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THE THERMAL COMFORT OF EARTH BUILDING: MODELING OF THERMAL BEHAVIOR OF COMPRESSED EARTH BLOCK DEPENDING ON BOTH OF CEMENT CONTENT AND WATER CONTENT

JURY

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Résume

Afin d'assurer un confort thermique de qualité dans les bâtiments en terre, une attention particulière doit être portée au type de matériau à utiliser ainsi qu'à ses performances thermiques et son évolution avec l'ajout de ciment et la présence d'eau dans le matériau.

Les travaux de recherche menés dans le cadre de cette thèse proposent des techniques et des procédés pour une meilleure compréhension du comportement de la conductivité thermique vis-à-vis de la teneur en ciment, de la teneur en eau et de leur interaction, afin de réduire la consommation énergétique des bâtiments en terre.

Pour atteindre ces objectifs, nous avons :

- Étudié la minéralogie et la granulométrie (distribution granulométrique) de la terre utilisée pour réaliser les échantillons de blocs de terre comprimée (CEB).
- Fourni, sur la base d'une campagne expérimentale prolongée, une analyse de conductivité thermique liée au bloc de terre comprimée stabilisée avec différentes teneurs en ciments et en eau.
- Développé et testé avec succès un modèle mathématique basé sur la méthode des volumes finis pour modéliser le transfert de chaleur à travers des échantillons de CEB avec différents teneurs en ciment et en eau.
- Proposé une validation d'un modèle Technico-Economique Optimum (TEO) pour le bâtiment en CEB en respectant les effets combinés des deux teneurs. Cet optimum est déterminé en utilisant l'évolution des propriétés thermiques du bloc de terre comprimée en fonction de la stabilisation (teneur en ciment) et de la teneur en eau (présence d'eau).

Les résultats expérimentaux et numériques montrent que la conductivité thermique évolue similairement pour les deux teneurs, en ciment et en eau. L'allure des courbes obtenues sont en S, avec un point d'inflexion qui dépend du matériau utilisé. L'ajout d'une faible teneur en ciment n'affecte pas la conductivité thermique de manière significative. Pour un contenu spécifique, proposé ici comme TEO, la conductivité augmente rapidement avant de stagner. Le TEO correspond au point d'inflexion de la courbe en S.

Mots-clés : Construction en terre, bloc de terre comprimée, Optimum technico-économique (TEO), conductivité thermique, teneur en ciment et en eau, méthode des volumes finis.

Abstract

In order to ensure a high-quality thermal comfort in the earthen buildings, special attention should be given to the type of material to use as well as to its thermal performance and its evolving with cement adding and the presence of water in the material.

The research work carried out as part of this thesis proposes techniques and processes for a better understanding of thermal conductivity with respect to cement content, water content and their interaction improvement in order to reduce energy consumption of earth building.

To reach this aim, this research work:

- Studied both the mineralogy and the granulometry (particle size distribution) of the earth being used to make the samples of compressed earth blocks.
- Provided, based on an extended experimental campaign, thermal conductivity analysis related to the compressed earth block stabilized (CEBs) with different cement and different water, contents ratios.
- Developed and successfully tested a mathematical model based on the finite volume method to model heat transfer through samples of CEBs with different ratios of cement content and water content.
- Proposed a validate a Technico-Economic Optimum (TEO) model for CEB building with respect to the combined effects of these two contents. This optimum is determined by using the evolution of the thermal properties of the compressed earth block according to the stabilization (cement content) and water content (water presence).

The experimental results as well as the numerical results show that the thermal conductivity is found to evolve in the same manner with respect to cement and water content following an S curve, with a specific-material's inflexion point. Adding a small content of cement does not significantly affect the thermal conductivity. For a specific content suggested here as a Technico-Economic Optimum the conductivity rapidly increases before being stagnated. The TEO corresponds to the S-curve inflexion point.

Keywords: Earth construction, compressed earth block, technico- economic optimum (TEO), thermal conductivity, cement and water content, finite volume method, control volumes.

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Nomenclature

Symbol	Designation	Unit
PI	Plasticity index	[%]
LL	Liquid limit	[%]
PL	Plastic limit	[%]
Ca	Coefficient activity	
MBA	Methylene Blue Adsorption of the earth	$[m^2/g]$
Sa	Surface area of the earth	$[cm^2]$
m	The mass of the test sample	[g]
m_t	The mass of the control calcium carbonate test sample	[g]
V_b	The volume released during the test on the material	$[cm^3]$
V_t	The volume of carbonate dioxide released by the control calcium carbonate	$[cm^3]$
θ_b	The temperature of the test room, when testing the material	[°C]
θ_t	The temperature of the test room, when testing on the control calcium carbonate	[°C]
ρ	The density	$[g/cm^3]$
ρ_d	Dry density	$[g/cm^3]$
Q	Heat flow	[W]
h	Convection heat-transfer coefficient	$[W/m^2]$
A	Area of the material	$[m^2]$
σ	Stefan–Boltzmann constant	$[\approx 5.67 \times 10^{-8}\ W/m^2k^4]$
ε	The emissivity of the material	
k	Thermal conductivity	$[W/m.K]$
K_C	Thermal conductivity of the material	$[W/m.K]$
α	Thermal diffusivity	$[m^2/s]$
T	Temperature	[K]
T_c	Temperature at the center of the ring	[K]
T_{int}	Initial Temperature	[K]
$\dot{Q}$	The heating power of the ring	[W]
R	Radius	[m]
R_r	The radius immersed of thin circular ring in the sample	[m]

C_p	Specific heat of the porous medium	$[J/kg.k]$
t	Heating time	$[s]$
$\dot{q}$	Heat flux	$[W/m^2]$
$\mathrm{erf}(x)$	The error function of x variable	
$\mathrm{erfc}(x)$	The complementary error functions	
m_h	Humid mass of the sample	[Kg]
m_d	Dry mass of the sample	[Kg]
L	Thickness of the layer	[m]
H	Height of the sample	[cm]
t_h	Heating time	$[s]$
t_m	Measuring time	$[s]$
r	Radial coordinate	
z	Axial coordinate	
E	East	
W	West	
N	North	
S	South	
PE, PN	The segments	
P	The main node	
i	The index of discretization along the axis of $''r''$	
j	The index of discretization along the axis of $''z''$	
k	The index of the $''t''$	
Vc	Control volumes	
W	Water content	[%]
D	Cement content	[%]
Kc	The magnitude of thermal conductivity	$[W/m.K]$
Kc_0	Value of the magnitude Kc when $D = 0$ or $W = 0$	
n, m	Degree of variation (n= m= 3 in our case)	

n', m'	Degree of variation (n', m'= 3 in our case)	
a_D	Cement saturation limit	$[W/m.K]$
b_D	Constant introduced to approach the asymptotic limit	
Kc_D	The magnitude Kc as a function of D	$[W/m.K]$
Kc_{D0}	Value of the magnitude Kc when $D = 0$	$[W/m.K]$
a_w	Water saturation limit	$[W/m.K]$
b_w	Constant introduced to approach the asymptotic limit	$[W/m.K]$
Kc_W	The magnitude Kc as a function of W	$[W/m.K]$
Kc_{W0}	Value of the magnitude Kc when $W = 0$	$[W/m.K]$
Kc_{int}	The magnitude of the interaction component between 'D' and 'W'	$[W/m.K]$
a_{DW}	The absolute saturation limit of the cement / water interaction	$[W/m.K]$
b_{DW}	The trend constant towards the saturation limit (asymptote)	
D_{TEO}	Technico-Economic Optimum of the cement content of the CEBs samples	
W_{TEO}	Technico-Economic Optimum of the water content of the CEBs samples	

General Introduction

The architect cannot build or design a good structure without understanding the relationship between human-made architecture and the natural environment comprised of vegetation, animals, microorganisms, soils, rocks, atmosphere and natural resources and physical phenomena such as air, water and climate. As there are devastating consequences of failure to consider the environmental surroundings and its ecosystem. The building must be adapted to the climate and its various elements, in the moment that the construction is completed, it becomes a part of the environment, as a tree or stone, and becomes exposed to the same effects of the sun, rain or wind like anything else exist in the environment. We need to make buildings that are friendly to the environment and greener which can be adaptable to the surroundings, in other way, we need to create buildings that are energy efficient, like green buildings or sustainable buildings which are designed to reduce the overall impact of the built environment on human health and nature. As Egyptian Architect Hassan Fathy, philosopher of architecture and engineer of the poor, he said "It is unreasonable to build an eastern house in Europe, or a European house in the Arabian desert, the nature of the local climate dictates the style of the house. It is a mistake to transfer ideas from one country to another, without any regard for climatic conditions and local social traditions.", and he said "Look at the ground under your feet, then build."

The term "green architecture" has become a popular a powerful term in the recent times, some people may think it is a new term or a modern thought that will be applied to architectural designs, it may also come to the mind of many to link the term in green color and restricted within a certain range. The green building is not a building plated by green color certainly, and not building around it a lot of the plantations and trees. Green building is a new concept called on the buildings which provides all the conditions, thermal comfort, and the possibilities to protect and strengthen the environment during the reconstruction and living in it. But what we should know is that the green architecture in its tacit concept has been applied a long time ago and since the beginning of construction. It is an instinct within all humans seeking to stay longer and seeking every method that seeks to preserve their natural sources. If we are to study some of the foundations of green architecture, such as energy conservation and reduce the consumption of existing resources, we find that the same ideas existed in the old architecture since very ancient times, we will also find the most civilizations in the architecture of history applied many of the foundations which currently exist for green architecture. This leads us to the existence of ancient ideas and foundations of green architecture seeking to preserve natural energies and respect the environment and reduce the impact of construction on them.

As environmental problems are increasing, at present, earth construction is considered a powerful alternative to modern construction techniques and has become a solution to many problems in both the industrial and the developing world. The adoption of earth architecture reinforces restores the intimate relationship between human and the environment. Earthen construction has certainly stood the test of time, but is not free of some defects, but most of the disadvantages can be avoided using modern techniques available. Earth was the most pervasive material and closer to primitive human. This material, which raised his attention and prompted him to use it and take it as a raw material for his residence. There is no doubt that the earth is the natural medium and the material that embraced the human, and the earth gave to humans all the necessary food and shelter, and derived from the human strength and confidence, and he is derived from it the strength and confidence, and it was at the same time a great comfort to the primitive human. He resorted to cavities in difficult times and adhere to them and interact with them throughout history, and from this presence and adhesion and interaction emerged the idea of using soil as a material for construction, this material is close to human, which are easily formed to response all their life needs, primarily the need to shelter and housing. Historical sources indicate that earth was the first material that was used in the field of construction, besides other materials such as stone, wood, bamboo, Reeds, and palm fronds.

For hundreds of years, the earth has been the most widely used construction material in the world, having different specifications and characteristics from among other raw materials used in the production of building materials for walls. The soil is considered a low-cost, healthy materials, environmental material and energy-saving. And on the basis of this material, many cities build by it which is still inhabited until now, it was widely used in Mesopotamia, Yemen and Egypt, and was later used by the Romans, the peoples of the Middle East, India, and the emperors of China. And during the Middle Ages, the building by earth was not only practiced in Europe but also in North America, by Indians, Mexico, and the Andes. This architecture was practiced in diverse civilizations, in Africa, such as the Berber, Hausa and other civilizations. At present, more than one-third of the world's population lives in earth houses. In any case, the archaeological remains of many cities and villages in various parts of the world are the best evidence of the importance of this material in building. The settlements, most of which are built of raw, unburned soil.

Earth is used to create a home's walls, replacing other building materials such as concrete, wood, gypsum, plaster, fiberglass, or stone. We can use earth bricks, that are considered as non-toxic, recyclable and sustainable construction materials. Moreover, you can find earth blocks easily as it can be produced locally, using some stabilizers as straw or cement to make it stronger.

Researchers believe that there is a spiritual dimension associates between human with earth, which is considered the main component of his creation, that contributed to in more adoption of this material as a major component of his architecture. And because of the earth material achieves a great deal of acclimatization and harmony between human and his biosphere, this compatibility and harmony helped the continuation of the earth architecture through the different ages. Despite, earth is among the oldest building materials in the world but it is still very popular in architecture today. The reason for the high popularity of earth building materials is in their fixed value, durability, and multiple natural resources. Also, it saves energy. This is because it does not consume energy in the manufacturing process, and because of its good insulation ability. Thus, its use also contributes to reducing environmental pollution. It can be reused at any time: it is sufficient to grind the dry clay and mix it with water in order for us to use it again. Then it is, unlike other building materials.

By returning to earth construction techniques, we seek to obtain and have an efficient and economical technique that also provides technical performance that can even compete with concrete.

The Compressed Earth Block (CEB) technique has been developed for low-cost construction, as an alternative of adobe, and with some advantages. Its evolution lies in the fact that it combines both the advantages of rammed earth and adobe.

The beauty of compressed earth block is that the main ingredient is earth, it is very abundant. It is not fired so that the unique moisture-regulating and heat-accumulating properties are preserved. The wall absorbs moisture in wet weather and gives it back when the air is dry.

CEB is a material obtained by compression of earth. The physical and mechanical properties of CEB can be improved by adding a binder to the mix, usually Portland cement, before compression, this is the stabilization process.

