initial mass of the brick before abrasion in (g);

m_1: Mass of the brick after the abrasion test in (g).

Figure II.19: Abrasion test.

II.11.3 Erosion test

To simulate raindrops, a resistance to erosion test was carried out on specimens measuring 10 x 10 x 10 cm^3. It was carried out in accordance with the New Zealand Standard NZS 4298[88], which is intended for rough terrain and is based on the Geelong method. The Geelong test is specifically recommended for ads that have the potential to include pigment. Given that it's an aggressive test, it simulates accident scenarios that arise primarily when earth's cracks are not repaired. A 400 mm-tall drop of water is allowed to fall onto the sample, which is inclined at 30 degrees Celsius (see Figure II.20). The test lasted between 20 and 30 minutes (adapted from the standard, which was 20 to 60 minutes), and the depth of the hole was measured. According to the New-Zeelandaise standard [88], an erodibility index between 3 and 5 has been derived from this value. With a depth of entry ranging from 5 to 10 mm, the material was deemed erosive and the erosion class was 3. A hole depth of 10 to 15 mm corresponds to class 4, and the material has been deemed extremely erosive. Finally, the material failed the test with a class of 5 and a depth of more than 15 mm.

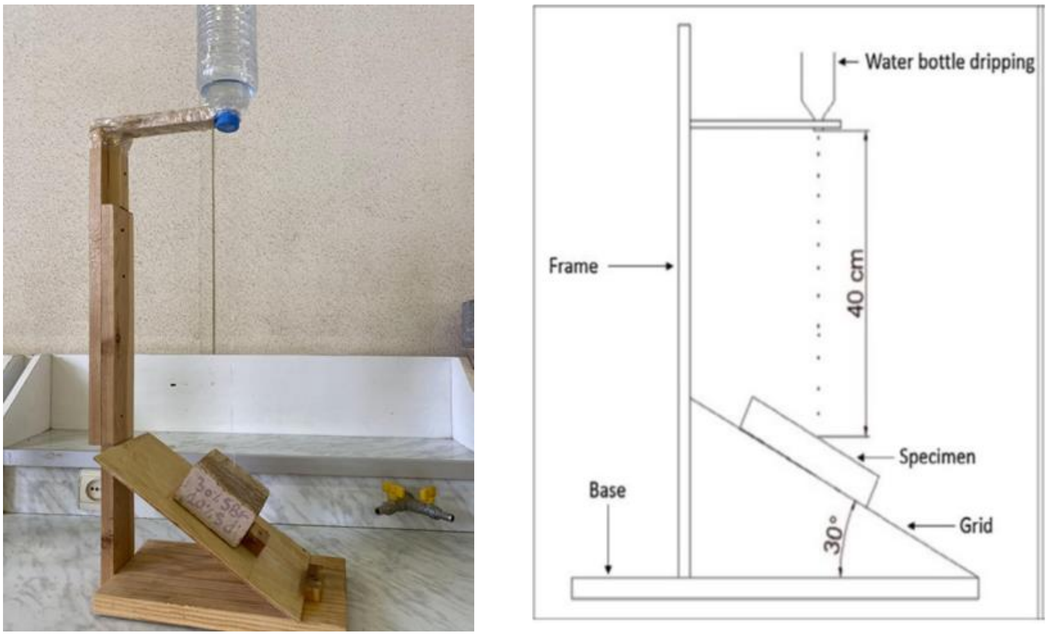


Figure II.20: Erosion test.

II.11.4 Wetting and drying

To determine the behavior and performance of adobe bricks under alternating wetting and drying conditions (saturation in winter and drying in summer), a series of drying/wetting tests was conducted on different bricks according to ASTM D559-57 [89]. The testing principle is as follows:

- Dry the bricks to a constant mass at a temperature of 60-75°C.
- Weigh each brick (dry mass) and subject it to a series of 12 cycles, including:
  - ✓ 5 hours of immersion, after which the block is weighed.

- ✓ 42 hours of drying in an oven at a temperature of 75°C. The bricks are brushed, weighed, and the entire cycle should not exceed 48 hours. This cycle is repeated twelve (12) times, after which the bricks are dried at a temperature of 75°C until a constant mass is achieved. The results of this test indicate the maximum allowable mass loss after 12 cycles of drying/wetting.

Fitzmaurice[90], recommended strict limits for weight loss according to ASTM D559 standards[89]. The permissible mass loss for rural constructions is:

- 5% for any climate with an annual rainfall exceeding 500 mm.
- 10% for dry climates with an annual rainfall of less than 500 mm.

However, according to the standards IS 1725[91], the specified limit value is 3%.

It should be noted that these laboratory tests are generally more severe than real-world conditions[92].

II.11.5 External sulfate attack

To study the influence of sodium sulfate on adobe bricks, two procedures can be used:

- The capillary water absorption test, according to AFNOR XP P 13-901[93], was used as a basis to test the durability of adobe bricks exposed to an aqueous solution of sodium sulfate. The bricks are placed on aluminum support bars in PVC containers, and an aqueous solution of sodium sulfate is gradually added until it reaches a height of 2 mm. The solution is replenished as its level decreases due to absorption. No visual signs of aluminum corrosion were observed on the support bars during the experiments.
- The RILEM TC 127-MS-A.1 [94], was used as a basis. This study recommends capillarity and subsequent immersion of masonry bricks using a 5% mass concentration of sodium sulfate as an accelerated procedure. In this study, only capillarity was used, also referencing NBR 9779 [95], which deal with capillarity tests on hardened concrete and mortar samples. The influence of contact time with the aqueous sodium sulfate solution was examined.

Capillary absorption time was studied to test the durability of adobe bricks exposed to sodium sulfate:

- The bricks were placed inside the container on aluminum support bars, and an aqueous solution of 5% mass concentration sodium sulfate was gradually added until it reached a height of 2 cm from the base of the bricks. This time was recorded as time zero (t = 0 h);

- At t = 4 h, the solution was replenished to 2 cm;
- At t = 1 week, the bricks were removed from the solution and weighed, obtaining Mw_1 (in grams);
- The container was emptied and cleaned, then the bricks were placed inside on support bars to dry. The samples remained in a closed room with a temperature and relative humidity of 27.5 ± 0.5°C and 71.5 ± 5.0%, respectively;
- After two weeks, the bricks were gently brushed until loose particles were removed. They were then weighed again, obtaining Md_1;
- Steps 1 to 6 were repeated until sample failure occurred.
- The mass loss of the specimens was calculated using the following equation

$$\boldsymbol{Mij}\ (\%) = \frac{(Mij - Md_1)}{Md_1} X\ 100 \qquad \text{(II.10)}$$

Where:

i = w (wetting by capillary absorption) or d (drying);

j = cycle 1, cycle 2, cycle 3 ... for d values or cycle 2, cycle 3, cycle 4 ... for w values;

Md_1 = mass of bricks weighed at the end of the drying phase of cycle 1.

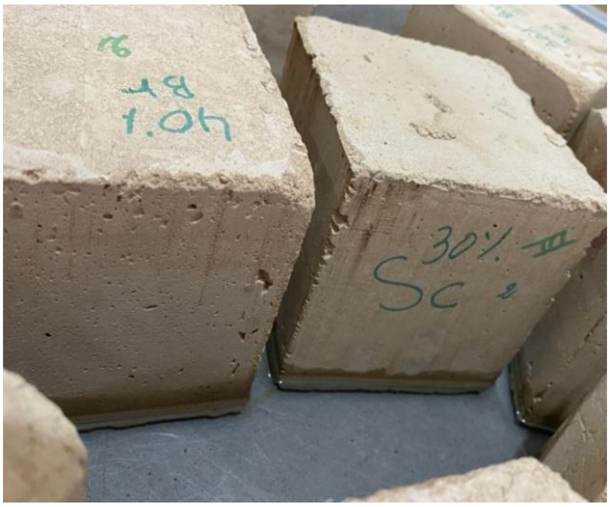


Figure II.21: External sulfate attack test.

II.12 Conclusion

This chapter has provided an overview of the chemical, physical, and mechanical properties of the various raw materials used in the composition of adobe bricks developed in this study. These materials include soil and stabilizers such as waste from fired bricks, quicklime, and various sands such as crushed sand, dune sand, and river sand. The formulation proportions of adobe blocks and the results of raw material characterization have been presented, along with the testing methods and standards used to characterize the manufactured blocks.

Chapter III

Influence of natural sands and brick waste on the physico-mechanical properties of adobe

III.1 Introduction

This chapter focuses on analyzing the effects of dune sand and fired brick waste on the physico-mechanical and thermal properties of adobe bricks. The experimental program of this chapter is divided into three distinct phases.

The first phase explores the impact of curing time and lime dosage on the mechanical strengths of bricks. Special attention is given to analyzing the influence of curing duration on the mechanical properties of lime-based bricks to determine the optimal curing time and lime dosage for subsequent phases of the study.

The second phase examines the effect of different percentages of natural sands (crushed sand, river sand, and dune sand) as well as fired brick waste used as sand on the mechanical strengths of adobe bricks. This phase aims to conduct a comparison among these different types of sands. Once the optimal sand contents are determined, adobe bricks are subjected to tests for total absorption and capillary absorption.

The third phase investigates the effect of the combination of fired brick waste and dune sand on the physico-mechanical characteristics and thermal conductivity of lime-stabilized adobe bricks.

The different phases of the study are structured according to Figure III.1, which illustrates the various parameters considered in this study, as well as the tests conducted on the adobe bricks.

III.2 Effect of lime dosages and curing time on the mechanical strength of adobe

Research has shown that earth bricks stabilized with lime and stored at room temperature of 20 to 30°C require a very significant curing period exceeding one month to ensure satisfactory strength development [96]. The slow pozzolanic reaction of lime results in low short and medium-term strength. Therefore, to avoid the issue of storing bricks for an extended period, accelerated curing is essential.

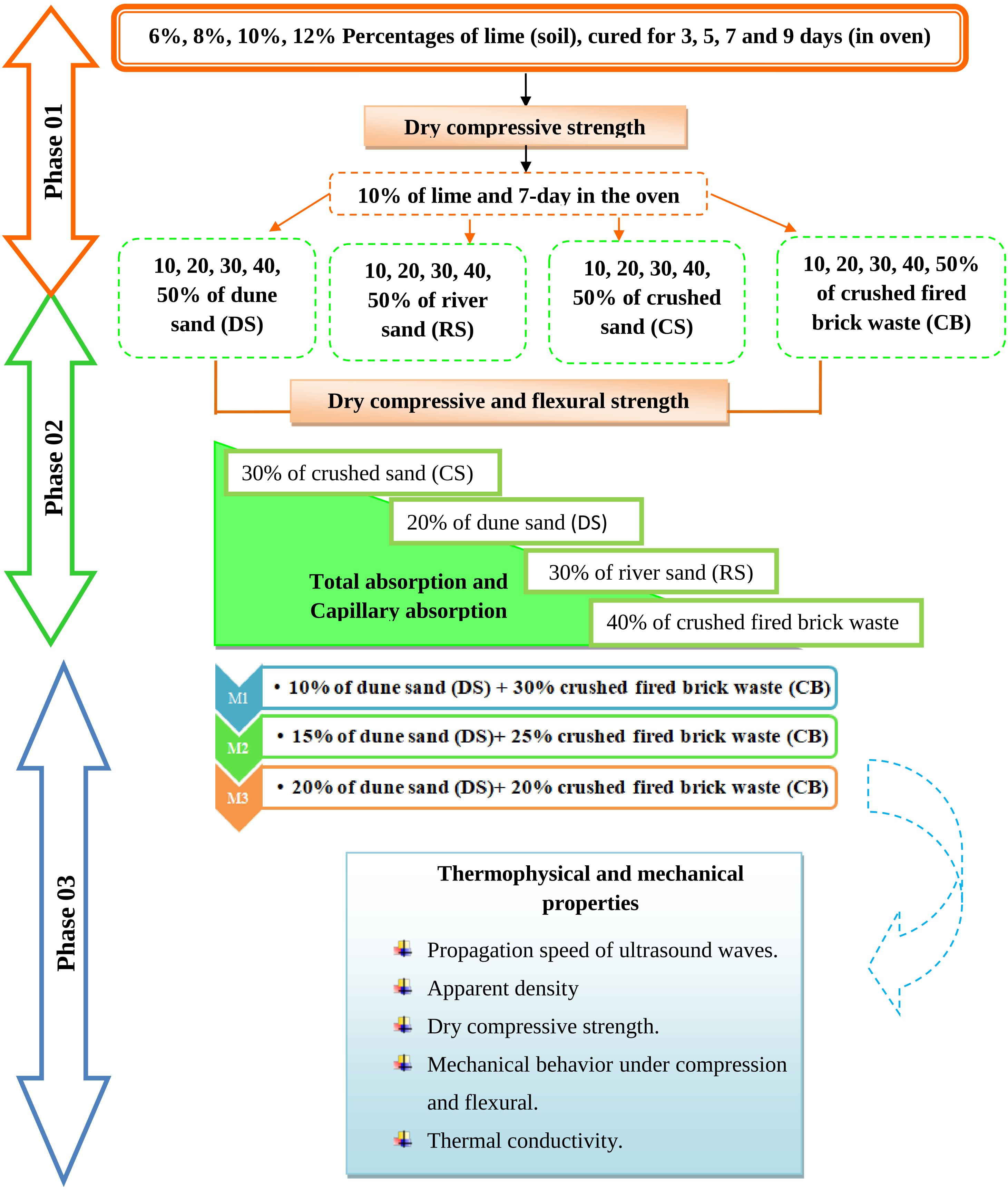


Figure III.1: Experimental program.

The bricks cured in the oven exhibit the highest compressive and tensile strength compared to other curing methods (laboratory curing and natural steam curing), These findings are consistent with those of Al-Mukhtar et al.[40], who observed that lime-stabilized soil subjected to high-temperature curing accelerates the pozzolanic reaction, leading to rapid development of mechanical strength.