The objective of the present work is to be able to master CEB and optimize their thermal property of this technique with stabilization and humidity, so that it offers the most qualities and that it is at the same time as economical as possible. Where, the technico-economic optimum (TEO) is sought for the thermal property of CEB.

The first chapter of this work, green building is defined and its relationship with the environment is explained, determine its standards and mention the alternative materials used in green construction. It was also mentioned that earth material is one of the alternative materials used in green building and environmentally friendly. Some examples have also been mentioned from around the world, this collection shows naturally built homes and public buildings from different climates using earth material and building techniques. As well, presents some previous literature research by some researchers related to some kinds of earth construction and their thermal properties, with the mention of thermal conductivity measuring devices that they used in their research. Also, the results that they are obtained have illustrated with figures and tables.

The limits of their studies that they are: (i) They were not studied the coupled effect of cement and water of thermal conductivity on the samples CEBs, (II) Their focus was on experimental results and they did not use any numerical model to obtain numerical results and compare them with experimental results. The new in our study and what has been added to previous studies are: (i)The samples are chosen compressed earth blocks (CEBs), (ii) Coupled effect of cement and water of thermal conductivity on the samples, (iii) Using a modelization to predict the technico- economic Optimum (TEO) of thermal conductivity of the compressed earth block according to the coupled effects of cement content and water content, (iv) Hot ring device to measure thermal conductivity.

In the second chapter, for manufacture the compressed earth blocks, the earth is considered the main building material used to manufacture CEB which use locally available soil. So, it is necessary to select the quality of good soil suitable for the block industry. For that, gives a presentation of the earth material which constitutes the basic element of the CEB technique, as well as a presentation of the tests that the earth material undergoes. Also, the physical and mechanical properties of CEB can be improved by adding a binder to the lateritic earth, usually Portland cement, before compression followed by cleaning. This is the stabilization process. Soil stabilization can be accomplished by several methods. A variety of tests are conducted to determine the suitability of the local soil for construction material. For example, a particle determination test reveals the relative proportions of gravel, sand, silt and clay in our soil sample. The grain size distribution of soils (Granulometry) is known to be an important parameter in providing initial understanding for the physical and mechanical behavior of soils in many engineering geology applications. The study of the particle size of the studied earth is essential before concluding on its aptitude for the technique of construction in blocks of compressed earth. The sample of earth material is subjected successively on a number of sieves - conveniently chosen in terms of mesh size - from the surface with the largest holes and ending with the one with the smaller ones. The knowledge of Atterberg limits and plasticity is often used to determine the amount of silt and clay in a fine-grained soil, as plasticity generally increases with higher clay content. On the other hand, it gives important information on the mechanical performance of a soil used as foundation or construction material.

Third chapter is focused on an experimental investigation to evaluate the thermal performance of compressed earth blocks (CEBs) produced. CEBs were analyzed in terms of thermal conductivity, thermal diffusivity, and specific heat with the effects of water and cement contents on it. The thermal conductivity has evaluated by a hot ring apparatus. In general, the results showed that compressed earth blocks presented that their thermal performance good without the effects of cement and water, and with their effects the thermal performance is not good.

In Fourth chapter, the heat transfer problem in cylindrical coordinates will be solved by the finite volume method (FVM). The basic idea of FVM is in the numerical formulation, the differential equation is replaced by a discrete approximation. The temperature field is approximated by values at discrete points. This gives a computational mesh. To divide the computational region into a series of no repeated control volumes (CV) and make each mesh point have a control volume around it. A set of discrete equations is obtained by integrating the differential equations to be resolved with each control volume. The field is considered at consecutive time-steps with a time increment Δt. In this study, only cylindrical meshes will be used, the increments in r and z directions. To validate the formulation will study the numerical efficiency by comparisons of numerical results compared with experimental results. The comparison shows that they are in excellent agreement.

The model presented in chapter fifth is proposed by Mr. Bouabid and Mr. Cherraj, gives the evolution of the thermal conductivity of the CEBs as a function of the cement content and the water content. This elaborate model also includes the physical interaction that naturally results from the combination of these two effects. It also makes it possible to predict the rate of cement and the water necessary to obtain a CEB with well-defined properties, which is particularly important in the case of the restoration or rehabilitation of a construction already in service. The modeling is applied to the experimental results obtained by a series of tests carried out for different of cement content and different water content. From this model, also proposed a technico-economic optimum for construction in CEB. This optimum corresponds to the best rate of stabilization for which the economic contribution of stabilization is proportionally compensated and justified by a technical gain in the properties of the material. A technical and economic analysis is carried out to show this proportionality.

Chapter I: The Green Building and thermal comfort

Introduction

Green building represents in the world one of the most significant and most exciting opportunity for sustainable growth at both national and global levels. Owing to the fact that the design of built environmentally has an impact on energy, on economy and the natural resources. Green building considers costs over the entire life of the building, whereas traditional building is often focused on initial design and construction costs. One of the main objectives of green buildings is to provide thermal comfort for individuals inside buildings. And it is not new, where Humans been building with local materials such as mud, straw, wood, and stone, and using renewable energy from the sun, the wind, and water for thousands of years. Due to the reason increase the interest in ecologically friendly constructions which also include the earth material, we need of earth reconstruction, the success of earth reconstruction depends on conducting scientific research studies to be confirmed their extent of structural safety and meet the needs of its users and low its cost, respect the environmental conditions located in it and providing thermal comfort. In this chapter demonstrate to the important of green building pro-environment behaviors. The green building standards and alternative building materials for green construction were identified and evaluated. Also, this chapter presents summary findings from several literature research of the thermal properties of different kinds earth building materials and display some of the devices used to measure the thermal conductivity of these materials. Thermal properties in earth building materials has been studied by researchers interested in the relationship between building materials, construction processes, and their environmental and thermal impacts. In the available literature, several experimental investigations have established the positive effects of the addition of stabilizer to various types of earth block such as straws, fibers, lime and cement on the thermal and mechanical properties of soil composite.

I. 1. Green Building

The term green buildings are the practices of building structures and the use of processes with high environmental efficiency in the use of resources throughout the life cycle of construction, from determine location, design, operation, restoration, maintenance, and even demolition and deportation. It is gaining importance in various countries [1]. These are buildings that ensure that waste is minimized at every stage during the construction and operation of the building, resulting in low costs according to the experts in the technology [2, 3, 4]. This practice expands and complements the classical building design concerns of economy, utility, durability, and comfort. Green buildings are known as sustainable and high-performance buildings. Also known as (green construction or sustainable building) expands and complements the building design concerns of economy, utility, durability, and thermal comfort [6]. The energy-efficient green building is made of natural materials, usually made from recycled materials. Green building is essentially a combination of updated construction techniques with a sharp eye on energy and water efficiency and conservation.

Green building benefits go beyond economics and the environment and have been shown to bring positive social impacts too. Many of these benefits are around the health and wellbeing of people who work in green offices or live in green homes [7].

Green architecture came as a normal reaction on the excessive usage of natural resources, and the great pressure on the environment, and negative effects caused by buildings and their materials, methods of use and the squandering during implementation, which led to the emergence of the concept of sustainable architecture, which is defined as meeting the needs of current generations without damage the ability of future generations to meet their needs.

That the integrated design is the first steps of the green building, through the participation of the architect in design since its earliest stages, and that helps in to dispense with mechanical means which correct design errors, and reduces of the cost of construction which rises with time, and that take into consideration conditions of the local environment and the use of available resources in them will reduce their negative impacts, and contributes to increased control of wasted energy in buildings [8], [9]. Some see that quotation the lessons from the heritage architecture which submitted for centuries good residence and healthy adopted natural ventilation and lighting, the open inner courtyard and the use of soil as building materials and insulators, is very important in the present era for sustainable living, as the use of local resources reduces the consumption of fuel used in the import of materials from abroad, which indirectly reduces the impact of the environmental fingerprint for buildings.

The determining the causes of high consumption for energy in the building, and ways to improve their performance using materials and mechanisms that would save energy and money through the use of natural and renewable energies and using thermal insulators to reduce heat gain inside the building. Return to the heritage buildings, which depends in the ventilation and natural lighting on the internal courtyard open, the windows and afforestation, and the use of soil as building materials and insulators [10]. This is not only to reduce energy using but also to the importance of these materials in providing a healthy and comfortable internal environment and to minimize environmental impact. With the inevitability of declining fossil fuels, and the threat of global climate change, reducing our energy consumption is an essential survival strategy. Choosing to build green saves energy. M. Samer [5] in Table (Table 1) presents a comparison between “green buildings” and “non-green buildings” or “traditional buildings”.

TABLE 1. COMPARISON BETWEEN “GREEN BUILDINGS” AND “NON-GREEN BUILDINGS” [5]

Building type	Green Buildings	Non- Green Buildings
Energy Consumption	Low	High
Indoor Environment Quality	Very Good	Good
Emissions	Low	High
Wast Management	Highly Efficient	Efficient
Building Materials	Environmentally Friendly	Not Environmentally Friendly
Project Practices	Sophisticated	Normal
Feasibility	> 5% than Threshold	Threshold

I.1. 1. Building types based on power consumption

Energy is used in buildings to provide a variety of services, including comfort and hygiene, food preparation and preservation, entertainment, and communication. Energy consumption is rapidly increasing due to the increase in population and urbanization. Residential energy requirements vary from region to region, depending on climate, dwelling type, materials used in the construction and level of development. Buildings are considered a major component of energy consumption. Buildings consume energy at different levels in every stage of the life-cycle. Further, building materials occupy a great share of this consumption [11].

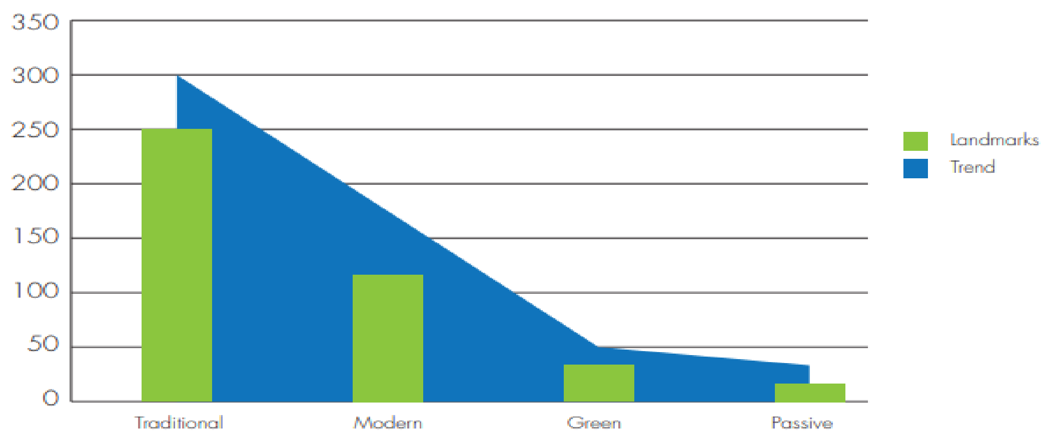


FIGURE 1. TYPES OF BUILDINGS BASED ON BASIC POWER NEEDS CONSUMPTION [11].

Figure 1 illustrates the curve that describes the behavior of each building type based on basic power consumption. Of all the building types, traditional building consumes use the most total energy. A typical traditional building consumes 250-300 kWh per m2 per year. Modern buildings are designed to consume about 160 kWh per m2 per year, whereas a construction based on Green Building principles can reduce that to 30 kWh.

If building a green home is our goal, then using environmentally or eco-friendly products should be on our list which can reduce the impact of construction on the environment. Each and every part of the house such as roofing material, building material, cabinets, counters and insulation of flooring should be environmentally friendly.

I. 1. 2. Green building standards (criteria)

The standards for GB vary from region to region in the world and some countries have set up their own definitions for GB, according to their climate. These standards are often developed by professionals, engineers and building scientists.

The assessment criteria cover the areas: Appropriate Site Development, Energy Efficiency and Conservation, Water efficiency and Conservation, Material efficiency Resource and Cycle, low embodied energy, Indoor Health and Comfort, Indoor air quality, and Building Environment Management. The major standards of GB include the follows basic qualifications [12], [13]:

1. Energy Efficiency: maintenance of its energy use. By increasing energy efficiency, we reduce the wastage of energy and thus use fewer resources for creating energy, which in turn

reduces its carbon footprint. A low energy use, adequate thermal mass or insulation, appropriate solar orientation and design, efficient heating and cooling design are among many other criteria.

2. A low embodied energy, the components of the home have to also be green like the earth building with low energy expenditure in the manufacturing, processing, transportation, etc.

3. Material Efficiency, the GB is only truly green if it uses environmentally friendly and sustainable materials and resources when being built; and afterwards for maintenance and running of the facilities. A high percentage of sustainable components, soil material, wood, ash, Straw bale, papercrete, tire construction are good examples. Adobe, compressed earth block and Rammed earth, cob and earth sheltered are great examples of environmentally non-intrusive, sustainable, construction as well.

A. Energy efficiency in building

Energy is one of the most important factors in economic growth and social development in all countries. Energy lost through walls, roofs and windows is the largest single waste of energy in most buildings. Energy loss in buildings means extra operating costs, loss of comfort, and reduced productivity. Also, it is observed that the CO2 emissions concerning energy have increased in the last 20 years. More than 40% of CO2 emissions in developed countries come from heating, cooling and powering buildings.

Saving energy in buildings is a day task. A significant percentage of energy is used to heat, cool and operate our homes and buildings. Energy efficiency helps to build a sustainable energy system, throughout decreasing energy consumption, and reducing carbon emission has guided to a concentrate on energy efficiency of buildings. Energy efficiency in buildings is compelling, cost effective and can help consumers to save money in the long term and help to meet energy targets and resource energy shortage. Buildings can be made energy-efficient by using quality building and insulation materials which help prevent heat loss and make the building airtight. High-quality design and craftsmanship are prerequisites in energy-efficient building. local raw materials used in construction, good insulation, efficient boiler, window glazing and recovering heat from ventilation systems are efficient ways to reduce emissions and to reduce consumption energy. One important way of improving energy efficiency in buildings is by focusing on choosing of building materials, which protect inside building from the conditions outside, lead to reduce energy consumption and provide thermal comfort [14], [15], [16], [17].

GB materials include non-toxic materials and furnishings, recycled-content or salvaged materials, wood, clay and other materials from renewable sources. Using green building materials can help ensure a healthy indoor environment while reducing the home's overall environmental impact.

B. Embodied-energy materials

The total energy required for the extraction, processing, manufacture and delivery of building materials to the building site is commonly known as embodied energy. Many natural resources and building materials require mining, processing, refining and ultimately manufacturing, transport and delivery before they are utilized in construction. Embodied energy describes the energy consumed in providing materials for building construction. Embodied energy does not include the operation and disposal of the building material. Energy consumption produces CO2, which contributes to greenhouse gas emissions, so embodied energy is considered an indicator of the overall environmental impact of building materials and systems.

Embodied-energy materials of a building can be lowered by using locally available, natural materials that are both durable and recyclable, with a design that incorporates components that are easy to recover and reuse, within a structure that is easy to dissemble and dismantle.

Low embodied energy building materials have some common characteristics: Durability reduces embodied energy over time. If materials can be separated easily, they use less energy. Locally sourced building materials don't have to travel great distances, saving on energy costs. Recycled materials use far less energy than new materials [18]. Waste of materials not needed for extraction, processing and manufacturing of materials uses more embodied energy. Renewable energy sources reduce the use of embodied energy. In essence, the efficiency of the extraction and manufacturing process will lower embodied energy levels (table 2 and table 3). The fuels used; the distance of transport; and the amount of recycled materials used play a big part in choosing low embodied building materials. The low embodied energy of green products ensures that very little energy went into their manufacture and production, with a direct reduction in carbon emissions [19, 20].

TABLE 2. EMBODIED ENERGY OF COMMON MATERIALS [21].

Material	PER embodied energy MJ/kg	Material	PER embodied energy MJ/kg
Kiln dried sawn softwood	3.4	Local dimensioned granite	5.9
Kiln dried sawn hardwood	2.0	Gypsum plaster	2.9
Air dried sawn hardwood	0.5	Plasterboard	4.4
Hardboard	24.2	Fibre cement	4.8
Particleboard	8.0	Cement	5.6
MDF (medium density fibreboard)	11.3	In situ concrete	1.9
Plywood	10.4	Precast steam-cured concrete	2.0
Glue-laminated timber	11.0	Precast tilt-up concrete	1.9
Laminated veneer lumber	11.0	Clay bricks	2.5
Plastics- general	90.0	Concrete blocks	1.5
PVC (polyvinyl chloride)	80.0	Autoclaved aerated concrete (AAC)	3.6
Synthetic rubber	110.0	Glass	12.7
Acrylic paint	61.5	Aluminium	170.0
Stabilised earth	0.7	Copper	100.0
Imported dimensioned granite	13.9	Galvanised steel	38.0

From table 2, Aluminium (170 MJ/kg), Synthetic rubber (110 MJ/kg), Copper (100 MJ/kg), Plastics general (90 MJ/kg), PVC (polyvinyl chloride) (80 MJ/kg), Acrylic paint (61.5 MJ/kg) and Galvanised steel (38 MJ/kg), have the most embodied energy because to the high energy required to produce them. Compared to Air dried sawn hardwood (0.5 MJ/kg) and Stabilized earth (0.7 MJ/kg) that require very less energy for production.

TABLE 3. EMBODIED ENERGY (EE) OF BRICK AND CONCRETE WALLS [22].

Product	Brick/Block Size: L × W × H (mm)	External Wall Thickness (mm)	EE of Material (MJ/Kg)	Mass per item/Littre (Kg)	EE of Wall (MJ/m2)	EE of Wall (MJ/m3)
Artisan Burned Brick/Block	300 x 150 x 130	150	4.76	7.6	810	5398
	20 mm mortar		1.11	1.65		
	220 x 110 x 65	220	4.76	2	1067	4849
	20 mm mortar		1.11	1.65		
Small-Scale Brick	220 x 110 x 65	220	17.136	2	3542	16.100
	20 mm mortar		1.11	1.65		
General Clay Brick	215 x 102.5 x 65	215	3	2	791	3677
	10 mm mortar		1.11	1.65		
Cement Stabilised Soil Blocks	290 x 140 x 115	140	0.68	8	176	1257
	10 mm mortar		1.11	1.65		
Hollow Concrete Block *	400 x 200 x 200	200	0.59	14	127	636

* Assumptions: 50% Hollow; 8Mpa compressive strength.

C. Alternative building materials for green building

Choosing eco-friendly building materials is often the first step to creating as green a property as possible. Green homes can be constructed in a number of very various ways, using materials that don’t seem to be a good fit at first sight, in which use local, processed and renewable natural materials. They are designed to suit their climate and geography, providing a modest shelter that can last for many centuries. The utilization of green alternatives materials in buildings would substantially reduce the energy demand, provides thermal comfort for occupants and improve the environmental impact and carbon footprint of building stock worldwide. In truth, there are actually a plethora of eco-friendly materials but they will need further scientific and technical developments before we can safely and confidently use them to build our homes [23].

There are several green alternatives for building material which can give a lower impact on the environment such as: Straw Bale, Grasscrete, HempCrete, Bamboo, Recycled Plastic, Wood, Rammed Earth, Mycelium, Ferrock, Timbercrete, Earth material, Wood, Straw, Bamboo, Stone, Tiny, Shipping-crate, recycled metal, and materials that are non-toxic and recyclable or that have been reclaimed from other construction projects.

There is a need for alternative building materials that require less embodied energy than conventional materials. Using earth-based materials reduces the climate change impact of building development, achieved through use of a sustainably renewable resource, including very high levels of thermal insulation and providing healthier living spaces. Earthen housing appears to meet the requirements of green construction. One of the most interesting traditional construction material is the earth blocks, made of raw soil, often improved by the addition of stabilizers to improve its mechanical properties. Building with alternative materials can be challenging but ultimately a rewarding adventure.

Based on the promising vision of future needs for green building and sustainable development, in my thesis I have chosen compressed earth material as conventional and eco-friendly building material for a sustainability building.

I. 2. The earth building materials

Earth is an environmentally friendly natural material. Its construction helps to reduce the depletion of natural resources and helps in saving energy consumed in cooling and heating, for its excellence in the ability to store heat and cold, and low conduction of external heat. Earth buildings are well known to be cold in summer and warm in winter. Soil material is an environmentally balanced natural substance and offers a climate internally healthy, because their use limits pollution, waste production and depleting of environment in all stages of manufacturing and even in the case of demolition, to distinguish it easily naturally recyclable. Earth construction has been in practice since the beginning of Human civilization. In fact, some of the oldest structures in till existence today are made of earth material. And earth construction appears as the Human ability to adapt to the environment in which He lives and use his talents to find simple and diverse techniques that satisfy his needs in the dwelling.

The development of human use of these techniques in the construction of building models has increased over the ages and has been enhanced by the experience and skills inherited through generations. It is related to taste, aesthetic harmony, and coupled with a wide knowledge by instinct and experience in construction engineering and knowledge of the physical benefits of soil, and how to deal with them and employ them according to the cultural, social and economic requirements in the region. Mostly, it considers environmental determinants such as climate, soil quality and available materials, where earth building depends on the selection of suitable soil with the nature and the climate of the region.

In many parts of the world the traditional knowledge and skills used to build natural homes has been, or are being, lost as people become more dependent on modern building that generally uses processed non-local materials.

The great development witnessed by the world during the last half of the twentieth century in the production of modern building materials, transport and communications, in an unprecedented manner, has had a significant impact on the reduction of the use of traditional materials and methods of construction in many countries. However, the construction of raw soil still retains its popularity in many city areas, especially in the developing world, because of its many advantages, most notably: the availability in the most of sites of implementation, and cheap price. Earthen architecture is still common in many countries, in Asia, Africa and Latin America, and less in Europe, North America and Australia (Figure 2).

With the last enquiry of climate change and the raise of a wide care to preserve nature, many wealthiest and rich persons in developed countries return back to natural and earth building.

Should we return to our Arab heritage and learn from our ancestors who lived in harmony with the environment without disrupting the ecosystem. Today, we are in dire need of modern environmental and economic technologies derived from our heritage in accordance with our age, reality, civilization and climate.

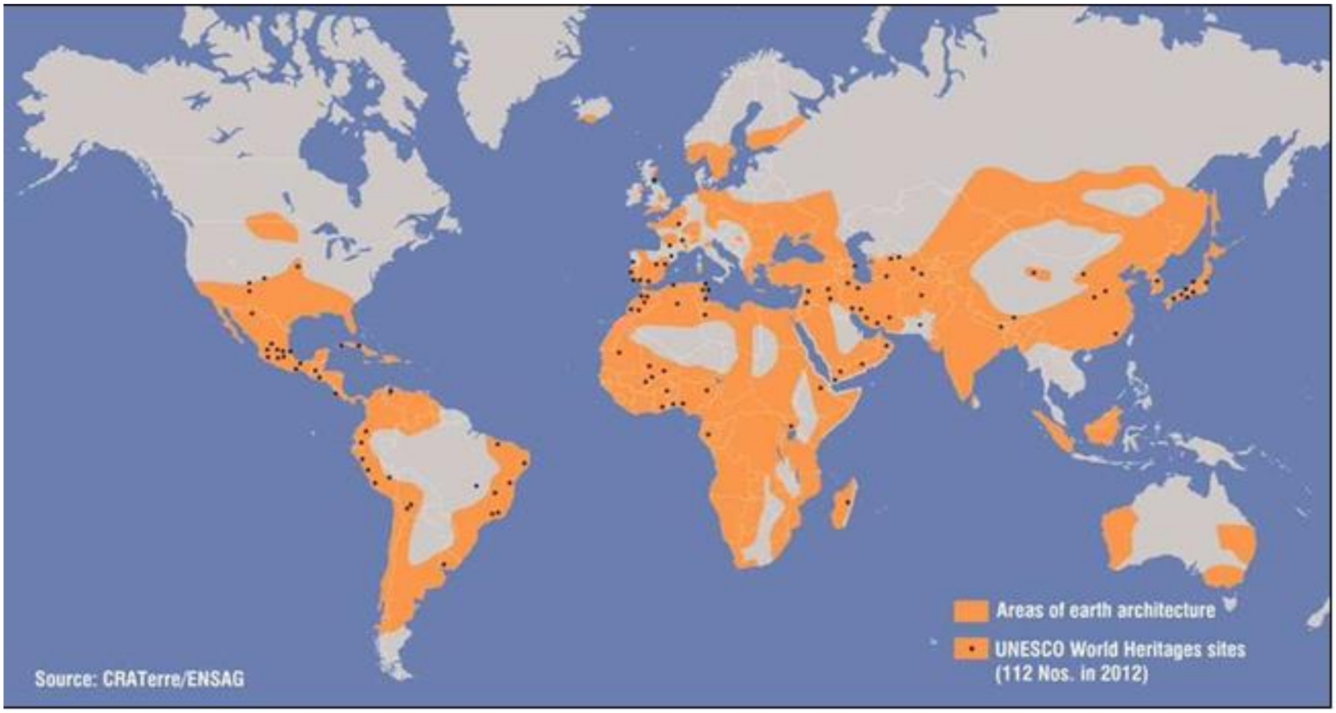


FIGURE 2. THE WORLD MAP ILLUSTRATES THE WORLDWIDE APPLICATION OF EARTH BUILDING.

I. 2. 1. Building technique by earth material in various parts of the world

Earth or raw materials buildings are often built with the knowledge and experience of a supportive techniques that can be applicable in nearly all regions and climates. These techniques rely heavily on human labor, natural resources and creativity, and specialized skills. Here are examples from around the world, this collection shows naturally built homes and public buildings from different climates using earth material and building techniques:

A. Adobe

Adobe brick is an ancient technique, which is made of clay and sand are mixed with a binding fiber such as straw to produce the brick. Water is added to the clay and left to set to become homogeneous. Straws are then blended in to bind the mixture and to prevent shrinkage and cracking. This final concoction is poured into a frame to form a brick shape. Once the shape is cast, the frame is removed and the bricks are left to dry in the sun. When its edges turn white, the brick is turned on its sides to allow all its surfaces to dry evenly. The drying process should be long and slow so the individual bricks can dry without cracking. The brick should be well dried out and ready for use after 2 – 3 weeks (sun dried, not kiln-fired Figure 3) [23], [24]. Excellent insulating properties make adobes ideal material for building. The use of adobe is very common in some of the world's most regions, such as Yemen, Latin America, Africa, India, the Middle East, and southern Europe.