To optimize the amount of lime added to the soil based on its dry compressive strength. This involved incorporating different amounts of quicklime into the soil. In this regard, Millogo et al.[97], indicated that adding different quantities of quicklime to the soil allowed detecting an optimal quantity of lime beyond which the compressive strength started decreasing due to decreasing of formation of C-S-H which resulted from the reaction between lime and clay minerals as well as to the high concentrations of calcite and the portlandite. Afterwards, the prepared samples were placed in the oven for periods of 3, 5, 7 and 9 day to determine the optimal curing period of the adobe bricks. This heat treatment favored the acceleration of hydration and the pozzolanic reaction between lime and clay. Figure III.2 clearly shows that the most interesting results were observed with a lime content of 10% and a curing period of 7-day.

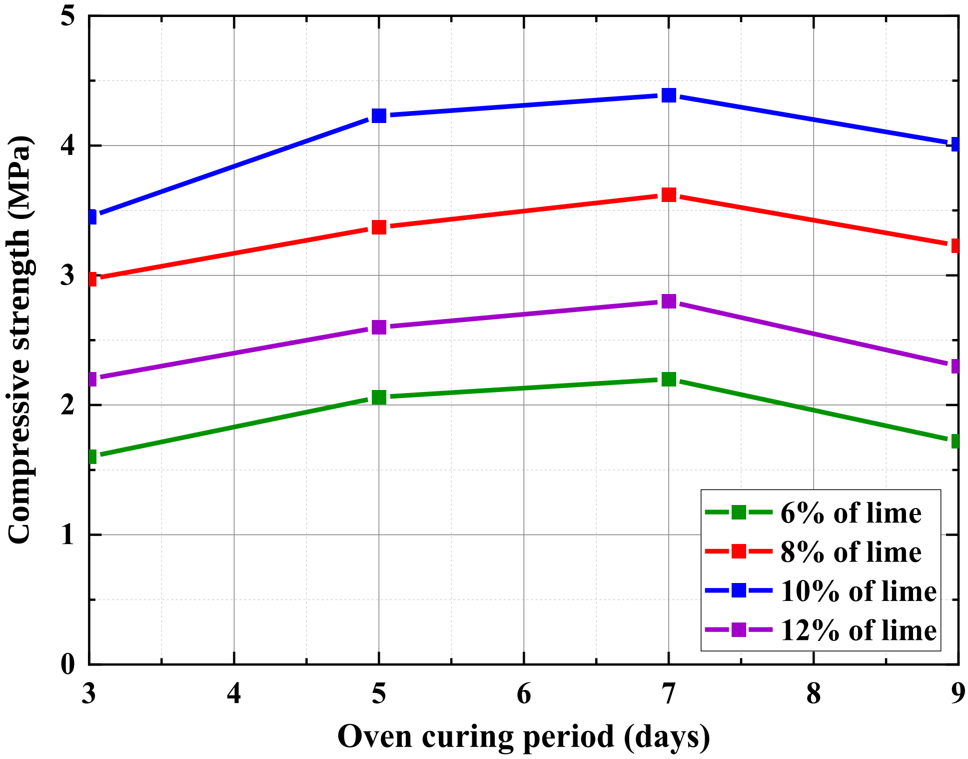


Figure III.2: Effect of lime dosage and curing time on the compressive strength of adobe bricks.

III.3 Effect of different sand types on the mechanical strengths and water absorption

III.3.1 Dry compressive strength

Figure III.3 illustrates the influence of the dosage of different sand types on the dry compressive strength (DCS). The results obtained allowed observing that the mixture containing 40% of crushed fired brick waste (CB) showed a maximum DCS value, which represents an increase of 80.86%, compared to the strength of RB. As illustrated in Figure II.6, this strength improvement is certainly due to the shape and roughness of the CB particles, which promoted better adhesion between the aggregates and the lime-soil matrix. Kasinikota and Tripura [13], attributed this strength increase to the pozzolanic reaction that generally occurs between fine particles, i.e. those with a diameter less than 0.15 mm, usually present in CB and lime. The analysis of bricks containing crushed sand and river sand (BCS and BRS) indicated an increase in DCS reaching up to 30%, depending on the dosage of these two sands. However, it was found that, beyond this proportion, the DCS begins to decrease. It is worth mentioning that the DCS increase for BCS and BRS was around 78.13% and 46.92%, respectively, over a dosage range extending from 0% to 30%. On the other hand, the lowest DCS value was obtained by adding dune sand (DS), with an optimum rate of 20%. This DCS value is 9.33% higher than that of RB. This, small increase in DCS is due to the uniform and spherical shape of the grains of the sand used, as shown in Figure II.9.

The compressive strength decrease of bricks, containing different types of sand added with optimal rates, is attributed to the deficit in fine particles of the soil because the cohesion between the sand and soil grains is ensured by these particles. As a result, the minimum plasticity required for the manufacture of adobe bricks is insufficient. It is noteworthy that the DCS values of the adobe bricks tested were found consistent with the strength requirements specified by the New Mexico State Standards [98] for Adobe Construction Walker.[99] (2MPa) and by the Standards New Zealand [88] (1.3MPa).

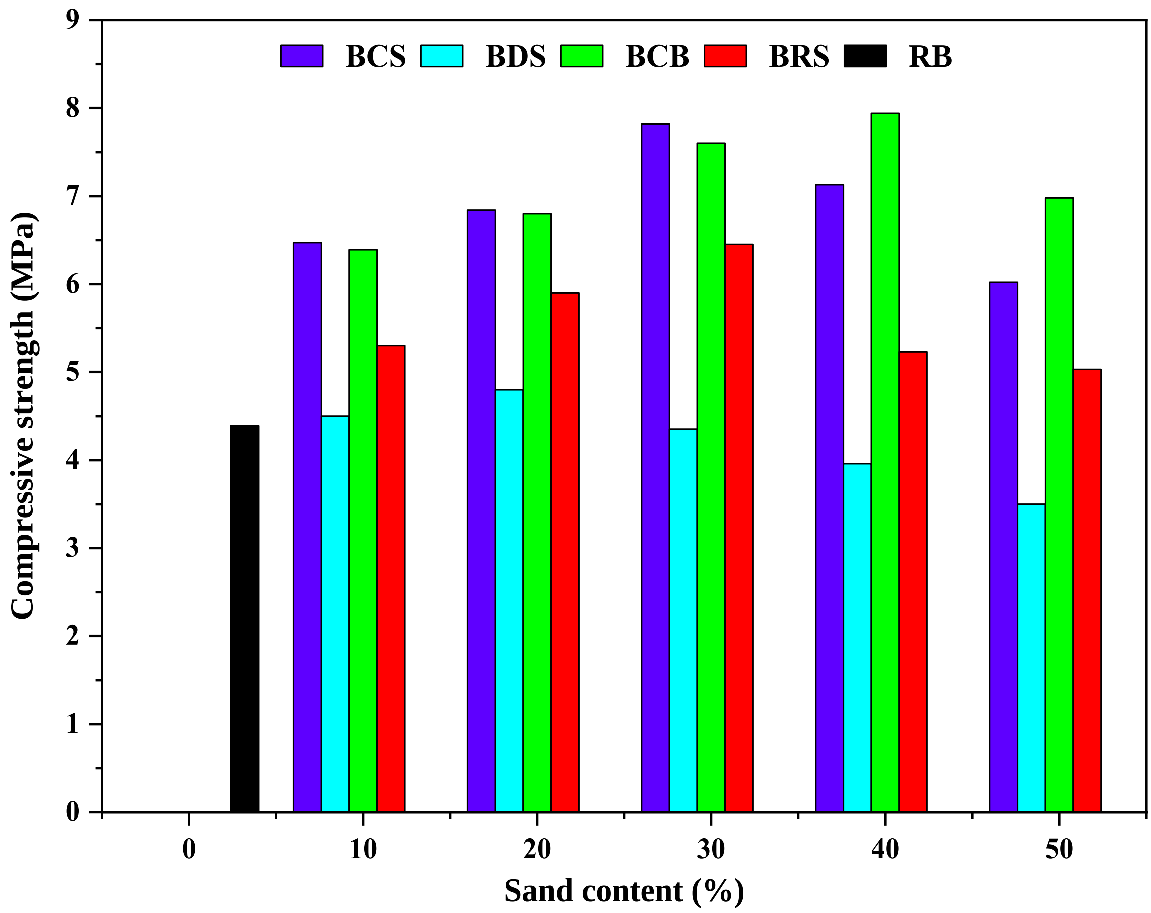


Figure III.3: Effect of type and sand dosage on the compressive strength of adobe bricks.

II.3.2. Flexural strength

The variation in flexural strength (FS) is shown in Figure III.4. It is clearly noted that this strength increases with the addition of CB, reaching 3.85 MPa at 40% dosage. This improvement corresponds to an increase of approximately 91.54% with respect to that of RB. Figure II.5 clearly indicates that the angular shape of the crushed fired brick aggregates and the rough texture of the crushed brick generally promotes a robust bond between the brick aggregates and the mixture matrix (soil + lime), which helps to increase the flexural strength [100].These results are in good agreement with those reported in similar previous works [10, 12]. Furthermore, after the addition of CS, the flexural strength results are almost similar, except that the optimum of this strength is detected at 30% of CS, which is certainly due to the angular shape of CS. However, it should be noted that the smooth and flattened shape of the RS particles and the rounded shape of the DS grains caused a reduction in the flexural strength of the bricks as compared to those of the bricks incorporating CB and CS. However, these strengths were greater than that of RB. Similarly, the optimum compressive strength was achieved by adding 30% and 20% of RS and DS, respectively.

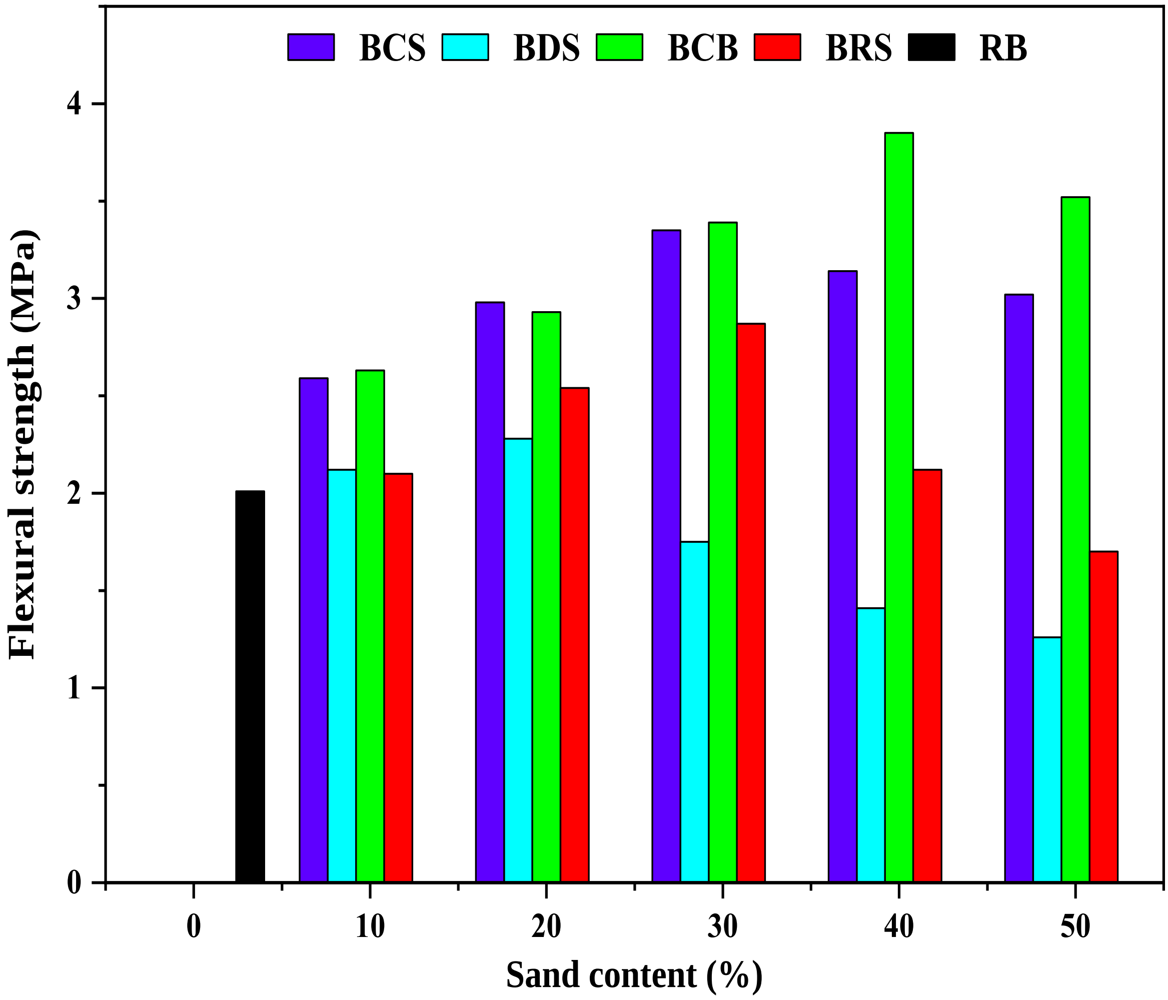


Figure III.4: Effect of type and sand dosage on the flexural strength of adobe bricks.

III.3.3 Total and capillary absorption

The previously recorded results, relating to the compressive strength and the flexural strength of bricks incorporating various types of sand, were used to determine their optimal values which were then utilized to determine the total absorption (T_A) and the capillary absorption coefficient (C_b) of the bricks under study. Figure III.5 represents the variation of C_b and T_A for the four types of sand. Analysis of the data at hand showed that B40CB gives the highest C_b and T_A values. These values reached 10.27g/cm^{-2}.min$^{1/2}$ and 16.53%, respectively. In addition, the increase (%) was approximately 17.64% for C_b and 12.21% for T_A with respect to RB. This increase is certainly due to the water absorption that was found higher for brick waste aggregates [70].In this regard, the results reported by [13],showed that whatever the size and quantity of CB particles, the water absorption of the compressed earth blocks increased as the replacement rate went up. However, low T_A and C_b values were obtained for B30RS, followed by B20DS, then by B30CS. Likewise, the C_b values decreased by approximately 38.14%, 31.27%, and 12.37% for B30RS, B20DS and B30CS, respectively, with respect to the RB values. Likewise, the T_A decreased by approximately 35.5%, 28.71%, and 10.38%, respectively, compared to the values found for RB. The findings of the first phase showed that fired brick waste can be used as a substitute for conventional sands such as crushed sand and river sand. These findings were also confirmed by the mechanical strength results. However, a challenge still remains regarding the high water absorption capacity of bricks incorporating CB sand, because it exceeds that of RB. For the purpose of reducing this absorption capacity, it is highly recommended to combine brick waste with dune sand which is known for its water absorption capacity lower than that of soil and CB.

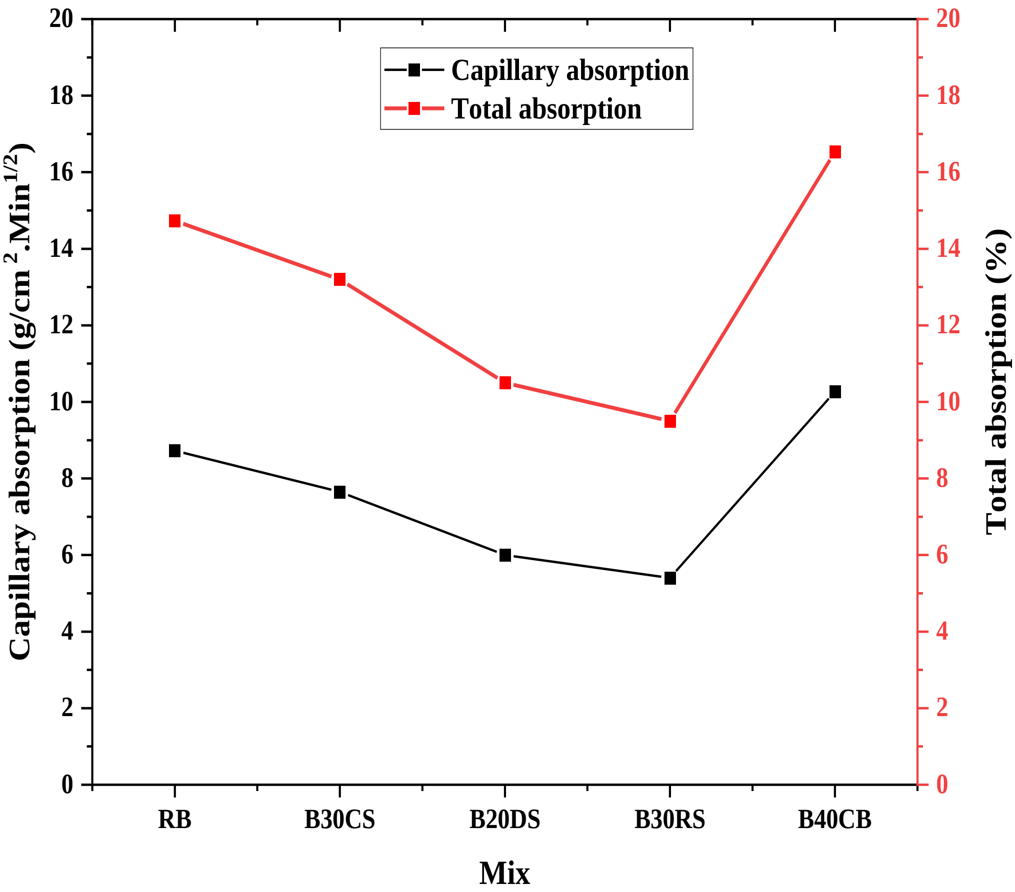


Figure III.5: Effect of sand type on the capillary absorption and total of adobe bricks.

III.4 Combined effect of crushed fired brick waste and dune sand on physical characteristics

III.4.1 Apparent density

The apparent density was measured for the different mixtures and the results obtained are presented in Figure III.6 which shows that the values obtained vary between 1543 kg/m³ and 1800 kg/m³. It should also be noted that the density of mixture M1 increased by 16.65% with respect to that of RB. This increase is explained, on the one hand, by the apparent densities of CB and DS which are higher than that of raw earth and, on the other hand, by the formation of new hydrates C-S-H after the addition of CB, which led to lower porosity, as clearly shown in Figure III.7.

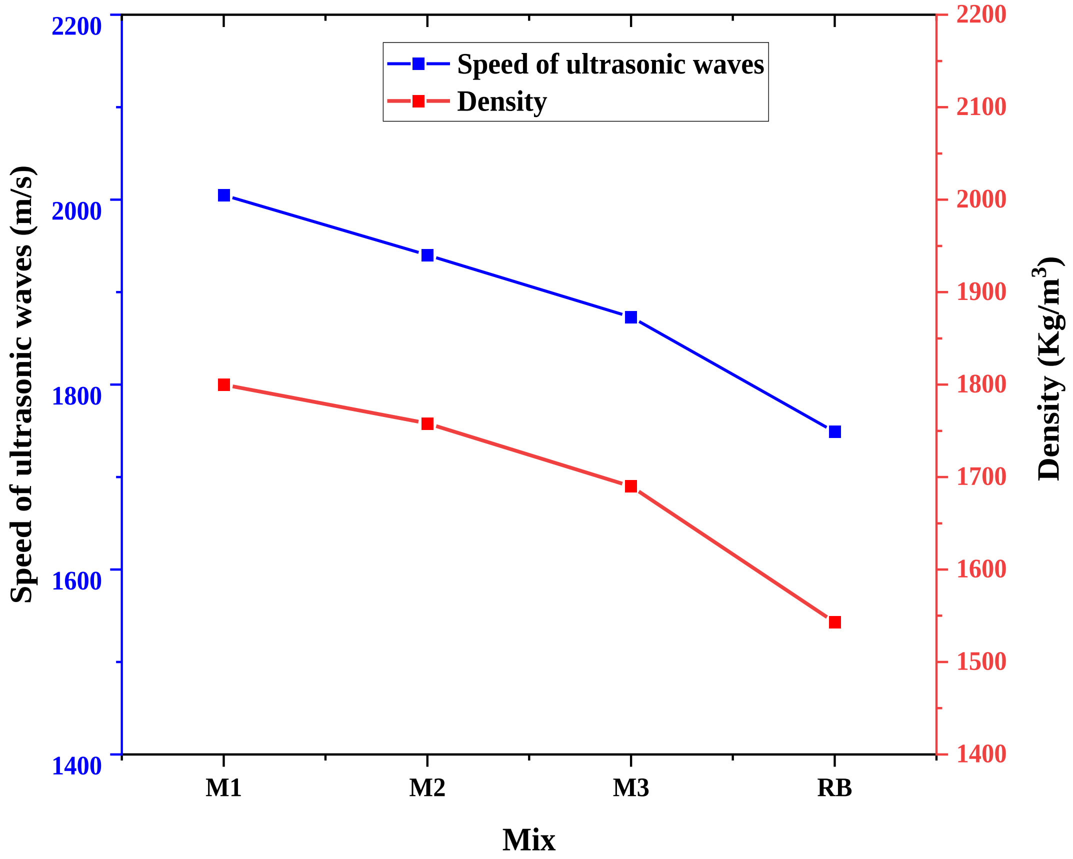


Figure III.6: Combined effect of crushed fired brick waste and dune sand on the apparent density and propagation speed of adobe bricks.

This same figure presents the SEM-EDX images of the different mixtures. It also shows that the structure of the M1 mixture is denser than that of RB and those of the M2 and M3 mixtures.

Similar trends have been reported in the study conducted by Joshi et al.[12], on adobe bricks. They replaced the excavated natural soil by 70% of masonry demolition waste and crushed bricks and hence observed an increase in dry density from 1670 kg/m³ to 1810 kg/m³. Fortunately, the densities of all mixtures remained within the acceptable range regarding the adobe bricks. These density values, as reported by researchers, are between 1540 kg/m³ and 1950 kg/m³ [12].

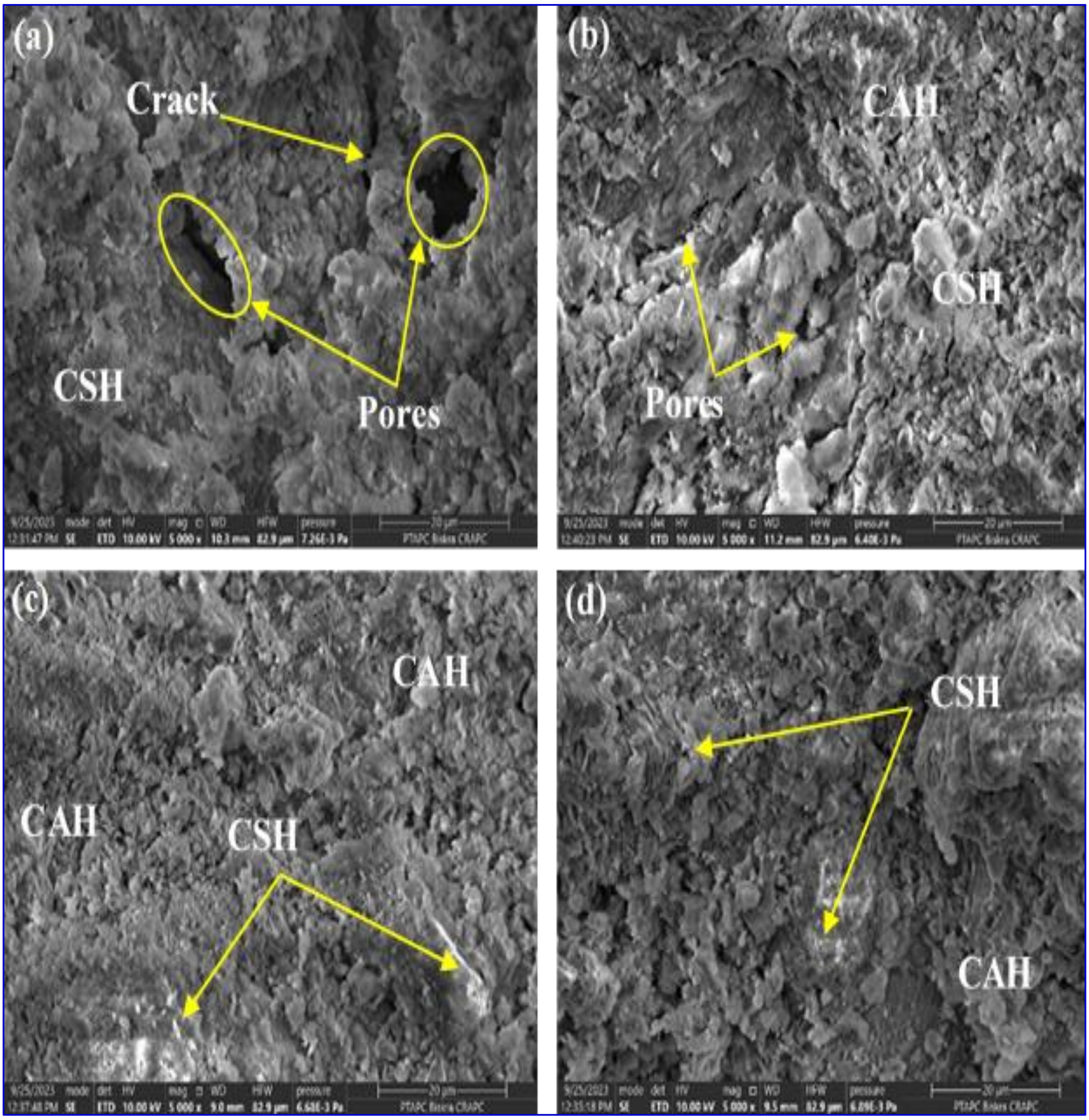


Figure III.7: SEM images(G=5000) of brick adobes: **(a)** RB, **(b)** M1, **(c)** M2, **(d)** M3.

III.4.2 Propagation speed of ultrasound waves

The test carried out here was primarily intended to detect the presence of voids or cracks within the prepared adobe bricks. Analysis of the results of the ultrasound propagation speed test, as presented in Figure III.6 revealed that the lowest wave propagation speed value was observed in the RB mixture. On the other hand, the M1 mixture presented the highest wave propagation speed value which was found equal to 2005 m/s. It was also observed that the wave propagation speed increased as the quantity of fired brick waste went up. It was indeed shown that this increase was around 14.63%, 10.92% and 7.08% for mixtures M1, M2 and M3, respectively, with respect to RB. These increases could be attributed to the decreased amount of CB that was replaced by dune sand. As shown in Figure III.7, this replacement resulted in the formation of voids within the mixtures. These findings are consistent with those reported for the apparent density. It has in fact been observed that the higher the density of the adobe bricks, the greater the wave propagation speed.

III.5 Combined effect of crushed fired brick waste and dune sand on mechanical behavior

III.5.1 Dry compressive strength

Figure III.8 illustrates the variation in dry compressive strength (DCS) of bricks for the different mixtures under study. For this, samples with dimensions (10×10×10) cm^3 were used to measure the DCS. It was in fact observed that the DCS of the prepared mixtures increased as the percentage of CB went up, in comparison with RB. Indeed, a straightforward increase in compressive strength was easily observed. This increase was of the order of 71.75%, 53.75%, and 44.19%, respectively, for mixtures M1, M2 and M3, with respect to that of RB. The highest compressive strength value was recorded for mixture M1, with an average of 7.54 MPa, while the lowest, of approximately 4.39 MPa, was obtained for RB. In comparison with the study carried out by Khoudja et al.[101], it was noted that the dry compressive strength values of adobe bricks incorporating the combination of dune sand and waste bricks were higher than that of adobe bricks containing 30% sand crushed, as reported in[101].