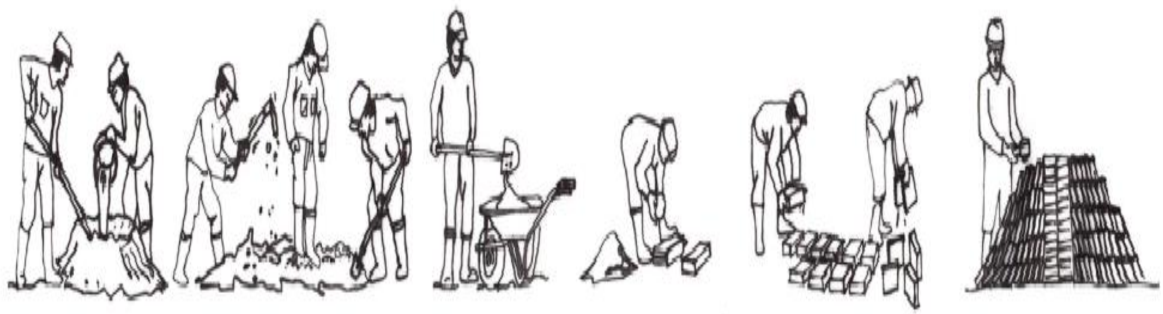


FIGURE 3. ADOBE BUILDING TECHNIQUE BY EARTH MATERIAL [25]

B. Wattle and Daub

One method that ancient human used was called wattle and daub. It was a unique process, as a composite building material used for making walls, in which vertical wooden stakes, or wattles, are woven with horizontal twigs and branches, called wattle is daubed with a sticky material usually made of some combination of wet soil, clay, sand, animal dung and straw. This method is one of the oldest known for making a weatherproof structure (Figure 4). The wattle and daub technique were used already in the Neolithic period [26]. It was common in houses of a Linear pottery and Rössen cultures of Central Europe, but is also found in Western Asia (Çatalhöyük, Shillourokambos) as well as in North America (Mississippian Culture) and South America (Brazil). In Africa it is common in the architecture of traditional houses such as those of the Ashanti people [27]. Fragments from prehistoric wattle and daub buildings have been found in Africa, Europe, Mesoamerica and North America. A review of English architecture especially reveals that the sophistication of this craft is dependent on the various styles of timber frame housing. This traditional walling system with a history of 6000 years [28].

FIGURE 4. WATTLE AND DAUB BUILDING TECHNIQUES BY EARTH MATERIAL [25].

C. Rammed Earth

Rammed earth is a technology that has been used by human civilization for thousands of years and can last a very long time. The worldwide tradition of rammed earth construction has shown that it is possible to achieve strong majestic buildings that have withstood the test of time and even earthquake episodes. Examples of such great architectures include the famous examples the Alhambra at Granada. But there are hundreds of other sites throughout Spain, the great Kasbahs and ksour of Morocco and the long stretches of the Great Wall of China. The most durable of the earth-building forms, rammed earth may be used for making building blocks or for constructing whole walls in place, layer by layer. In making building blocks, the soil is rammed into a wooden box-shaped mold [29]. In building up whole walls, two wooden planks separated by a spacer bolt are used as a form, and the earth is rammed into this in layers. When the form is filled, it is removed and superimposed on the top of the wall and more earth is rammed again until the desired height is reached. The final texture of rammed earth walls is unique and beautiful, so they typically do not need any mortar, plaster or render (Figure 5). The walls are fireproof, rot resistant, seismic resistant and impervious to termites [30]. Wall thicknesses are at least 12 inches (30 cm), a mass that results in a high thermal capacity, keeping the internal conditions uniform in climates having large variations in temperature from day to night. Rammed earth walls are a popular choice for interior walls because of their high thermal mass [31]. Which helps maintain a comfortable temperature within the house, damping temperature swings that normally occur on hot summer days or cold winter nights.

FIGURE 5. RAMMED EARTH BUILDING TECHNIQUES BY EARTH MATERIAL [25].

D. Cob Earth

Cob building is a traditional technique that has been used for thousands of years and in all kind of climates. It is a mixture of sand, clay, straw and water that is mixed together to make a malleable mud that is formed into monolithic walls (Figure 6). When the cob dries it becomes hard and creates incredibly durable walls and columns. Cob is similar to adobe, but lumps of cob are applied wet to build up a wall, bench, or as thermal mass around stoves [32, 33], allowing sculpting easily a home as it progresses. Cob standing structures are found in many of the oldest places like central Asia, the Middle East and sub Saharan Africa. Known regionally as "tabya" cob was also used commonly in the Maghreb and al Andalus regions, Cob were also used cob throughout the history of England and the UK [34], [35].

FIGURE 6. COB EARTH BUILDING TECHNIQUE BY EARTH MATERIAL.

E. Light Earth

Light earth building is referred to as (light straw clay or straw clay), a natural building material used to infill between a wooden frame in a timber framed building. It can also be used with wood chips, hemp fibers, sawdust or some other lighter material. Then packed into formwork to make walls, while the formwork being removed once the wall is semi dry (Figure 7). Light earth is a blend between rammed earth and cob. A mixture of clay and straw was used as an infill material for timber framed building from at least the 12th century in Germany and elsewhere in Europe. It's an easy technique, cheap to make, extremely effective, and has a higher thermal mass than strawbale (though not as high as rammed earth) [36], [37].

FIGURE 7. LIGHT EARTH BUILDING TECHNIQUE BY EARTH MATERIAL

F. Bag Earth

The Earth bag is an alternative building technique with sandbags. The main materials used for construction are: sand, earth, clay, straw and wood. The bags are stacked to create buildings of various sizes and shapes quickly and relatively (Figure 8). In the 1980s, the idea of earth bags was developed by an Iranian-born architect Nader Khalili who popularized the notion of building permanent structures using bags filled with earthen materials [38]. At present, there are over 15,000 Earth bag buildings worldwide. Earth bag homes cut the heat and humidity and this is what makes these homes cool in the summers and warm in the winters [39, 40].

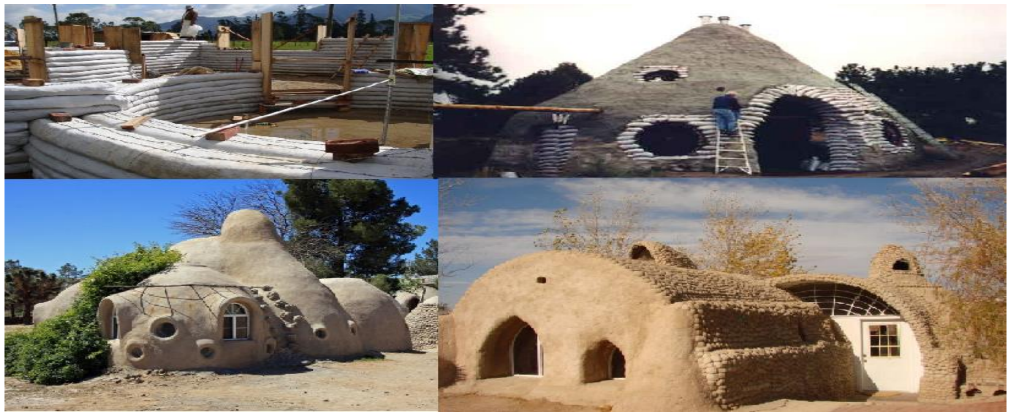


FIGURE 8. BAG EARTH BUILDING TECHNIQUE BY EARTH MATERIAL.

G. Compressed earth block (CEB)

Compressed Earth Block (CEB), also known as a pressed earth block or a compressed soil block, is a natural masonry blocks produced manually or hydraulically using an Earth Block press. The compressive strength is a basic measure of quality for compressed earth blocks (Figure 9). A wide range of soils can be used for the production of these blocks with a balanced of proportions of clay, sand and gravels. If the blocks are made stable with a chemical stabilizer such as cement they are known as stabilized compressed earth block [25], [41]. Building with Compressed Earthen Blocks is becoming more popular due to their low cost and relative abundance of materials, and particularly bring together advantages of both adobe and rammed earth. So, I choose this type of earth block in my research topic and will talk about it in detail in later chapters.

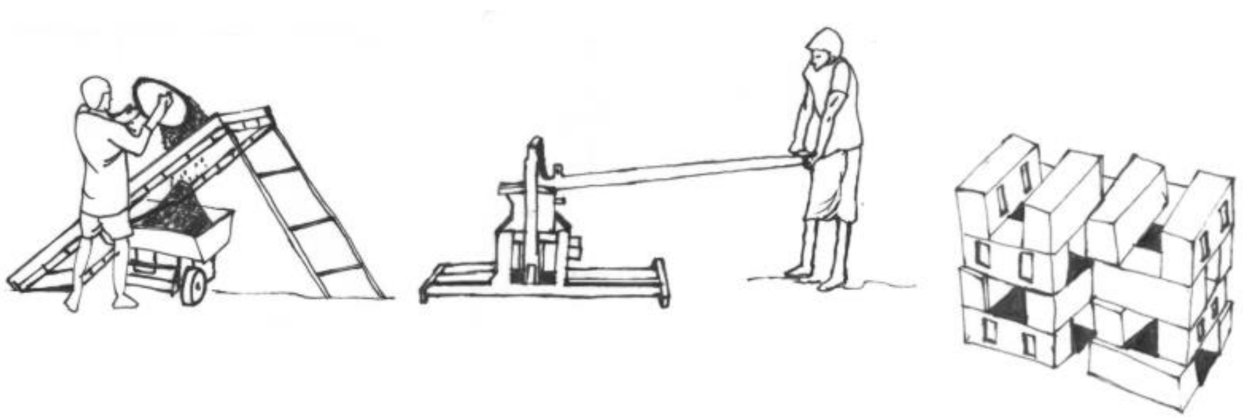


FIGURE 9. COMPRESSED EARTH BLOCK BUILDING TECHNIQUES BY EARTH MATERIAL [25].

I. 2. 2. Thermal comfort and earth building

The most important physiological factors that strongly affect the human is the thermal comfort, which is linked to the surrounding environment. The thermal comfort is a mental state in which a person feels satisfied with the circumstances of the environment surrounding him, as a condition in which the person does not feel cold or hot or feels any discomfort due to any imbalance in the thermal environment.

Human works continuously to maintain his comfort, physical and psychological health, and the importance of dwelling and all types of buildings and their impact on the comfort and human health. It is necessary to explain the climate of the dwelling and the elements that affect it. The availability of climate elements at a comfortable degree in the home is from the core of people's interesting at all times of the year, especially in times of hot and cold, people are working to mitigate the impact of low or high temperatures, by use the means of cooling in the summer and the means of heating in the winter [42]. The use varies with means of adaptation due to climate variability from region to region. The cooling means are very important in hot areas, and heating means are very important in cold areas. Among the fields of interest in the house is the human preservation of air purity inside the house because of its impact on health and comfort.

Providing thermal comfort inside the building is one of the most important aspects of construction. Designers should control the outer shell of a building to mitigate the impact of external temperatures and humidity. Thermal comfort can be reached through the selection of building materials. The choice of building materials for the construction are very important to provide thermal comfort and protection from external conditions because they are responsible for determining the duration of heat transfer to and from the building. Therefore, we should take care of the physical properties such as thermal conductivity, thermal resistance, and thermal diffusivity.

The heat is transmitted in summer from outside the building into it, and this trend is reversed in winter. The amount of heat transferred depends on several factors, the most important is the difference between internal and external temperatures, and the thickness of the building elements such as walls, ceilings, floors and its area, and the nature of the materials. For example, ordinary concrete, solid bricks and building stones are materials with high thermal conductivity, while wood and soil are considered materials with lower thermal conductivity. The reason is that the material contains air or gases trapped within pores. The insulation system by use of natural materials, helps to reduce thermal transfer coefficient for ceilings, floors and walls. So as to reduce leakage and heat transfer from outside the building to inside it in summer and from inside the building to outside it in winter.

As I mentioned earlier, in order to ensure thermal comfort in buildings, special attention must be paid to the selection of building materials. When we identify the properties of building materials used, we can choose the best not only for mechanical resistance but also for thermal comfort. Earth block is an alternative wall building material offering significant economic, environmental advantages and thermal comfort. This makes earth block a promising option. The estimating and controlling the thermal behavior of building materials plays major role in determining the thermal comfort of the building. This means that if we determine the thermal behavior of the earth block then we can control the thermal comfort inside the building.

It protects building by reducing the impact of harsh natural environmental challenges such as climate change, humidity and solar radiation. But it has declined after the emergence of modern building materials such as cement, this is due to the fact that the soil structures faced some structural problems. But in light of the growing need to achieve sustainable architecture and the significant knowledge progressing the field, many modern global attempts have been made to reuse again soil in the construction [43].