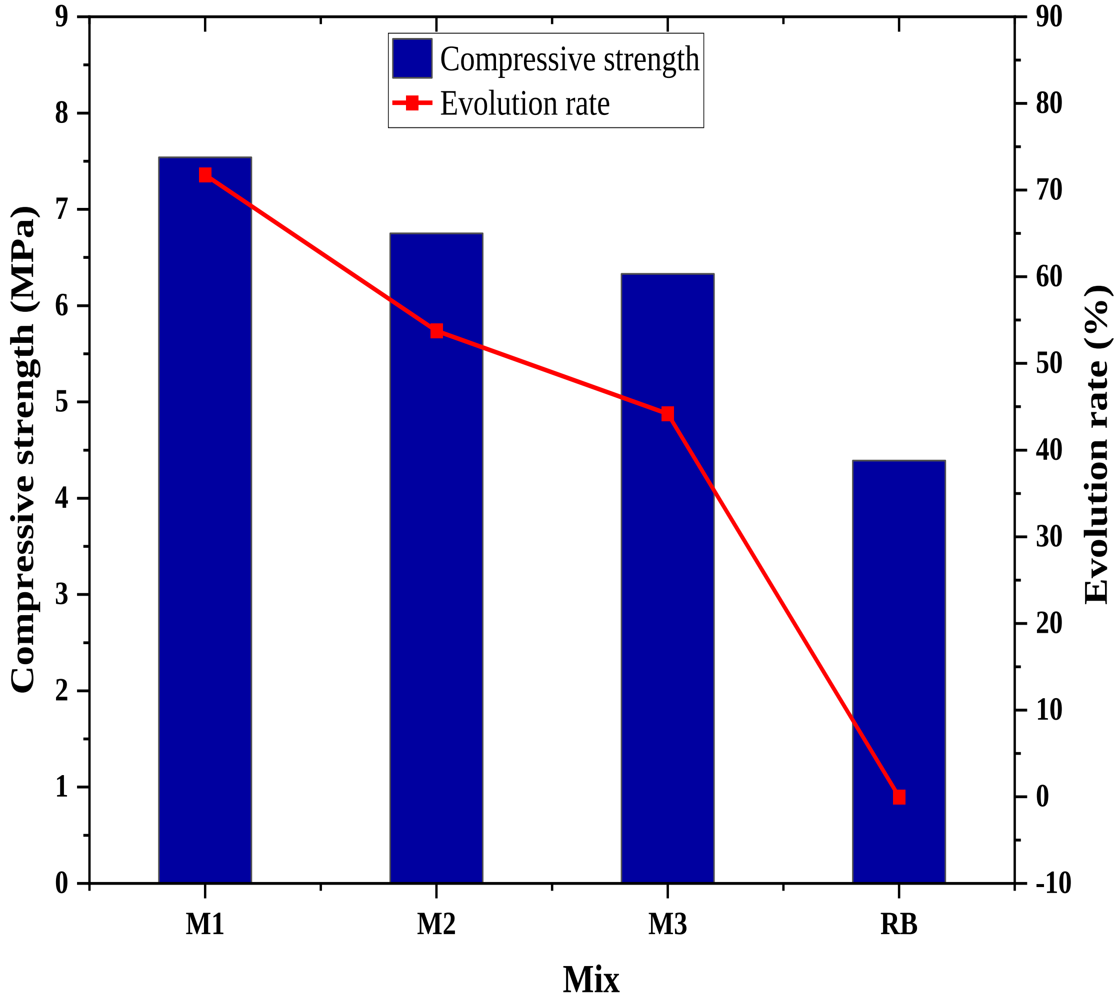
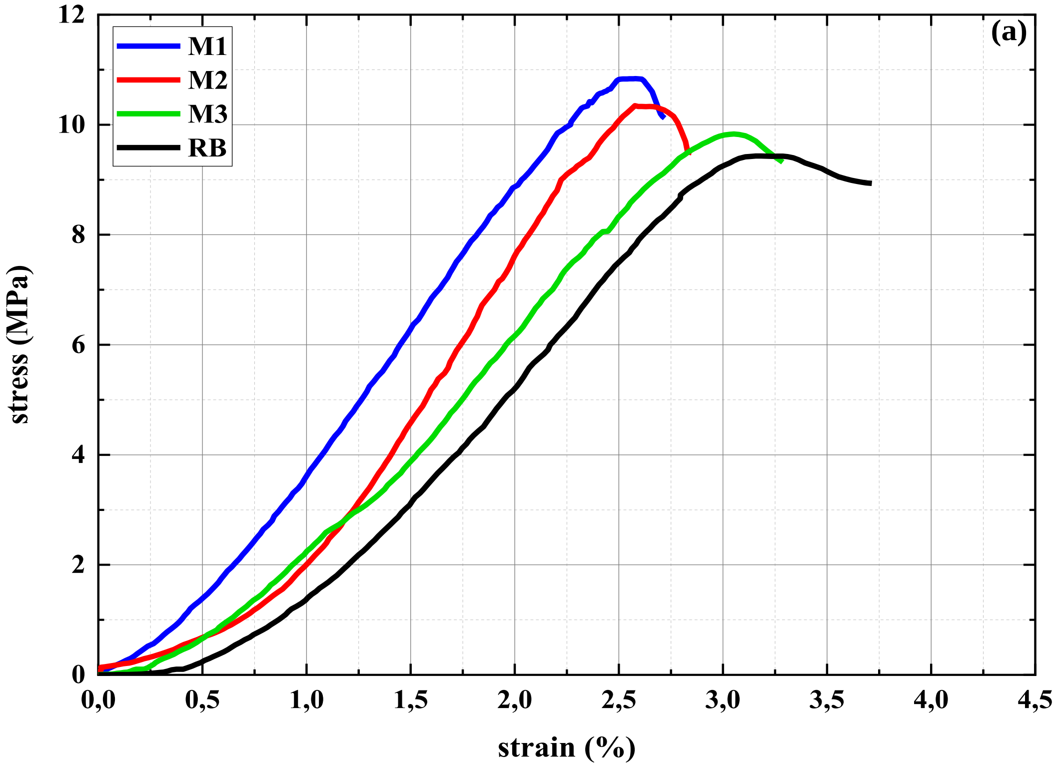
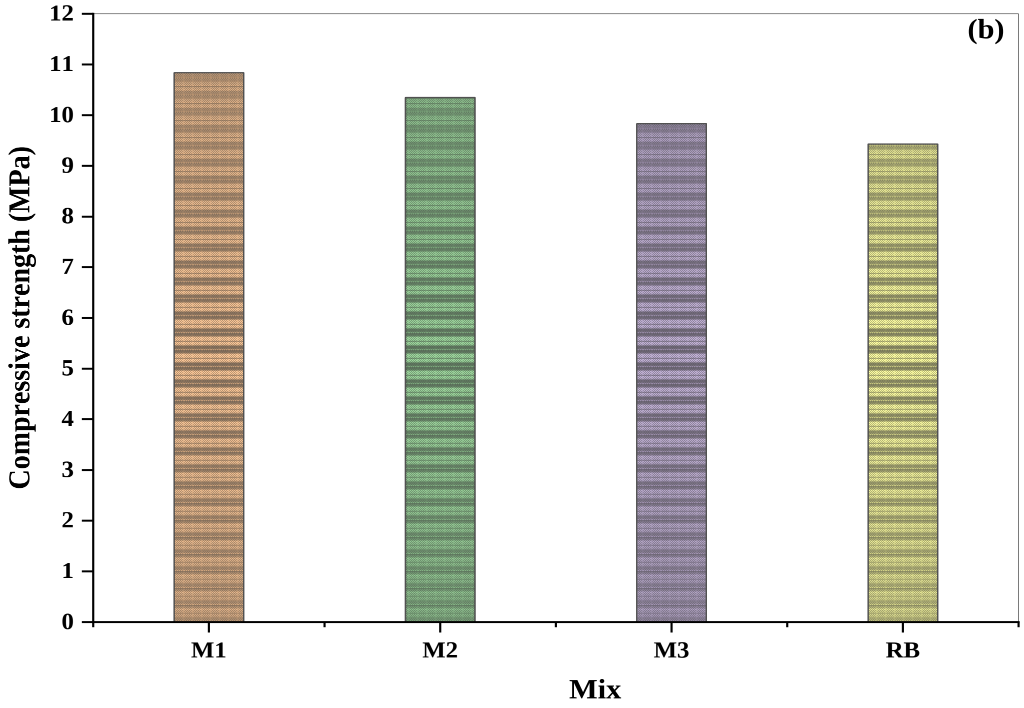


Figure III.8: Combined effect of crushed fired brick waste and dune sand on the compressive strength of adobe bricks.

III.5.2 Mechanical behavior of adobe bricks under compression

Figure III.9 and Figure II.16 illustrate the mechanical behavior of various adobe brick mixtures under compression. The mechanical behavior was investigated by examining the stress-strain curves obtained from half samples of dimensions (4x4x16) cm^3, via the three-point flexural test. As for Figure III.9, it depicts the effect of different mixtures on the mechanical behavior of the samples under compression. Additionally, Table III.1 summarizes the mechanical parameters obtained from the stress-strain curves, including the average of the maximum stress and ultimate strain, as well as the apparent modulus of elasticity. Analysis of the stress-strain curves presented in Figure III.9-a suggests that all adobe bricks exhibited quasi-linear elastic behavior, followed by a brittle failure. It was seen that strains increased as a function of the applied stress. Regarding Figure III.9-b, it shows that the maximum compressive stress values were observed in the following order: The M1 mixture came first, followed successively by the M2 and M3 mixtures. However, the minimum value was recorded for the RB. This interpretation is quite consistent with that made for the results presented in Figure III.9. Furthermore, Figure III.9-c presents the elastic modulus results of the different mixtures prepared. It was noted that the modulus of elasticity follows the same trend as the compressive strengths. It was indeed observed that the elastic modulus values varied between 225.22 MPa and 363.20 MPa, which correspond to deformations of 2.54% and 3.33%, respectively (see Table III.1). It should be pointed out that increasing the percentage of CB in the mixtures resulted in an increase in their modulus of elasticity. This increase corresponds to approximately 61.26%, 37.70%, and 17.73% for the mixtures M1, M2 and M3, respectively. According to Joshi et al. [12], this elastic modulus augmentation could primarily be attributed to the presence of a fraction of CB whose particle size is similar to that of natural sand. The elastic modulus of the mixtures M1, M2 and M3 were found to exceed those of the reference mixtures which contain 30% crushed sand and 11% lime that were examined in the study carried out by Khoudja et al. [101].





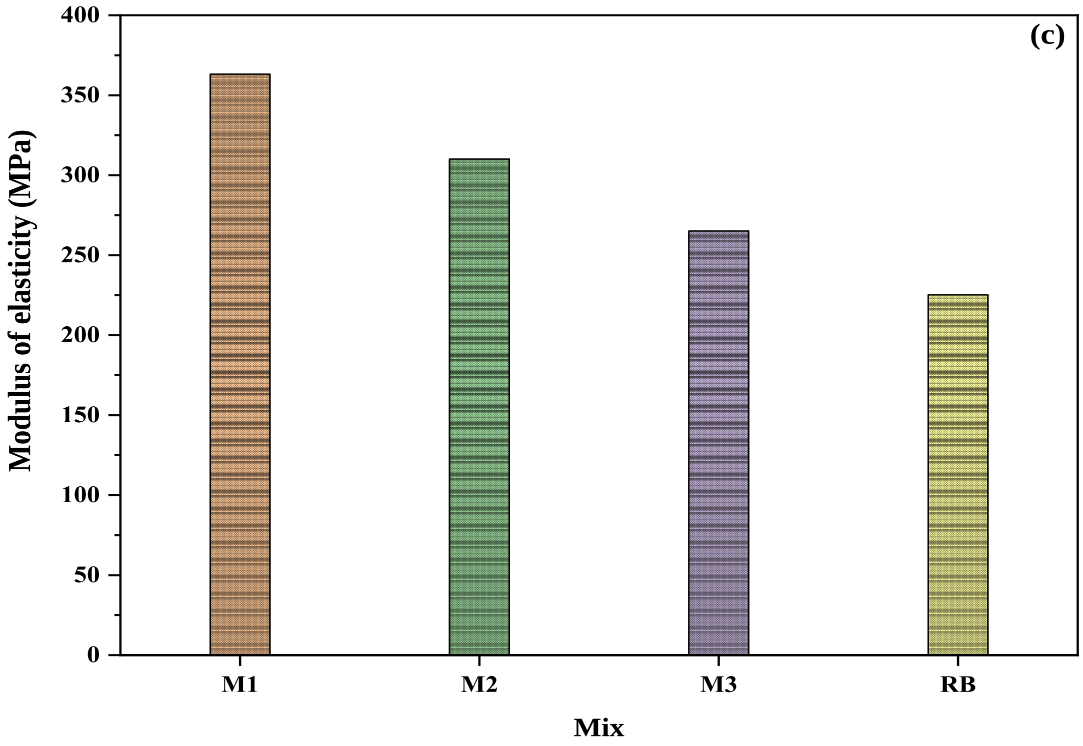


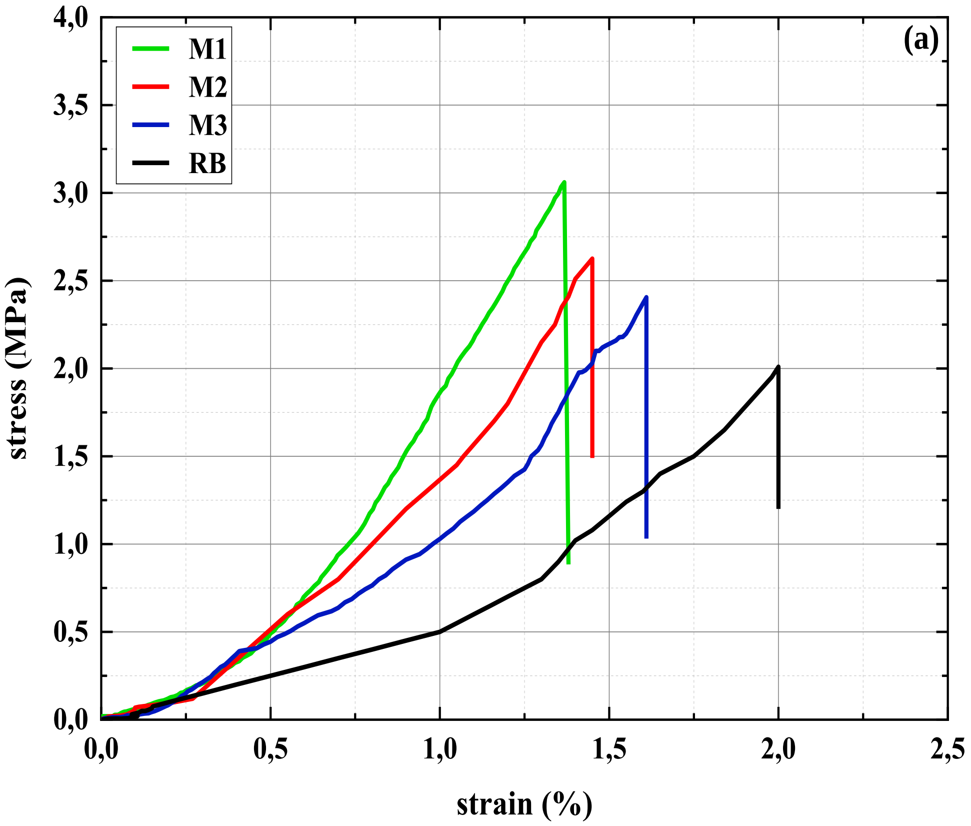
Figure III. 9: Combined effect of crushed fired brick waste and dune sand on the mechanical behavior in compressive: (a) Stress-strain curves; (b) Compressive strength; (c) Modulus of elasticity.

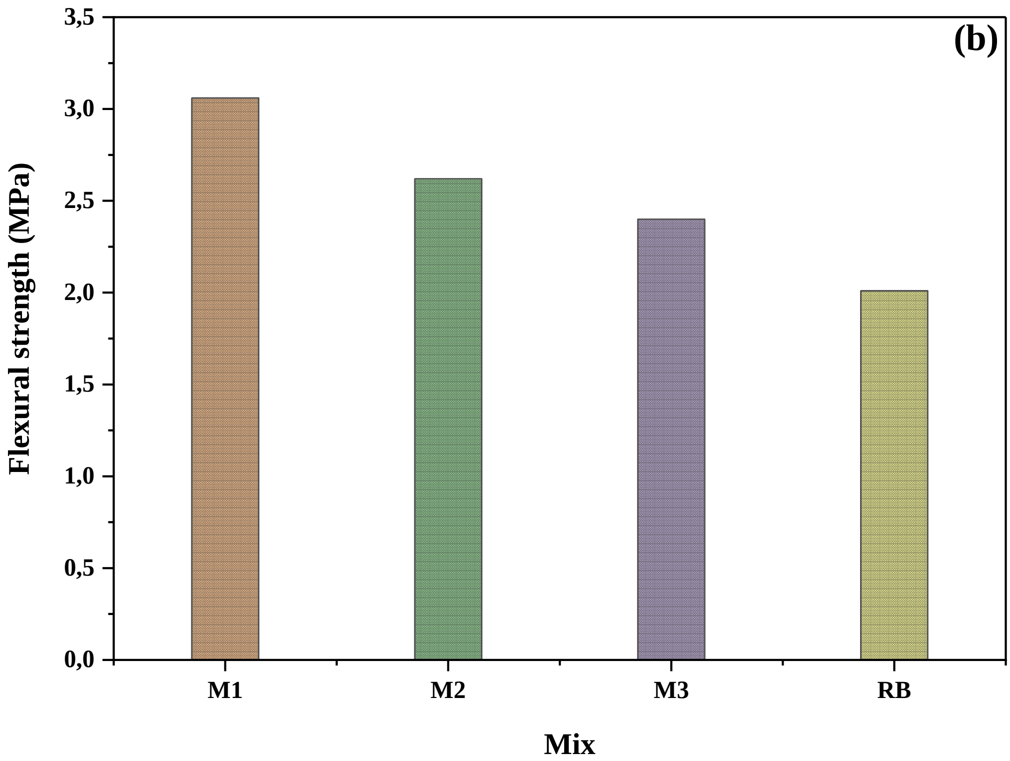
Table III.1: Compressive mechanical parameters.

Mixture	Compressive strength (MPa)	Apparent modulus of elasticity (MPa)	Ultimate strain (%)
M1	10.83	363,20	2.54
M2	10.34	310,13	2.58
M3	9.83	265,16	3.05
RB	9.43	225,22	3.33

III.5.3 Mechanical behavior of adobe bricks under flexural

The three-point flexural test was carried out in order to determine and analyze the mechanical characteristics of adobe bricks of dimensions (4x4x16) cm^3 that were manufactured with the different mixtures presented in Figure. II.17. Regarding Figure III.10, it shows the way the various mix combinations may affect the flexural mechanical characteristics of adobe bricks. Close examination of Figure III.10-a clearly indicates that the RB, as well as the other bricks, exhibited an essentially linear elastic behavior until reaching the maximum load, after which a sudden rupture occurred. It was also noted that the combination of fired brick waste and dune sand led to an increase in flexural strength, as compared to the RB, as presented in Figure III.10-b and Table III.2. This increase was of the order of 52.23%, 30.34%, 19.4% for mixtures M1, M2 and M3, respectively, in comparison with RB. On the other hand, it was observed that the ultimate deformation of the bricks under study decreased as the percentage of crushed brick waste (CB) increased, which explains the increase in the fragility of bricks as the CB content went up. Figure III.10-c and Table III.2 present the results relating to the modulus of elasticity, for the different mixtures. It is noteworthy that the trend seen for the modulus of elasticity is similar to those observed for the compressive and flexural strengths. The values of this modulus were found to fluctuate between 490.25 MPa and 380.63 MPa. Increases of about 28.79%, 23.30% and 11.83% were observed for mixtures M1, M2 and M3, respectively, in comparison with that of RB.


(a)
M1
M2
M3
RB
stress (MPa)
strain (%)
4,0
3,5
3,0
2,5
2,0
1,5
1,0
0,5
0,0
0,0
0,5
1,0
1,5
2,0
2,5


(b)
Flexural strength (MPa)
3,5
3,0
2,5
2,0
1,5
1,0
0,5
0,0
M1
M2
M3
RB
Mix

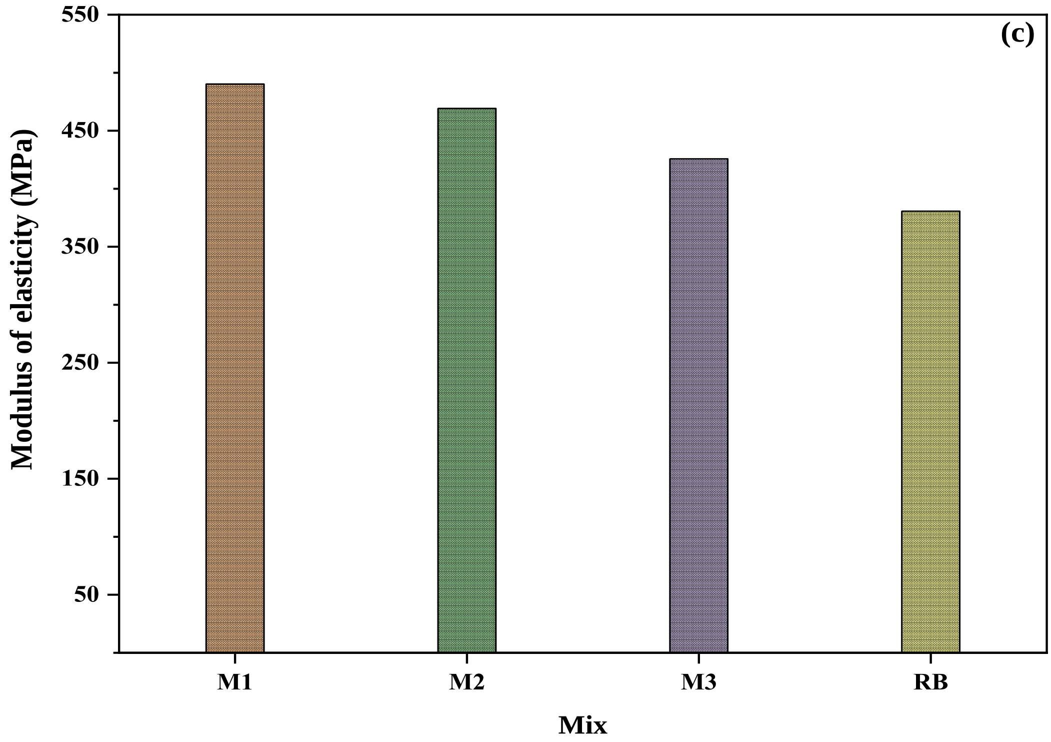


Figure III. 10: Combined effect of crushed fired brick waste and dune sand on the mechanical behavior in flexural: (a) Stress-strain curves, (b) Flexural strength and (c) Modulus of elasticity.

Table III.2: Flexural mechanical parameters.

Mixture	Flexural strength (MPa)	Apparent modulus of elasticity (MPa)	Ultimate strain (%)
M1	3.06	490,25	1.38
M2	2.62	469,23	1.45
M3	2.40	425,69	1.61
RB	2.01	380,63	2.00

III.6 Thermal conductivity

Figure III.11 illustrates the variation in thermal conductivity (TC) for the different mixtures. It is worth mentioning that the presence of CB and DS in the bricks incorporating raw earth and lime resulted in increases in TC. It was found that the thermal conductivity of the M1, M2 and M3 mixtures increased, respectively, by 23.20%, 16.66% and 11.11%, with respect to that of RB whose thermal conductivity is equal to 0.54 W/m.C°. This increase may be explained by the fact that the porosity of the BR is higher than that of the M1, M2 and M3 mixtures. It was also revealed that the porosity factor does affect the thermal conductivity (TC) of the samples, because closed pores reduce the TC, due to the low thermal conductivity of air[102]. Finally, Figure III.11 clearly shows that the thermal conductivity follows the same trend as the direction of the apparent density and ultrasound propagation speed.

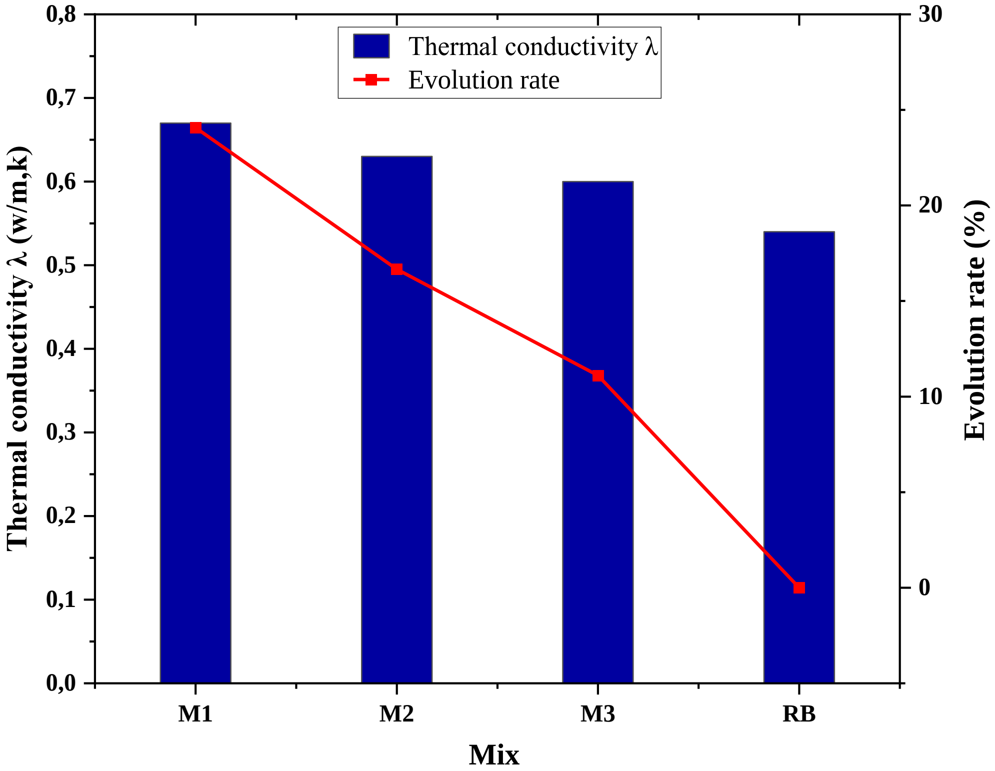


Figure III.11: Combined effect of crushed fired brick waste and dune sand on the thermal conductivity of adobe bricks.

III.7 Conclusion

A comprehensive experimental study was conducted to assess the impact of incorporating crushed brick waste and dune sand as replacements for the soil-sand mixture on the physico-mechanical, thermal, and durability properties of earthen bricks. Additionally, microscopic analyses were also conducted. This study was carried out in three phases:

- First phase: Effect of lime dosages and curing time on the mechanical strength of adobe.
- Second phase: Effect of different sand types on the mechanical strengths and water absorption
-Third phase: Combined effect of crushed fired brick waste and dune sand on physical characteristics and thermal proprieties.

The following conclusions were drawn from the experimental results:

- Findings of this experimental study showed that an optimal compressive strength level could be achieved for adobe bricks prepared with a lime percentage equal to 10%.
- Incorporation of 40% CB resulted in significant improvement in the compressive and flexural strength. The increases were estimated at 80.86% and 91.54%, respectively. Furthermore, close examination of the results obtained with conventional sands, such as RS and CS, suggests that these types of sand can be advantageously replaced by brick waste for the purpose of improving the strengths of the bricks under study. In addition, it was found that, with the incorporation of CB, the total and capillary absorption increased and exceeded those of RB.
- A slight strength increase was observed with the incorporation of 20% DS, which is not the case for the other types of sand. Addition of 20% DS to the mixtures resulted in a decrease in the T_A and C_b. These decreases were estimated at 34.75% and 24.74%, respectively.
- Incorporation of CB and DS during the adobe bricks preparation process helped to decrease voids in the matrix, which improved the bricks' characteristics in general, notably their physical characteristics, as the SEM technique indicated. Moreover, the apparent density, incorporating the M1 mixture (30CB+10DS), were improved by 16.65%, thus leading to an increase of approximately 14.63% in the propagation speed of ultrasonic waves.
- With regard to the M1 mixture, it increased the compressive and flexural strength of bricks by 71.75% and 52.23%, respectively, as compared to the RB. It was also noted that the elastic modulus significantly increased by 83.4% in compression and 52.23% in flexion.
- Combining CB with DS adversely impacts the thermal insulation of adobe bricks, leading to a 23.20% increase in thermal conductivity compared to reference adobe bricks. Nevertheless, these conductivity values remain relatively low when compared to other materials like fired brick and concrete.