I. 2. 2. 1. Climate factors affecting thermal comfort inside the building

There are many factors that effect on thermal behavior of building, then effect on thermal comfort inside building. The most commonly used indicator of thermal comfort is air temperature. However, air temperature alone is not a valid or accurate indicator of thermal comfort. It should always be considered in relation to other environmental and personal factors: air temperature, radiant temperature, air velocity, humidity and uniformity of conditions, while the personal factors clothing, metabolic rate, acclimatization, the state of health, expectation and access to food and drink. The Health and Safety Executive view is that ‘reasonable comfort’ is achieved when at least 80% of its occupants are thermally comfortable.

One of the most important factors affecting the thermal comfort which my thesis addressed is the humidity. This factor in particular has been applicated within experimental and numerical experiments that have been conducted to investigate the effect of humidity on thermal conductivity in compressed earth block [44], [45].

I. 2. 2. 2. The effect of humidity on the thermal comfort in the building

One of the most important factors affecting the thermal comfort that we will study is the Humidity. The main causes of humidity inside the building are: rain penetration, level of site, drain ability of soil, climate condition, closeness or not to oceans or seas, defective orientation of building, moisture entrapped during construction, defective construction e.g. joints, poor quality of construction material, bad design, faulty construction or bad workmanship, leakages from pipes, rainwater, surface water and groundwaters, rise of ground moisture. The presence of moisture inside the building has negative effects on the building and on the occupants of the building. The most important negative effects are: an unhealthy situation for building users, lack of cohesion in the buildings, efflorescence for walls, floors and ceilings, the corruption of wood used and bending, exposing the iron used for shock, damage of paint, damage to electrical installations, damage to floors, walls and ceilings, breeding fungi and bacteria in the building and the thermal behavior changes inside the building and thus negatively affects the thermal comfort inside the building. Humidity is one of the most confusing of all climatic parameters in assessing the indoor living, affects comfort in a number of ways both directly and indirectly, and the avenues by which humidity affects comfort are not completely known.

In hot and humid climates, air movement plays a key role in heat exchange between the body and the environment, reducing the sensation of heat and consequently improving occupants' thermal comfort. Additionally, in this type of climate, air moisture levels should be maintained within acceptable ranges, as several studies have demonstrated that this variable has a measurable impact on occupant's thermal sensation. Thus, when the temperature and humidity are high, and air movement is low, thermal comfort may not be achieved. In air-conditioned spaces, humidity is fairly static. Furthermore, such systems usually dehumidify the ambient air. Some investigations conducted in climate chambers indicate that humidity influences thermal perception when indoor temperatures exceed 27 °C. Bioclimatic analysis is a systematic procedure for the assessment of thermal comfort in relation to external climate. It has the purpose of identifying desirable adaptations of structure to meet human comfort needs under specific climatological conditions. For example, the desert environment requires low density bricks in the sense with high pores, which will increase the efficiency of the outer walls in thermal insulation. And for the mountain environment, very cold and heavy rain, it is suitable high density building bricks in the sense with a few pores and low absorption capacity of rain water [45], [46].

I. 3. Literature Review (Published Literature on thermal comfort in earth building and the devices to measure the thermal conductivity)

In fact, several numerous studies have been carried out on the thermal behavior of earth materials. For example:

P. Meukama et al [47] studied thermo physical characteristics of economical building materials. Cement stabilized compressed bricks were tested. An experimental study was carried out on the thermal properties of bricks made from lateritic soil. The objectives of the work reported in this paper are to determine the effect of addition of cement, pozzolan or sawdust in lateritic soil brick on the thermal properties. Besides, the objective was to study the influence of the water content on the thermal conductivity (k) and the thermal diffusivity (α). This study shows that the compressive strength can be further increased by the addition of ordinary Portland cement to the lateritic soil mix. The device used to measure the thermal conductivity of the samples was the box method as shown in Figure 10. (a), the thermal conductivity measurements are based on steady-state heat transfer. The measurement apparatus used for the thermal diffusivity is the same as that for thermal conductivity measurement. In addition, it has an incandescent lamp as shown in Figure 10. (b). Diffusivity measurement is undertaken by using a flash method, and the specific heat has been determined experimentally using calorific method. The studied samples were: Mix 1: lateritic soil with 8% of cement. Mix 2: 45% of lateritic soil, 45% of natural pozzolan, 10% of cement. Mix 3: 81% of lateritic soil, 9% of sawdust, 10% of cement. The experimental results for the three mixes are presented in tables 4, 5 and 6 and in the figures 11 and 12. The results indicate the effect of the addition of natural pozzolan or sawdust is to decrease the thermal conductivity. It has been shown that water content is a major variable affecting thermophysical properties of the tested samples. The coefficients of thermal conductivity and thermal diffusivity were strongly influenced by the material's water content. The thermal properties as a function of water content give non-linear relations (figure 11). The obtained behaviors show a rapid increase for low water content and a maximum diffusivity for Mix 1 (figure 12). The addition of natural pozzolan or sawdust in bricks made from laterite leads to maintain their strength while decreasing their thermal conductivity.

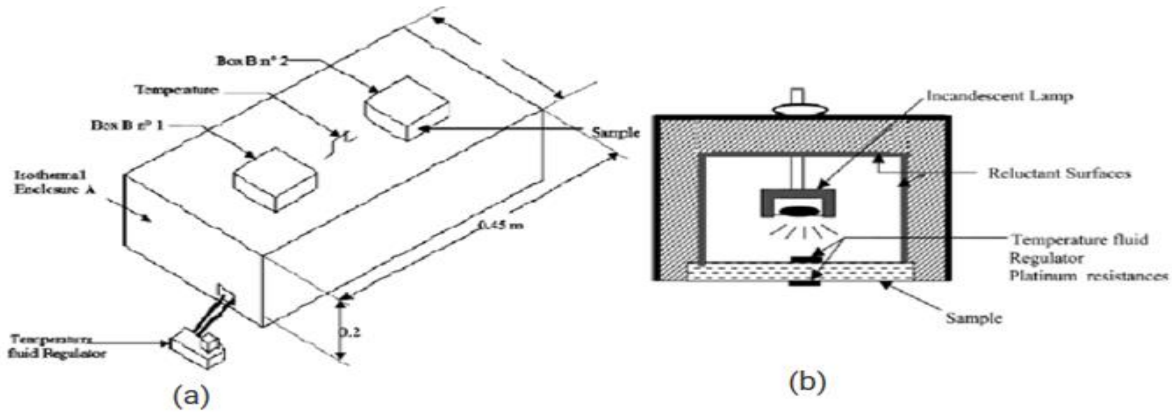


FIGURE 10. (A) EXPERIMENTAL SETUP OF THE BOX METHOD. (B) THERMAL DIFFUSIVITY.

TABLE 4. EXPERIMENTAL THERMAL CONDUCTIVITY AND DENSITY OF THE TESTED SAMPLES.

Sample	Compacting pressure (MPa)	ρ (kg m^{-3})	k (W m^{-1} °C^{-1})
Mix 1	5.3	1491	0.75
	6.7	1807	0.95
	8.5	1966	1.15
Mix 2	4.1	1329	0.65
	5.8	1576	0.69
	8.9	1643	0.71
Mix 3	6.5	1050	0.50
	7.1	1098	0.51
	9.6	1207	0.65

TABLE 5. COMPARISON BETWEEN THERMAL DIFFUSIVITIES MEASURED BY TWO METHODS.

	ρ (kg/m^3)	ω (%)	C (kJ/kg °C)		α_1	α_2
			Drier sample	Wet sample	10^{-7} m^2/s	10^{-7} m^2/s
Mix 1	2023	3.45	1.013	1.12	4.19	4.68
	1930	3.41	0.898	1.01	4.87	5.18
	2070	3.34	1.1	1.20	3.82	4.60
	average	3.40	1.00	1.11	4.30	4.82
Mix 2	1734	2.71	0.951	1.04	3.79	4.01
	1777	2.82	0.909	1.0	3.85	3.83
	1772	2.38	0.969	1.04	3.71	3.75
	average	2.64	0.943	1.03	3.78	3.86
Mix 3	1220	3.25	0.816	0.922	4.92	3.03
	1274	3.69	0.905	1.02	4.26	2.71
	1241	3.76	0.912	1.03	4.33	2.54
	average	3.57	0.878	0.99	4.50	3.02

α_1: relation (3) with experimental thermal conductivity.
α_2: experimental results (flash method).

TABLE 6. COMPARISON BETWEEN THERMAL CONDUCTIVITIES OBTAINED USING BOX METHOD AND FLASH METHOD.

	Compacting pressure (bar)	k_1 (box method) (W m^{-1} $^0C^{-1}$)	k_2 (flash method) (W m^{-1} $^0C^{-1}$)	Relative difference (%)
Mix 1	20	1.03	1.04	1
	15	0.87	1.01	14
	10	0.79	0.89	11
Mix 2	20	0.56	0.62	10
	15	0.49	0.60	18
	10	0.46	0.58	21
Mix 3	20	0.46	0.44	4
	15	0.43	0.38	12
	10	0.36	0.34	6

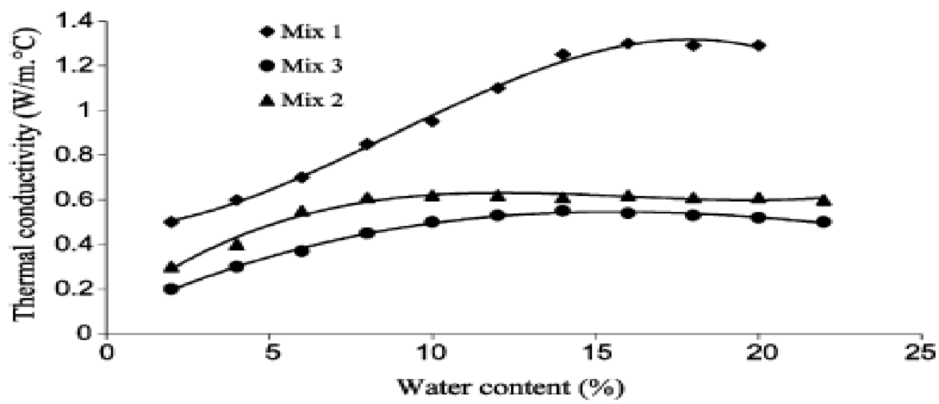


FIGURE 11. THERMAL CONDUCTIVITY OF THE THREE TESTED MATERIALS.

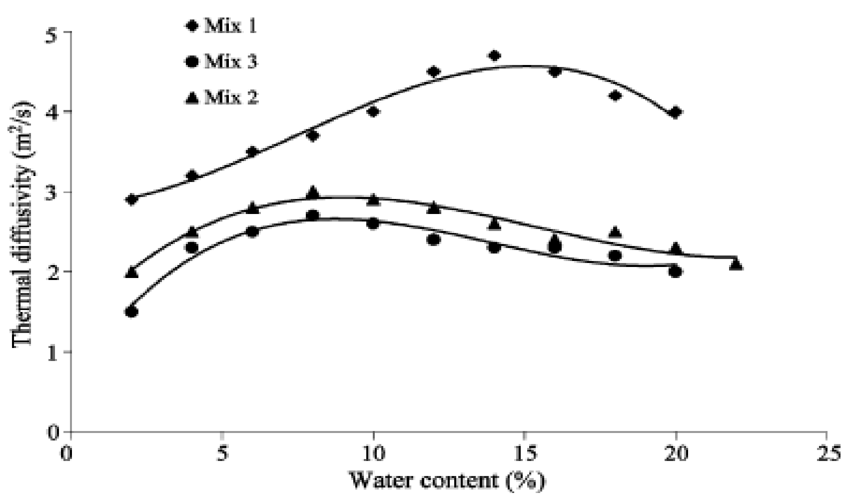


FIGURE 12. THERMAL DIFFUSIVITY AS FUNCTION OF WATER CONTENT.

Moro Olivier Boffoue et al [48] studied the influence of the cement content on the thermomechanical properties of compressed and stabilized clay blocks. The work aims at determining the compressive strength and the thermal conductivity of the blocks based on compressed and cement stabilized clay on the one hand and to study the variation of these properties as a function of the cement content. The samples for this study were made from a basic raw material composed in mass weight of 80% clay and 20% sand (used as a degreaser). The device used to measure the thermal conductivity of the samples was the flowmeter method (Figure 13). The measurements made with a flowmeter show that the average thermal conductivity of these blocks is 0,91 Wm-1 K-1. The results show also that the thermal conductivity and the compressive strength of the blocks vary according to the cement ratio in a non- linear manner. However, the thermal conductivity of the blocks with high cement ratio is close to that of the blocks without cement (Figure 14). A study of the thermal mechanical properties of clay blocks stabilized in cement shows that these blocks have good strengths and low heat conductivity values but these parameters vary depending on the cement content.