Chapter IV

Influence of the combination of brick waste and dune sand on the durability of adobe

IV.1 Introduction

In this chapter, the aim is to understand the impact of combining fired brick waste and dune sand on the durability of adobe bricks. Guettala et al. [92], demonstrated that laboratory durability testing conditions for compressed earth blocks (CEB) appear to be much harsher than natural climatic conditions. Indeed, this study includes durability tests such as total absorption, capillary absorption, erosion, abrasion, wetting-drying cycles, and exposure to external sulfates. The results of these tests are analyzed to determine the most effective mixture to achieve the target properties of adobe bricks. Figure III.1 depicts the proportion of the mixture examined in this chapter, along with the durability tests carried out on the adobe bricks.

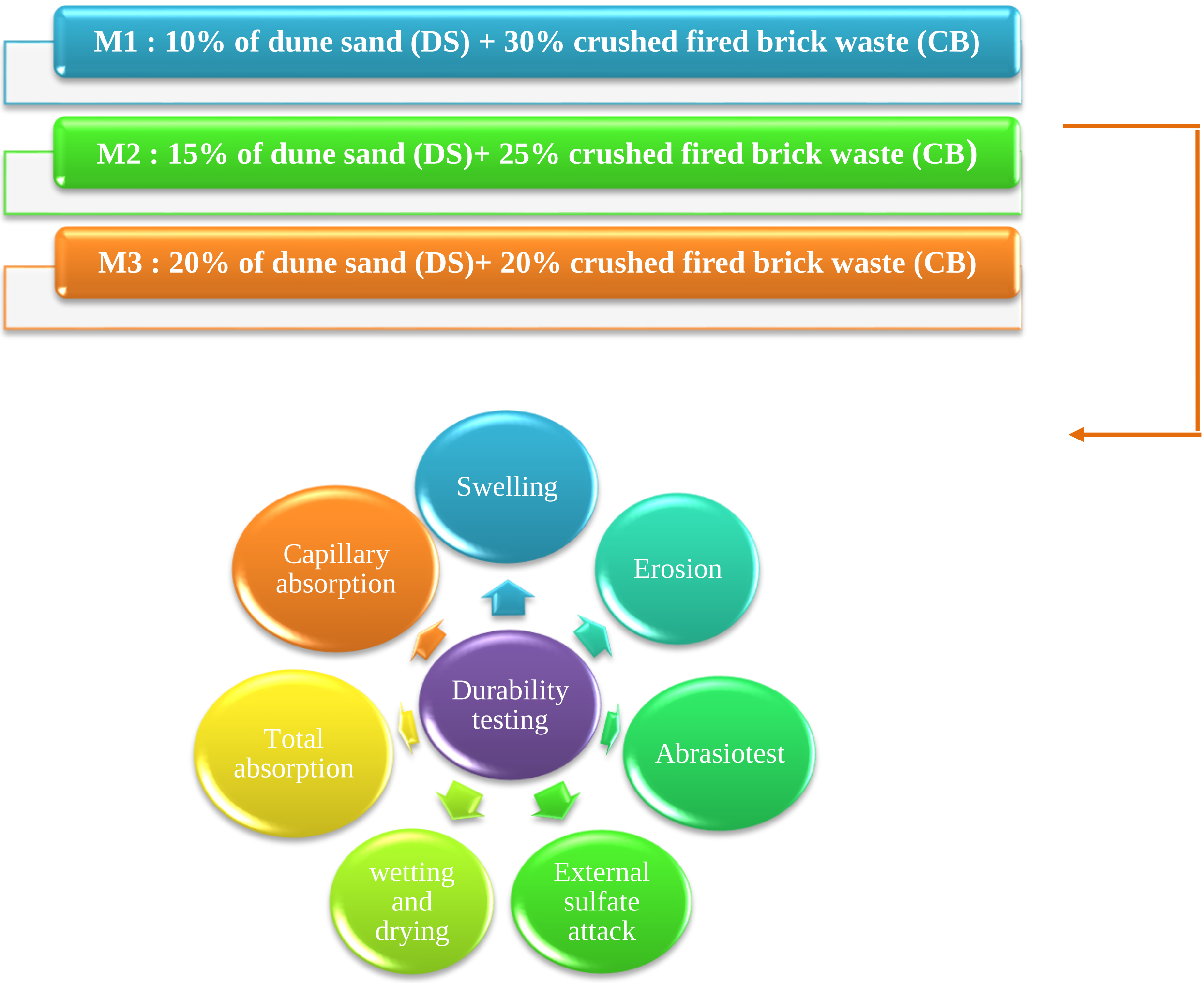


Figure IV.1: Experimental program.

IV.2 Combined effect of crushed fired brick waste and dune sand on durability of adobe bricks

IV.2.1 Total absorption

The total absorption (T_A) of the different mixtures was measured and the results obtained are presented in Figure IV.2 which explicitly shows that the water absorption decreases with increasing DS rate. It was also seen that the T_A of mixtures M1, M2, and M3 decreased by approximately 9.30%, 15.13%, and 25.66%, respectively, with respect to that of RB. This could be attributed to the progressive reduction of soil in the mixtures following its replacement by the combination of CB and DS. It should also be remembered that the absorption capacity of DS is lower than those of soil and CB, as illustrated in figure III.7. It is also worth emphasizing that the maximum water absorption value of 13.36 % was recorded for the M1 mixture. In addition, the Australian Standard proposed by Walker.[99] indicates that the water absorption capacity of bricks must be below 20%. Fortunately, the total absorption values of all mixtures tested in the present work turned out to be below this threshold percentage.

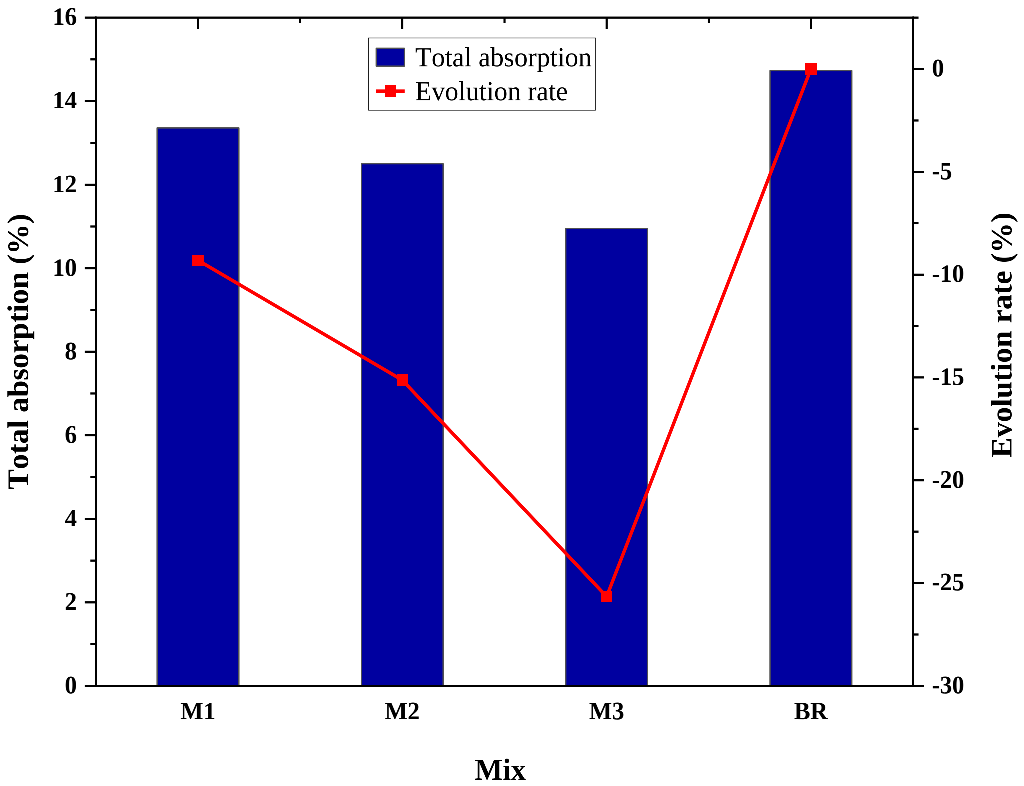


Figure IV.2: Combined effect of crushed fired brick waste and dune sand on the total absorption of adobe bricks.

IV.2.2 Capillary absorption

The results of the capillary absorption test are illustrated in Figure IV.3, It is easily noticed that the M3 mixture presents the lowest absorption coefficient C_b value which is equal to 5.81 g/cm^2.s^{-1}; it is 22.84% lower than that of RB. It should be noted that this C_b is more than twice that found for adobe brick containing 30% crushed sand. This result is similar to that found in the study conducted by Khoudja et al. [101], Similar to the total absorption, it was noted that the coefficient C_b decreased as the quantity of brick waste replacing dune sand increased. In this analysis, the C_b values can be considered as representing low capillarity, which is consistent with the recommendations of Standard XP P 13-901 [93] which requires C_b values less than 20.

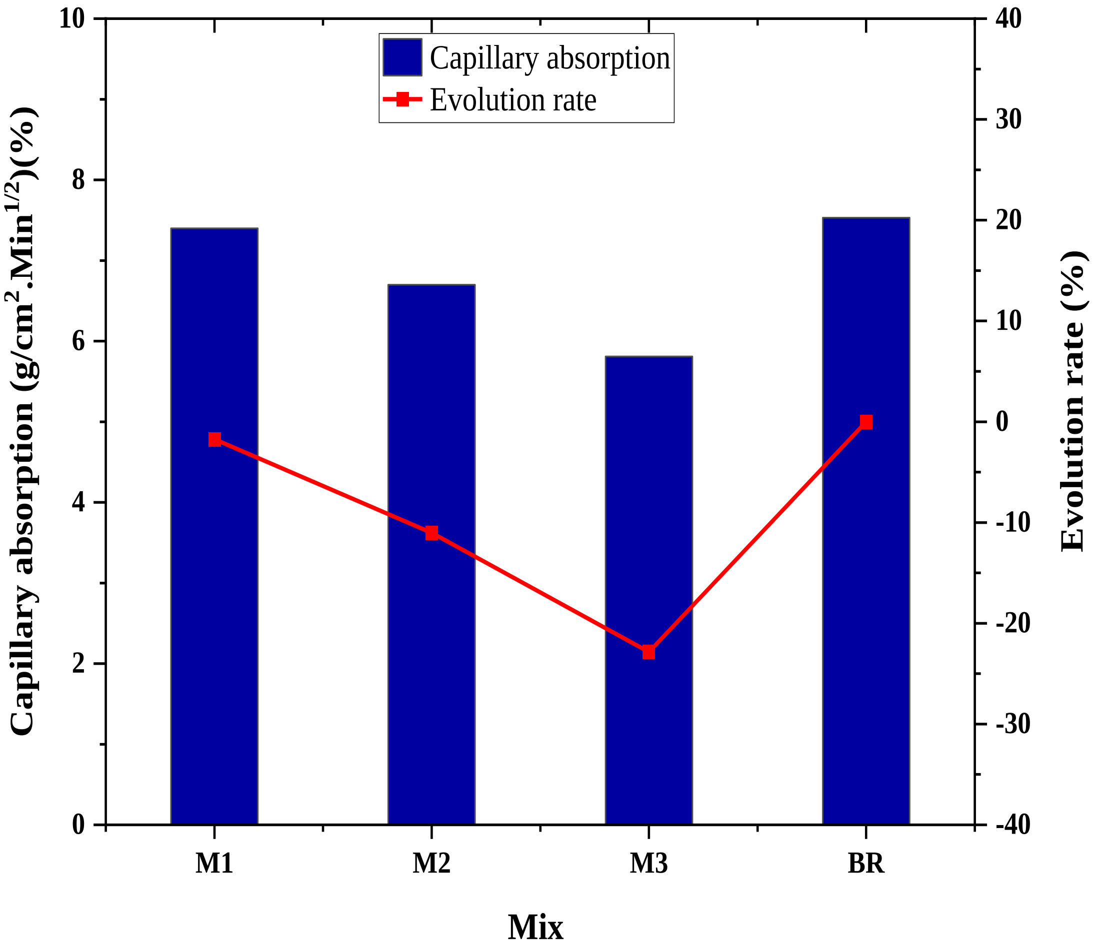


Figure IV.3: Combined effect of crushed fired brick waste and dune sand on the capillary absorption of adobe bricks.

IV.2.3 Erosion resistance test (ER)

Heathcote [103] highlighted that two primary factors greatly influence the degree of surface erosion in earthen walls: the kinetic energy of raindrops and the moisture content of the wall. Higher moisture content reduces the internal cohesion of the wall material, rendering it more vulnerable to erosion from rainfall. Consequently, a brief but intense rainfall has a lesser erosive effect compared to prolonged rainfall, even if the quantity of rainwater is the same. Figure IV.4 illustrates the variation of erosion rate (ER) according to the content of fired brick waste (CB) and dune sand (DS) in the mixture. The results obtained indicate that as the content of CB increases in the mixture (CB and DS), the erosion depth decreases. According to the New Zealand standard NZS [104], bricks (BR) exhibit erosion depth values classified in class 3, indicating susceptibility to erosion. However, the bricks M1, M2 and M3 display erosion depth values lower than those defined by class 3, suggesting that these bricks are slightly erosive. These findings underscore the fact that the combination of CB and DS in earthen bricks enhances their resistance to erosion, thereby aligning them with the requirements of the New Zealand Standard [104] for adobe bricks construction (see Table IV.1).

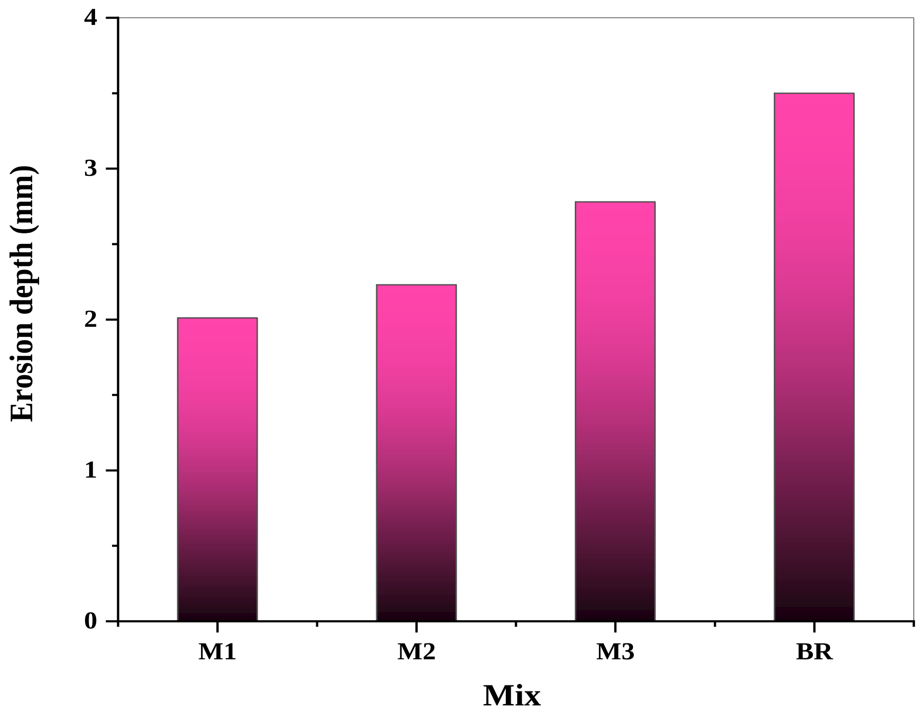


Figure IV.4: Combined effect of crushed fired brick waste and dune sand on the erosion resistance of adobe bricks.

Table IV.1 : Class of erodibility index

Class of erodibility Index	Depth of Pitting d (mm)	Note
3	3<***d***< 5 erosive	Erosive
4	5 <***d***< 10	Very erosive
5	> 15	Failed the test

IV.2.4 Abrasion resistance

This test aims to subject adobe bricks to mechanical erosion applied by friction from a metal brush at a constant pressure over a certain number of cycles. The abrasion resistance test illustrates the erosion of bricks under the abrasive action of wind. The results shown in Figure IV.5 highlight the positive effect of adding varying proportions of waste fired brick and dune sand on abrasion resistance. The abrasion coefficient (Ça) of the bricks was observed to surpass the recommended threshold of 5 cm^2/g [74] as noted. However, the RB does not surpass this value.

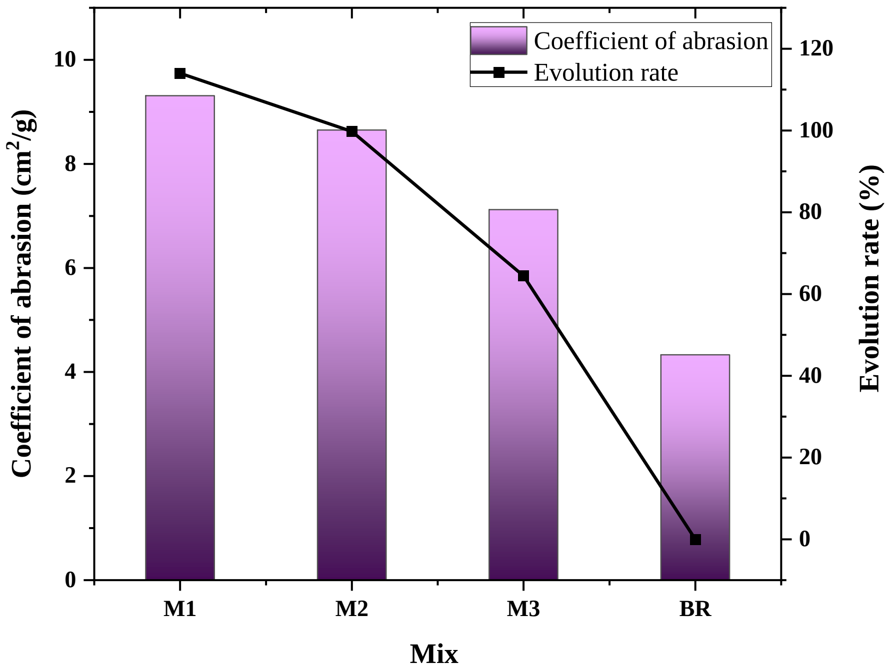


Figure IV.5: Combined effect of crushed fired brick waste and dune sand on the abrasion resistance of adobe bricks.

Increasing the quantity of waste fired brick is accompanied by a general increase in abrasion resistance. The increase in abrasion resistance (compared to RB) for M1, M2, and M3 is 115.01%, 99.76%, and 64.43% respectively. This increase is explained, on one hand, by the apparent densities of adobe bricks incorporating waste fired brick with dune sand, which are higher than those of raw earth, and on the other hand, by the formation of new C-S-H hydrates after the addition of waste fired brick, leading to a reduction in porosity. Figure III.7 also presents SEM-EDX images of the different mixtures, showing that the structure of mixture M1 is denser than that of RB and the mixtures M2 and M3.

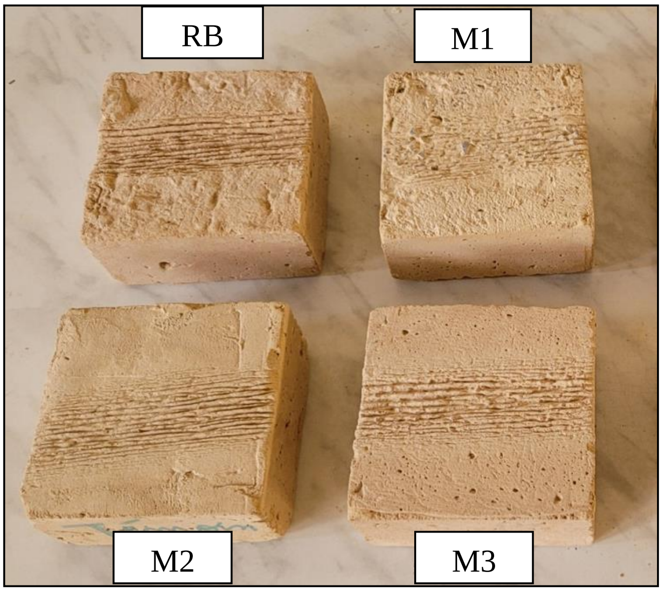


Figure IV.6: The mass loss of RB, M3, M2, and M3.

IV.2.5 Swelling

Swelling is a clear indicator of building degradation, especially in semi-arid climatic regions similar to our study area (Benyahia et al.[105]). Figure IV.7 illustrates the swelling variation of adobe bricks immersed in water for mixtures M1, M2, M3, and reference blocks (RB). The swelling variation ranges from 1.14% to 2.73 %, the results indicate a reduction in swelling (compared to RB) for M3, M2, and M1, with values of 58.24%, 43.22%, and 30.76% respectively. This could be attributed to the gradual reduction of soil content in the mixtures due to its replacement with the CB and DS combination, It has been observed that the swelling increases with the increase in the proportion of brick waste in the mixture (brick waste + stabilized soils). This increase is attributable to the high water absorption capacity of adobe brick waste. A similar observation was made by Joshi et al.[12] in their study on the incorporation of fired brick waste in the stabilization of adobe bricks.

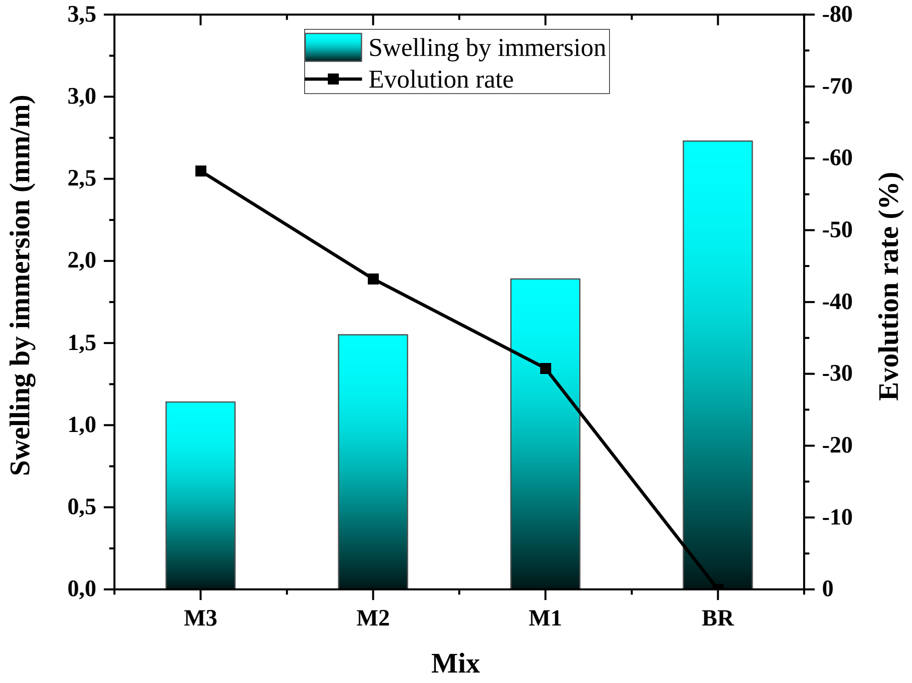


Figure IV.7: Combined effect of crushed fired brick waste and dune sand on the abrasion resistance of adobe bricks.

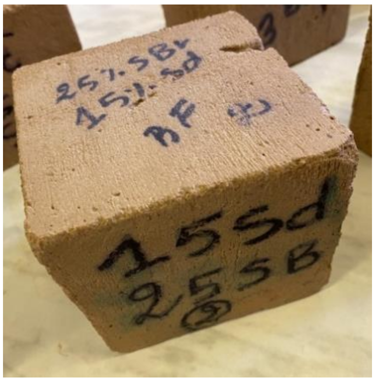
IV.2.6 Wetting and drying

The weight loss of bricks for different mixtures during each wetting-drying cycles is presented in **Figure III.10**. The results obtained reveal that cracks begin to form on the reference brick as early as the first three cycles of wetting-drying, and this deterioration worsens significantly by the fourth wetting-drying cycle, as illustrated in **Figure IV.8**. However, the addition of CB and DS appears to have a positive impact on the durability of the bricks against wetting-drying cycles. The visual appearance of samples after completing 12 wetting and drying cycles is shown in **Figure IV.9** based on these images, mixtures M1, M2, and M3 exhibit sharp angles and fewer broken edges.

Cycle 1 **Cycle 2**

Cycle 3 **Cycle 4**

Figure IV.8: The mass loss of RB.



M3 **M2** **M1**

Figure IV.9: The mass loss of M3, M2, and M1 in cycle number 12.

As shown in **Figure IV.10**, weight loss increases with the increasing number of cycles. Nevertheless, this weight loss decreases with the decrease in CB content. After 12 wetting-drying cycles, this mass loss reaches approximately 5.17 %, 4.65%, and 4% for blends M1, M2, and M3 respectively. The loss of mass resulted from the separation of soil particles under the interstitial pressure of water following immersion and brushing. Additionally, the elevated water absorption of crushed brick waste induces more significant swelling during wetting and drying, consequently causing increased mass loss. These observations correspond with the mass losses emphasized in [13, 61]. The weight loss of mixtures M1, M2, and M3 exceeds the specified 3% limit value according to IS 1725 [91]. However, these values are lower than the maximum 10% value recommended for dry climates by ASTM D559-96 [106].

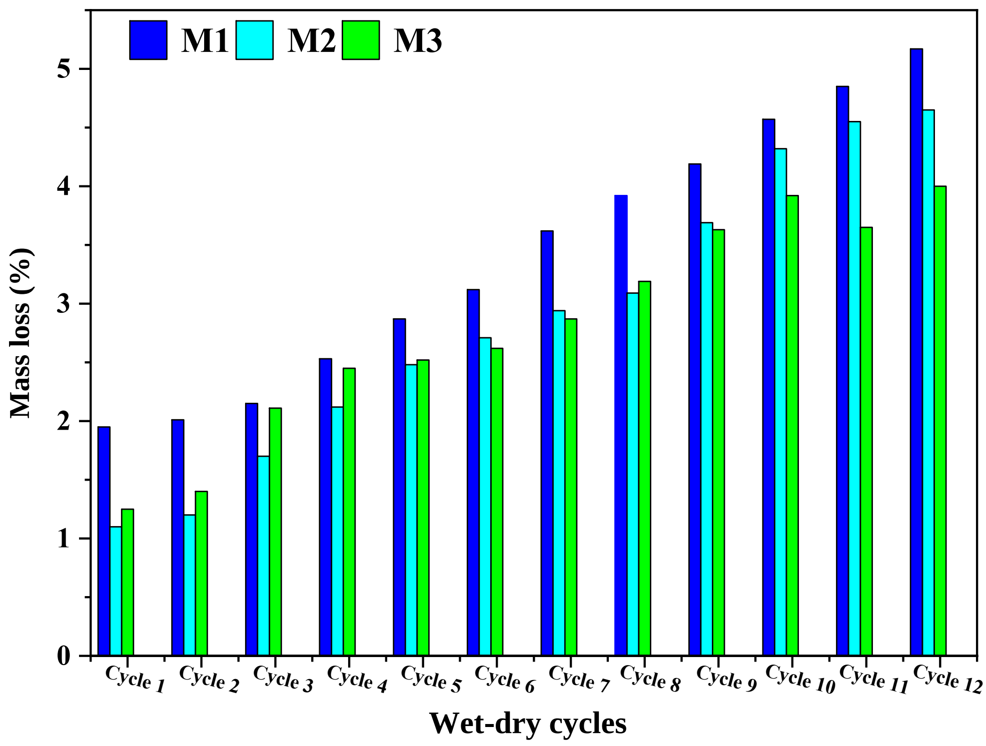


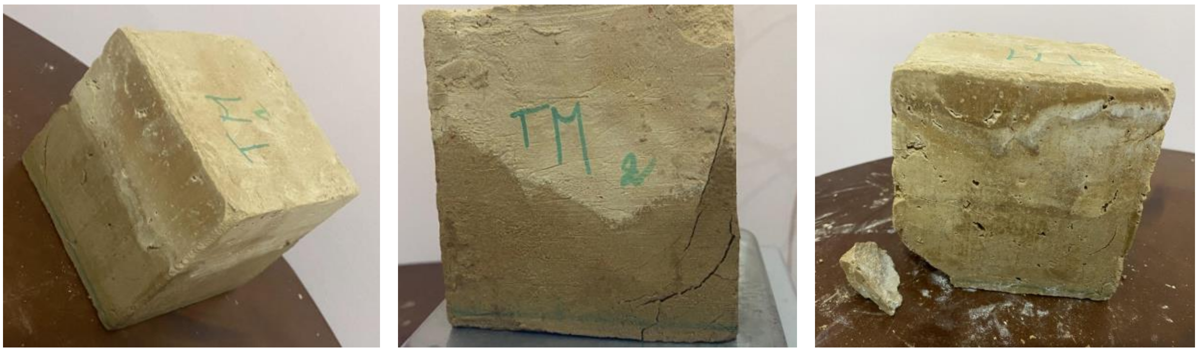
Figure IV.10: Variation of mass loss of different mixture M1, M2, M3 and RB.