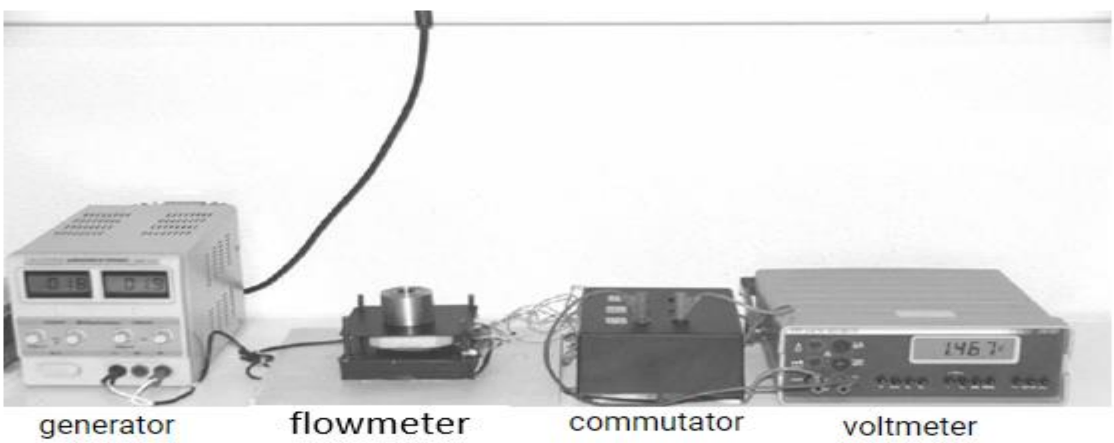


FIGURE 13. EXPERIMENTAL DEVICE FOR MEASURING THERMAL CONDUCTIVITY.

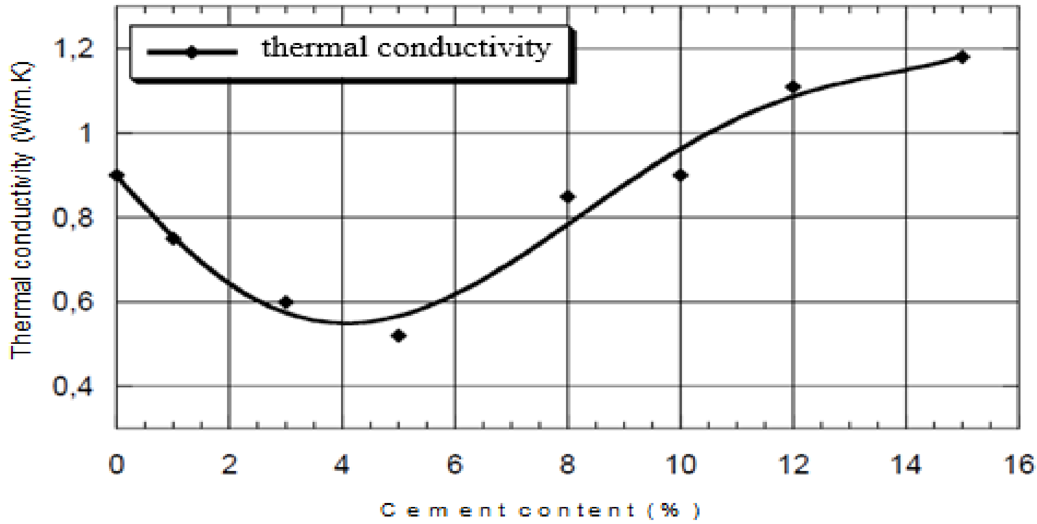


FIGURE 14. VARIATION OF THE THERMAL CONDUCTIVITY AS A FUNCTION OF THE CEMENT CONTENT.

Azakine Sindanne S et al [49] studied thermophysical characterization of earth blocks stabilized by cement, sawdust and lime. The incorporation of stabilizers was conducted in CSEB for different percentages: 4%, 8% and 12% for each type of stabilizer. The device used to measure the thermal conductivity of the samples was the hot iron method. In the light of this experimental investigation, the results were: Thermal conductivity of CSEB increased with the increase of the percentages of cement and lime. The use of sawdust as a stabilizer in CSEB decreases the thermal conductivity and increases the thermal resistance. We can see from the figures 15 and 16 that the thermal conductivity and the thermal resistance are evolving in a non- linear manner with respect to the stabilizer content.

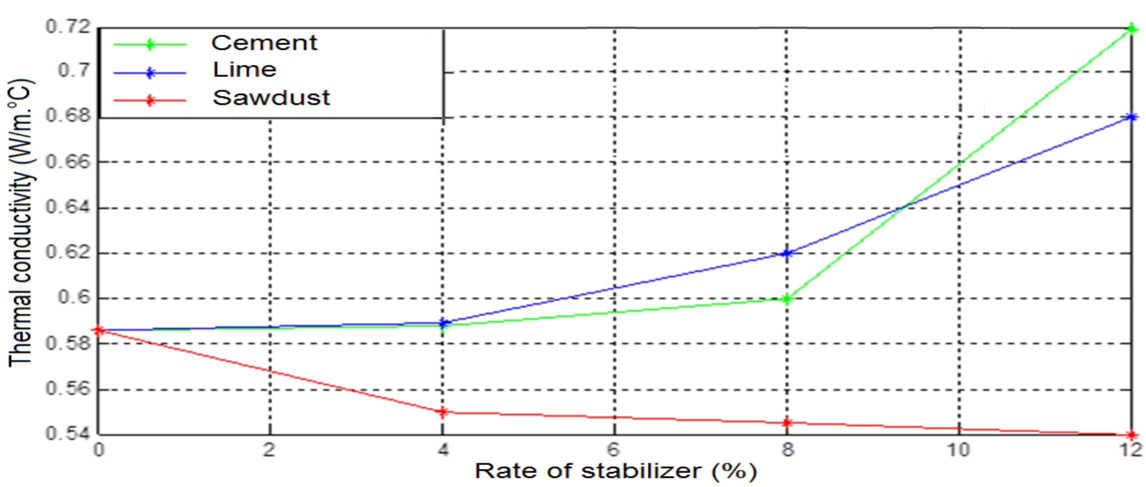


FIGURE 15. CURVES OF THERMAL CONDUCTIVITY DEPENDING ON THE RATE STABILIZERS.

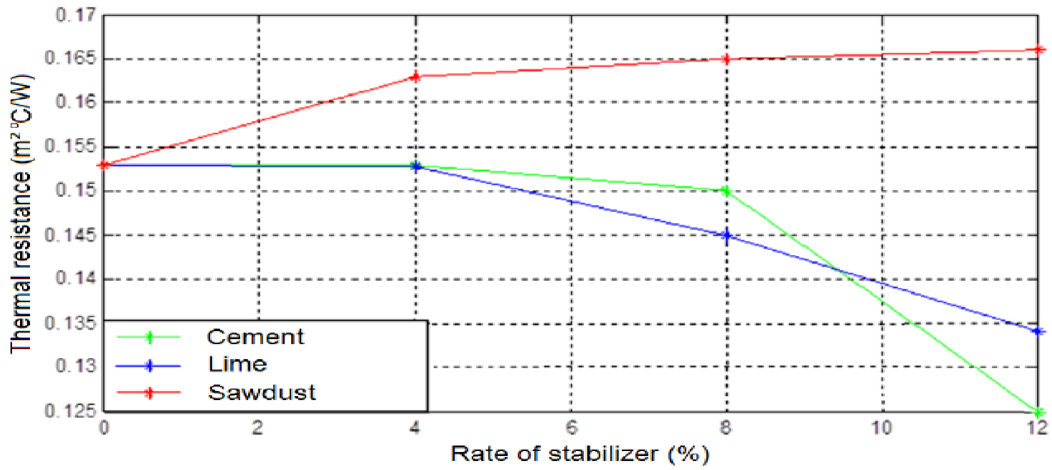
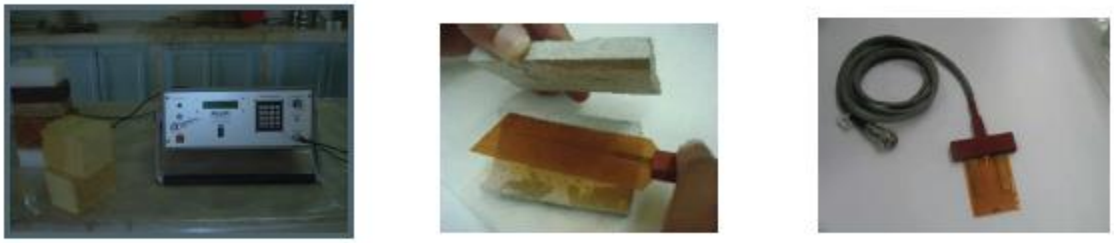


FIGURE 16. CURVES OF THERMAL RESISTANCE DEPENDING ON THE RATE OF STABILIZERS.

H. Benouali et al [50] studied thermophysical characterization and thermal monitoring of two buildings built by compressed earth blocks. The objective of this work is to develop and quantify these performances in winter and summer seasons, the National Center of studies and Integrated Research on Building Engineering in Algeria built and instrumented two residences made of CEB, in order to describe their thermal behavior of summer and winter and this, under a climatic external request, representative of the Northern area of the country. The device used to measure the thermal conductivity was the hot wire method (Figure 17). The two buildings designated PB and PM respectively, with approximately 80 m² of living space each and obeying the principle of bioclimatic, are both made on the ground floor, on the same site, with the same material and the same construction method, but with differences in the design of walls and roofs. The PB prototype (Figure 18) is made of a homogeneous load-bearing wall of compressed earth blocks with a flat roof comprising a layer of cork insulation, while for the PM prototype (Figure 18), the walls are insulated. from the outside by 9 cm of expanded polystyrene (PES) and a flat roof insulated by 16 cm of PES and surmounted by a sloping roof in tiles, on which is placed an area of 8 m² of solar panels. The behavior of these constructions is described and the parameters of thermal inertia of the wall are determined. It is found that a construction wall made of the CEB homogeneous material seems able to fulfil the passive heating and cooling needs.



(a) (b) (c)

FIGURE 17. CT-METER (A), PROBE FOR MEASURING THERMAL CONDUCTIVITY (B), PROBE FOR MEASURING SPECIFIC HEAT (C).

Prototype MEDENEC (PM) Prototype Bioclimatic (PB)

FIGURE 18. CEB BUILDINGS MADE AT CNERIB.

The thermophysical characteristics of the CEB are used in the construction of the two prototypes PB and PM are given in table 7.

TABLE 7. THE THERMOPHYSICAL CHARACTERISTICS OF THE CEB.

ρs (kg/m^3)	λ exp (W/m °C)	α exp. (m^2/s)	Cp exp. (W.S/kg.°C)	b exp. W/(m^2.°C.$S^{1/2}$)
2000	1,10	$5{,}5\ 10^{-7}$	936	1416

Two sequences in extreme climatic conditions were used in this study a day representative of a hot and sunny summer (August 29, 2010), and a day representative of a cold and sunny winter (January 27, 2011). The extreme values of the hygrothermal parameters relating to these two sequences are given in table 8. For the maximum internal temperature, its examination (Table 8) shows for the prototype PB (resp. PM), a maximum summer temperature significantly lower than that of the external. A drop of 5.75 ° C (resp. 10.7 ° C) is noted. In winter, this drop is 3.5 ° C (resp. 7 ° C). For minimum internal temperatures, the PB prototype (resp. PM) offers a higher internal summer temperature than the external. A gain of 8.33 ° C (resp. 3.5 ° C) is observed. In winter, the gain becomes 6.5 ° C (resp. 2.6 ° C).

TABLE 8. MAXIMUM AND MINIMUM VALUES OF PARAMETERS FOR A SUMMER AND WINTER DAY.

		T int (°C)		Text (°C)	HR int (%)		HR ext (%)
		P B	PM		PB	PM	
Max	Eté	32,71	27,8	38,46	67	68	96,00
	Hiver	17,27	13,8	20,8	56,5	80	87
Min	Eté	30,92	26,1	22,59	64	41	30
	Hiver	16,37	12,5	9,9	55,5	75	34

Souhaila Boussaid et al [51] studied thermal behavior of cement stabilized earth. The study is interested in the thermal behavior of the earth stabilized with cement. The thermal behavior of soil in the presence of water has been highlighted by studying the influence of water content on the apparent thermal conductivity and diffusivity of the material. The device used to measure the thermal conductivity of the samples was the box method. Thermal parameters change dramatically and in a non- linear way with their water content the unstable raw ground (Figure 19).