IV.2.7 External sulfate attack

Sulfate is commonly found in soils, seawater groundwater, industrial effluents, acid rain, or in the air, and can cause damage under cyclic wet-dry conditions [107].

The natural occurrence of sulfate concentrations varies, ranging from 0.015% to 1% in water bodies, 0.0003–2% in groundwater, and approximately 0.26% in seawater [84],[85]. However, at these concentrations, the failure of tested materials may take several years to occur. Therefore, concentrations of 5%, was selected for accelerate the sulfate attack of samples.

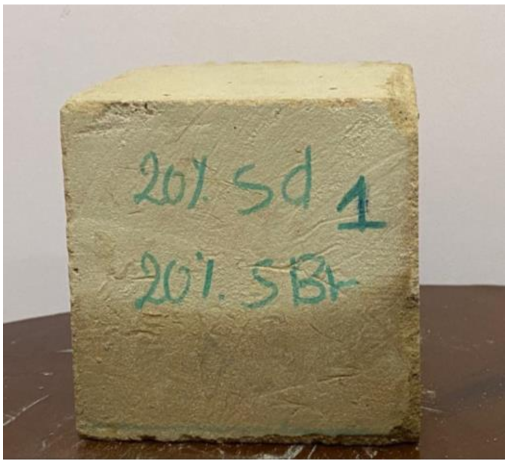
At the end of the capillary absorption and drying phases, the samples were weighed and photographed to assess the wear caused by the sodium sulfate solution. Failure of blocks was defined by the occurrence of intense spalling or cracking, Visual appearance of reference bricks after sulfate attack is shown in Figure IV.11, Visible damage and spalling was observed on the bricks from the initial days of exposure to the acidic environment. This phenomenon is frequently associated with the formation of significant ettringite crystals, which fill the pores and consequently lead to an increase in the mass of reference bricks. However, for bricks produced with crushed brick waste and dune sand (M1, M2 and M3), no sign of damage and efflorescence was observed in first cycle of capillary absorption (Figure IV.12). The tested bricks failed after six cycles, as evidenced by the visual appearance of the mixture, which showed a layer of efflorescence developing on the sides and faces of the bricks, as depicted in Figure IV.13.



1 day **2 days** **3 days**

Figure IV.11: Visual appearance of reference brick (RB) of exposure of acid attack.

M1 **M2**



M3

Figure IV.12: Visual appearance of mixture after one cycle of exposure of acid attack.

M3

M2

M1

Figure IV.13: Visual appearance of mixture after six cycles of exposure of acid attack.

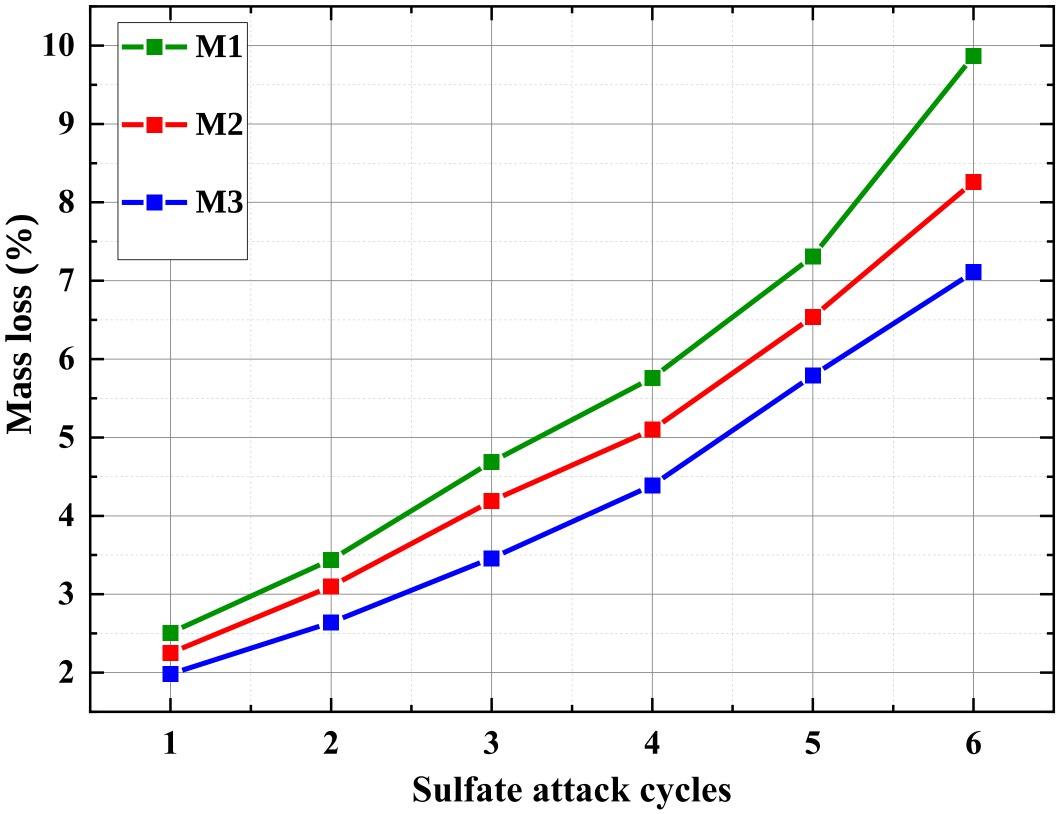


Figure IV.14: loss of mass over time of a different mixture (M1, M2, and M3).

The impact of acid attack on adobe bricks was also analyzed in terms of mass loss. The changes in mass loss results for different mixtures (M1, M2, and M3) after exposure to acid attack for varying cycles are illustrated in Figure IV.14. From the graph, it is evident that the mass loss of the bricks decreases with duration of exposure for all mixtures. Furthermore, the mass loss increases with the inclusion of CB in the mixture (CB+DS). The lowest mass loss, recorded at 7.11%, is observed in mixture M3 after six cycles of exposure to sulfate attack. Similar patterns were observed in a study conducted by Kasinikota and Tripura [13], on compressed earth blocks. They replaced sand-soil with crushed fired waste, observing the positive impact of crushed fired bricks on the blocks' resistance to sulfate attack.

IV.3 Conclusion

An exhaustive experimental study was undertaken to assess the impact of crushed brick waste mixed with dune sand as a replacement for the soil-sand mixture on the durability of adobe bricks. The following conclusions are drawn from the experimental results:

- The M3 mixture (20CB+20DS) contributed to reducing the total water absorption and capillary absorption of the reference bricks by 25.66% and 22.84%, respectively.
- The bricks M1, M2 and M3 display erosion depth values lower than those defined by class 3, suggesting that these bricks are slightly erosive. However, the reference bricks are classified as Class 3, indicating that these bricks are erosive.
- A significant increase in the abrasion coefficient is observed for bricks M1, M2, and M3, with respective increases of 115.01%, 99.76%, and 64.43% compared to the reference brick.
- Immersion swelling decreases with decreasing CB dosage in the (CB+DS) mixture. The lowest swelling value, reaching 1.14mm/m, is observed for M1.
- The inclusion of CB and DS seems to enhance the resilience of the bricks to wetting-drying cycles. Among the mixtures tested, M3 exhibits the low mass loss after 12 cycles or wetting-daring. The mass loss occurred due to the disintegration of soil particles under the pressure of water filling the gaps between them during immersion and brushing. Conversely, RB shows signs of deterioration after just three cycles of wetting-drying.
- The reference bricks deteriorate after the first cycle in a sulfate environment. In contrast, lime-stabilized adobe bricks incorporating fired brick waste and dune sand withstand this environment well. Mass losses range from 7.11% to 9.87%.

General Conclusion

General conclusion

Since ancient times, bricks have been used in construction in the form of raw and fired bricks. Today, bricks are widely recognized as one of the primary building materials. Despite the prevalence of fired bricks over traditional bricks, their production requires significant energy consumption. Particularly in developing countries like Algeria, reliance on fired bricks for affordable housing leads to unsustainable development. With the advent of modern construction materials such as concrete and steel, the use of earth construction has declined. However, it has been estimated that over two billion people currently live in earth-built houses worldwide. Today, in response to growing concerns about environmental degradation and energy consumption associated with industrialized materials, earth construction is once again garnering attention as a sustainable building material.

One primary contribution involves the development of new local materials for construction. The natural sands traditionally used in adobe brick manufacturing are replaced by waste from fired bricks obtained during their production stages, as well as dune sand, widely available in the Sahara and extracted at almost no cost. This substitution aims to produce adobe bricks with acceptable strength and durability performance. Economically, the use of these materials helps reduce the quantity of high-energy-consumption materials, which represent a high cost each year during their production, such as cement-based concrete or fired clay bricks. Additionally, from an environmental perspective, this helps reduce carbon dioxide emissions and waste stockpiling.

The use of the studied material in housing construction depends on its ability to meet construction requirements, particularly in terms of adequate mechanical properties and durability. The findings of this study can be summarized as follows:

Incorporating 40% of fired brick waste (CB) can replace conventional sands such as crushed sand and river sand in terms of mechanical strength. These findings were also confirmed by the mechanical strength results. However, a challenge still remains regarding the high water absorption capacity of bricks incorporating waste CB, because it exceeds that of the reference bricks. For the purpose of reducing this absorption capacity, it is highly recommended to combine brick waste with dune sand which is known for its water absorption capacity than is lower than that of soil and CB.

The mixture M1 (30% CB + 10% SD) provides the best values for the apparent density of adobe bricks, resulting in an increase in the propagation speed of ultrasonic waves. Additionally, the compression and flexural strength reach 7.54 MPa and 3.06%, respectively. This developed material can be used in the construction of load-bearing walls without significant risks of destruction, thus meeting the requirements for mechanical strength.

Combination of CB with DS led to a slight increase in the thermal insulation of adobe bricks as their thermal conductivity increased by 23.20% with respect to that of adobe bricks stabilized with lime only. But this slight loss of thermal insulation capacity seems very small, compared to the other gains obtained for the other studied characteristics.

Regarding the durability of adobe bricks, the combination of CB and SD has a positive effect. The mixture M1 (30% CB + 10% SD) exhibits the best performance in terms of erosion and abrasion. However, the mixture M3 (20% CB + 20% SD) shows the lowest values regarding total and capillary absorption, as well as swelling and weight loss during wetting-drying cycles and cycles of external sulfate attack.

Drawing from the findings mentioned above, this study introduces an innovative solution to enhance the mechanical proprieties and durability of lime-stabilized adobe materials by incorporating crushed fired brick waste and dune sand. Embracing this approach would undoubtedly promote the construction of durable mud housing on a large scale, potentially addressing the critical housing shortage, especially in poor nations.

Further Works

Further Works

- Study the effect of groaned granulated powder of dune sand on the physical, mechanical characteristics, and durability of lime-stabilized adobe bricks.

- Study the effect of finely groaned granulated of crushed fired brick waste on the physical, mechanical characteristics, and durability of lime-stabilized adobe bricks.

- Modeling and simulation of the behavior of building walls built with adobe bricks incorporating crushed brick waste and dune sand.

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List of scientific publications

List of publications and communications

International Journal Papers

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Ferdous Bezaou, Ouarda Izemmouren, Salim Guettala. (2024) ‘’Combined impact of dune sand and crushed brick waste on the characteristics of raw earth bricks.’’ *Studies in Engineering and Exact Sciences*, 5. (1), 1335-1362.

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2023

Ferdous Bezaou, Ouarda Izemmouren, Salim Guettala.‘’Mechanical properties and hygroscopicity behavior of unfired brick incorporated fired brick waste ‘’. *The First International Conference on Materials Sciences and Applications (hybrid) ICMSA*, February 08th and 09th 2023,Khenchela, Algeria.

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Ferdous Bezaou, Ouarda Izemmouren, Salim Guettala. ‘Study Of The Physical-mechanical Properties Of Compressed Earth Blocks Based On Aggregates ‘’.*1st International Conference on Scientific and Innovative Studies*,18-21 April, 2023, Konya, Turkey.

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2023

Ferdous Bezaou, Ouarda Izemmouren. ‘’A review on the use of natunal waste in stabilizing adobe bricks ‘’.*1st national conference on advanced materiels and thier application NCAMA’23*,18-19 0ctober 2023, Tipaza, Algeria.