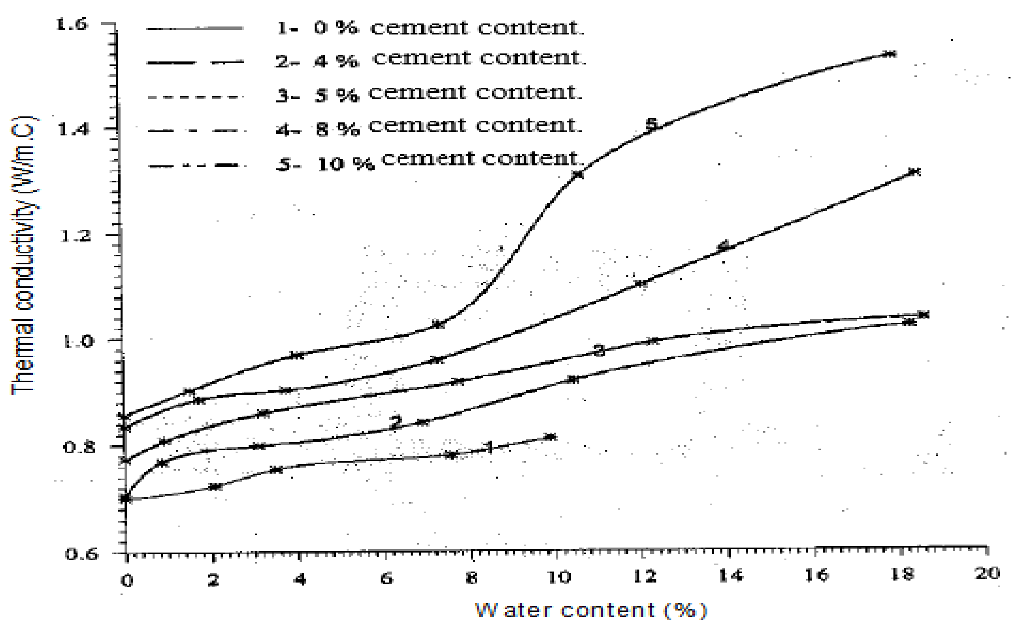


FIGURE 19. THERMAL CONDUCTIVITY OF THE SAMPLES DOSED AT DIFFERENT PERCENTAGES OF CEMENT ACCORDING TO THE VOLUME OF WATER CONTENT.

Taha Ashour et al [52] studied thermal conductivity of unfired earth bricks reinforced by agricultural wastes with cement and gypsum. The research objective of this study is the stabilized soils with natural straw fibers to produce a composite, sustainable, non-toxic and locally sourced building material. The earth bricks consist of soil, cement, gypsum and straw fibers. Two fiber types were used: wheat and barley straw. The device used to measure the thermal conductivity was the QTM-500 -Meter from the brand 'Kyoto Electronics' (Figure 20). The results revealed that the blocks manufactured with wheat straw fiber have a relatively high. The results illustrate that increasing fiber percentage either wheat or barely, caused thermal conductivity to decrease in comparison to bricks without reinforcement fibers. Also, increasing barley straw fiber percentage caused thermal conductivity to decrease. Finally, the increasing of gypsum percentage caused thermal conductivity to increase in comparison to brick materials without gypsum. For barley straw fibers, increasing gypsum percentages from 0% to 10% caused thermal conductivity percentages to increase from 0% to 51.6% with the same fiber content (Figures 21, 22, 23, 24 and 25).

FIGURE 20. THERMAL CONDUCTIVITY INSTRUMENT (THE QTM-500 -METER).

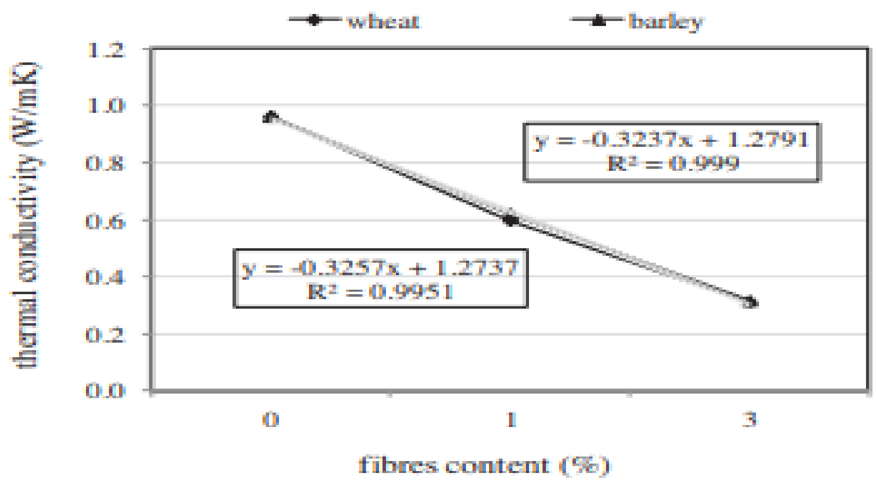


FIGURE 21. THE INFLUENCE OF DIFFERENT PERCENTAGES OF FIBERS CONTENT ON THE THERMAL CONDUCTIVITY OF BRICKS.

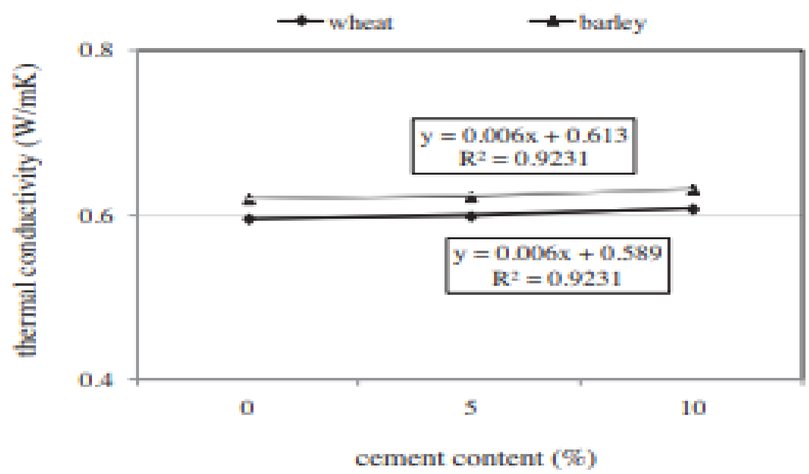


FIGURE 22. THE EFFECT OF CEMENT AND 1% FIBERS CONTENT ON THE THERMAL CONDUCTIVITY OF BRICKS.

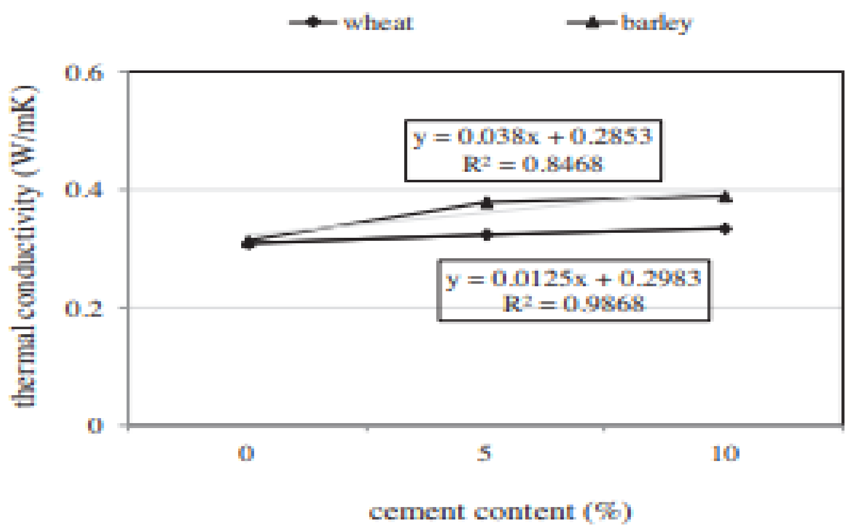


FIGURE 23. THE INFLUENCE OF CEMENT AND 3% FIBERS CONTENT ON THE THERMAL CONDUCTIVITY OF BRICKS.

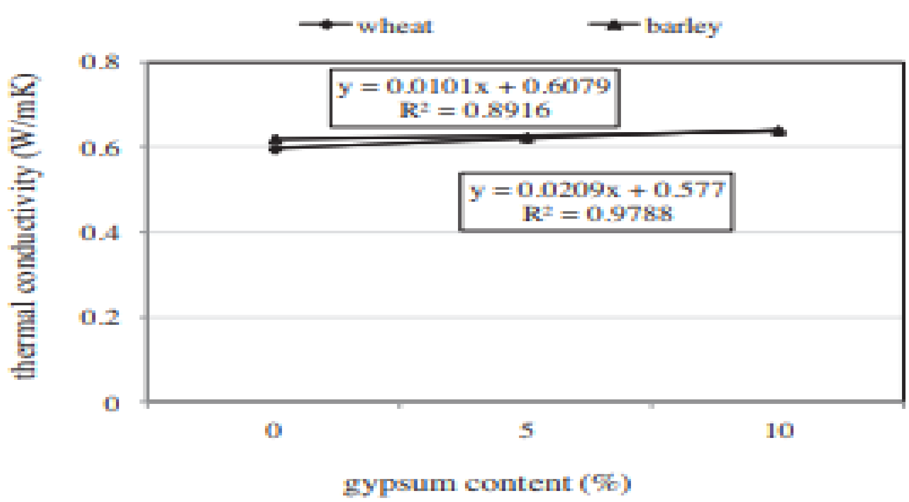


FIGURE 24. THE CONSEQUENCE OF GYPSUM AND FIBERS AT 1% ON THE THERMAL CONDUCTIVITY OF BRICKS.

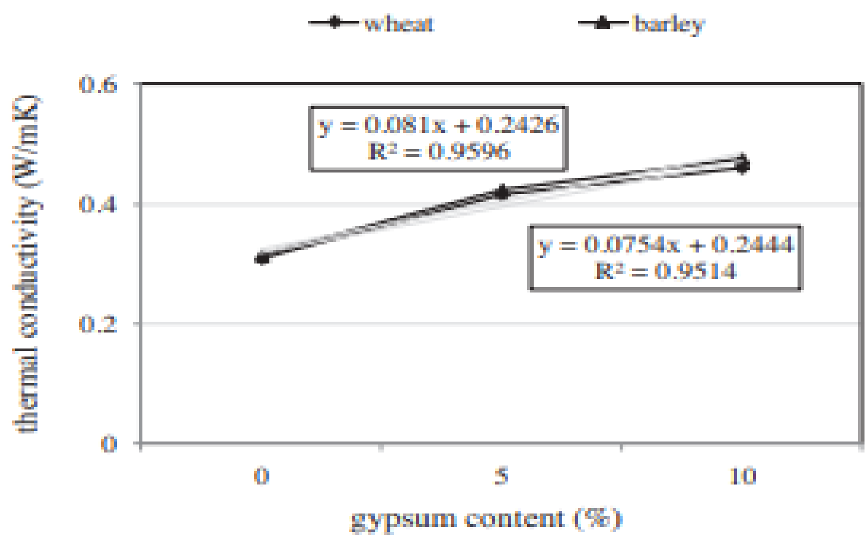


FIGURE 25. THE INFLUENCE OF GYPSUM AND 3% FIBERS CONTENT ON THE THERMAL CONDUCTIVITY OF BRICKS.

Conclusion

Green building is not only related to the management of energy saving and waste management, but also to how well the building materials do not harm the environment, both short term and long term. Energy efficiency and embodied energy, water efficiency and Material Efficiency were the four most important green building. It can be concluded that the most important factors in the construction phase are quality of materials of green building. Building materials for low-cost housing must be produced from locally available raw materials. Furthermore, these raw materials must be abundantly available or they should be renewable in nature. Natural buildings are a subsection of green building that uses actual earth materials for construction: earth, straw, stones, wood and recycled or upcycled materials. An earth is a material that is widely available in almost everywhere in the world and can be used in many types of earth construction, this green material provides unique thermal qualities. And compressed earth block (CEB) construction is the one of earth materials, is an earth-friendly building technology that is superior to concrete and wood construction in terms of its health benefits, affordability, durability, and energy efficiency. CEB technology is a contemporary improvement of ancient earth building methods.

The detailed previous studies have highlighted that earth based alternative materials and systems researched and developed in will have reduced impact on energy use. This is because they have less thermal conductivity. The thermal comfort research studies on alternative and earthen materials have become necessary. Earth construction encompasses several techniques such as, the most usual being: wattle and daub, cob, rammed earth, earth bricks (adobe) or compressed earth blocks (CEB). With its numerous assets such as its availability, recyclability and the low energy required for the transformation process and transportation, earth is increasingly being studied. In our study we choose compressed earth blocks (CEBs), CEBs this technique is inspired by the Rammed earth technique, but instead of building huge molds in the form of walls, mechanical machines have been created to produce brick cladding or compressed with small size and are used as concrete bricks in construction.

Chapter II: Stabilized Compressed Earth Block with Cement

Introduction

In order to manufacture the compressed earth blocks, some soil types are very suitable for certain types of construction, others cannot be used at all. Therefore, the soil quality should be tested to determine its behavior and evaluation. The objective in this chapter is to review the physical and chemical properties of soil, and stabilization of soil and present these parameters for the studied soil material. Stabilization and its effect on soil indicate the reaction mechanism with additives, effect on its strength, improve maintain soil moisture content.

II. 1. Compressed earth block

Compressed earth block (CEB) is obtained by compression of the earth material. It is a mixture of non-plant soil, raw or stabilized, consisting of gravel, sand, and fine particles (silt and clay), and an aggregate binder (cement or lime in many cases). It is slightly moistened, poured into a steel press and then compressed either with a manual or motorized press. It is the modern descendent of both the adobe block and the rammed earth. We can improve the physical and mechanical properties of (CEB) by adding a binder (cement or lime in many cases), as a stabilization process. If the blocks are stabilized with a chemical binder such as cement they are called compressed earth block stabilized (CEBs) [53]. Compaction of earth block causes a reduction in pore volume between the particles of earth block. This reduces the rate at which water can infiltrate and drain through the earth block. Block presses come in many ways: manual or motorized, mechanical transmission, hydraulic or pneumatic [54, 55, 58, 59].

The compressed earth block was introduced in the 19th century in France. The Frenchman architect Jean-François Cointeraux precast small blocks of rammed earth. He used hand rammers to compress the humid soil into a small wooden mold held with the feet: it was the “new pisé” (new rammed). Also, he developed “Crécise,” rammed earth a brick press derived from a wine press. With this earth materials he built the town of La Roche-Sur-Yon on the orders of the Minister of the interior of Napoleon I from 1804 to 1808 (Figure 26) [56, 57].

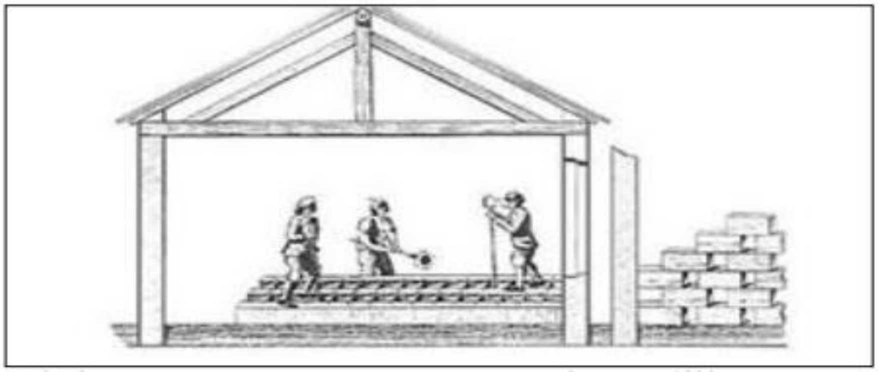


FIGURE 26. ANCIENT COMPRESSED EARTH BLOCKS, MANUALLY RAMMED. FRANÇOIS COINTERAUX, 1803, FRANCE [57].

The turning point in the use of presses and in the way in which compressed earth blocks were used for building and architectural purposes was observed during 1950's, following the invention of the first steel manual press called "Cinvaram". It was the result of a research program conducted by the engineer Raul Ramirez from the Colombian Inter-American Housing Center (CINVA) (Figure 27). This has then been used throughout the world. Within the '70s and '80s there appeared a new generation of manual, mechanical and motor-driven presses, leading to the emergence today of a genuine market for the production and application of the compressed earth block [57].

FIGURE 27. ORIGINAL CINVA RAM PRESS [57].

II. 2. The materials used to manufacture CEB

The mechanical and the thermal behaviors of the CEB depend on the material constituents. All materials used in this work are of local origin to manufacture the stabilized compressed earth blocks. The basic materials required for the production of CEBs are soil, cement stabilizer, and water. It is possible to produce ecological CEB with any kind of soil. The soil may be wet or dry when it is first obtained and will probably not be homogeneous. In order to have uniform soil, it is often necessary to crush it so that it can pass through a 5 mm to 6 mm size sieve.

The cement stabilizer is usually available in powder form, ready for use. Portland cement is standardized and there are a lot of brands on the market. The most used is the CPJ Portland, which we use.

The water we use was taken from the supply network as for drinking water. The water must be added gradually, without exceeding the amount of water required for the mixture, since the moisture has the function to provide the best compaction of the material while the samples manufactured will not stick to the walls of the mold.

II. 3. Procedure to manufacture Stabilized Compressed Earth Blocks

To manufacture the samples of (CEBs), it must be the collected good quality of soil. To know that, we are conducted several soil identification tests. Then, comes the process of stabilization of soil. Finally, Production of CEBs.

II. 3. 1. The earth material

II. 3. 1. 1. Definition

Soil is a mixture of minerals, organic matter, air, water, and microorganisms that forms at the surface of the earth. It is also known as a mixture of rocks particles, sand and humus, formed by geological phenomena and weathering. Weathering is the process of breaking down rocks by the action of the more or less simultaneous interaction of climatic factors (sun, wind, rain, frost) and chemical changes, brought about by biological agents (plants and animals) and migration of chemical substances through rain, wind, evaporation, surface and underground water. Soil can be broken down into two main parts: Agricultural soil or vegetation soil used for the production of plant and animal biomass. Then, the subsoil is low in organic matter, which provides the basic materials for construction [60], [61], [62], [63].

II. 3. 1. 2. Soil horizons and the layer of soil for earth construction

The soil is composed of horizontal layers with different physical or chemical characteristics and varying in thickness and color. These layers, called horizons, are represented a distinct soil that has built up over a long time period. The layers together form the soil profile. Soil scientists have created many different designations for different types of soil horizons. The first layer is called agricultural soil or vegetation soil, (up to 60 cm deep) used for the production of vegetal biomass and animal. It consists of a mixture of organic material with inorganic products of weathering; it is the beginning of a true mineral soil [60]. This horizon is typically darkly colored because of the presence of organic matter. The second layer is called subsoil layer, between 60 cm and 160 cm, poor in organic matter, often light- bright in color. It is an accumulation of mostly fine material that has moved downward, resulting in a dense layer in the soil such as clay and calcium carbonate. It also contains fragments of the rock that resisted the processes of alteration. This layer provides the basic material of earth construction. The third layer consisting of the layer formed by the solid rock (Figure 28) [63].

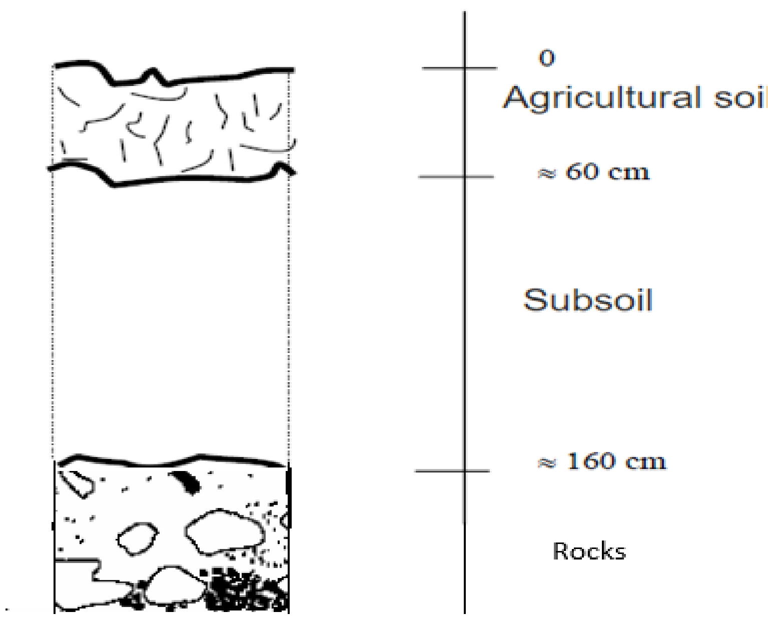


FIGURE 28 . SOIL HORIZONS [60].

II. 3. 1. 3. Soil constituent

The four major components of soil are: mineral matter, organic matter, water, and air or gas (Figure 29). The components of soil depend on the quantity of vegetation, soil compaction, and water present in the soil. Mineral matter forms count for about 40 to 45 percent of the soil volume. Mineral matter is the structure of the metaphorical soil apartments and provides the playground for materials to move. Mineral soil is composed of particles called gravel, sand, silt and clay particles, it's what forms the texture of the soil. These particles have voids or pores between them, and the pores are filled with either air (gas) and water. In general, water forms count for about 25 percent of the soil volume, and air forms for about 25 percent of the soil volume. Organic matter is called humus, forms weighting on average about 5 percent of the soil volume. The amount of the components is highly variable in the soil, depending on some factors such as soil management, cropping systems, and climate.

The classification of the soil material is made according to its organic and mineral composition, and also according to its particle size which is dimensional. It gives the weight percentages of the grain fractions in the solid phase as a function of their diameters. We distinguish in a material, gravel, sand (Coarse and fine), silt and clay.

The particle classes are defined according to the following dimensions (Table 9):

TABLE 9. THE PARTICLES CLASSES OF SOIL.

Stone		> 60 mm
Gravel	Coarse gravel	20 – 60 mm
	Medium gravel	6 – 20 mm
	Fine gravel	2 – 6 mm
Sand	Coarse sand	0.6 – 2 mm
	Medium sand	0.2 – 0. 6 mm
	Fine sand	0.06 – 0.2 mm
Silt	Coarse silt	0.02 – 0. 06 mm
	Medium silt	0.006 – 0.02 mm
	Fine silt	0.02 – 0.006 mm
Clay		< 0.002

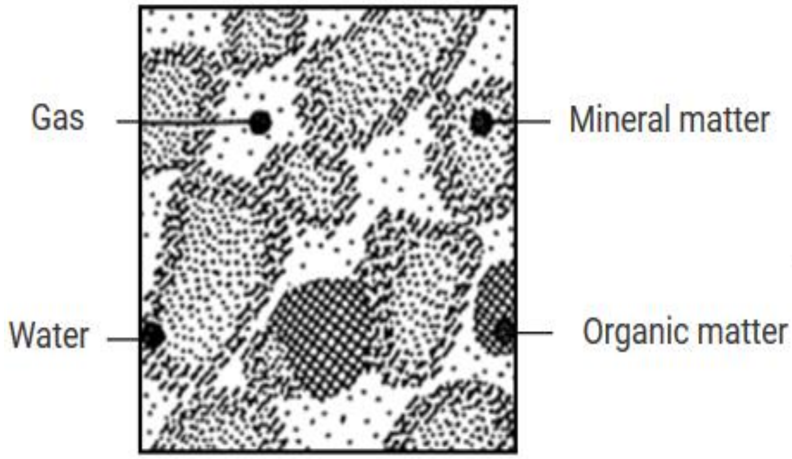


FIGURE 29. CONSTITUENT OF SOIL.

The compositions of these classes in the material determine its texture and ability to be used appropriately for a given application [60], [63], [64], [65].

II. 3. 1. 4. Appropriate soil for stabilized compressed earth block

The usage of earth in construction does not imply that any earth material is suitable for this technique. Identifying the properties of a soil is essential in producing good quality products. For example, cement stabilization will be better for sandy soils, and lime stabilization for clayey soils. From these properties it will be possible to have an idea of what to do with this soil (Table 10). In the past, the skilled builders had developed a sense that allowed them to appreciate in the field the aptitude of the earth by a visual examination, a touch test, etc. Currently, the earth material must first undergo a series of laboratory tests to characterize its ability to be used in earth construction or in other areas [66], [67].

TABLE 9. SUITABLE CHARACTERISTICS OF SOIL FOR STABILIZED COMPRESSED EARTH BLOCK (ACCORDING TO AFRICAN STANDARD) [67].

Characteristic	Limit
Organic matter	2% to 4%
Fine gravel and sand	50% to 70 %
Silt	15% to 30 %
Clay	5% to 15%

Binding strength	80 mm - 120 mm
Shrinkage	≤0.05%
Maximum particle size (MPS)	10-20a)
Maximum and minimum liquid limits (LL)	25–46
Plasticity indexes (PI)	2–30
Wet density	1850 to 2100 kg/m3
Dry density	1700 to 2200 kg/m3
Dry compressive strength	1 to 15 MPa
Bending strength	0.5 to 2 MPa
Thermal resistance (300 mm thick wall)	0.35 to 0.70 m^2. K/W
Optimum moisture content	3.5% to 14%

The good knowledge of soil components and its characteristics are necessary to be able to determine the possibilities of its use for construction, as well as the nature and quantity of materials used for stabilization to add, to get blocks of good quality. We used a number of simple tests which can give useful information (granulometry, sedimentometry, liquid limit, plastic limit, plasticity index, the activity coefficient, the surface area, water content, dry density). Our reference criteria for soil selection are the recommendations by CRATerre (Centre International de la Construction en Terre).

II. 3. 2. Identification of soil as building material (Laboratory tests)

II. 3. 2. 1. Physical analysis of soil

a. Granulometry of soil (Particle-size distribution)

Granulometry is an essential physical property of soils, is the measurement of the size distribution of the grains; also called particle size distribution test. Often characterized by the percentage of particles with certain diameter ranges (in micron meters). The particle size analysis makes it possible to determine the respective quantity of the different elements constituting of soil: gravels, sands, silts and clays [68], [69], [70], [71]. Two methods are used to determine the curve of particle size of soil: sieving and sedimentation (or laser). Sieve analysis consists of filtering the soil on the fraction of grains larger than 0.08 mm (80 μm) through a series of standard sieves superimposed in descending order (the finest below) and determining the fractions of grains retained by each sieve (Figure 30).

FIGURE 30. THE GRAIN SIZE DISTRIBUTION ANALYSIS.

b. Sedimentation

Sedimentometry is the complement of the particle size, is carried out on the fraction lower than 80 microns meters for which it is difficult, even impossible, to make it pass by very fine sieves (Figure 31). From particle size and sedimentometry together, it allows to establish the granulometric curve of the earth. In order to use this earth for construction, it is recommended that its granulometric curve be between the fuseau limits (|CRATerre [33]), approaching better the ideal curve (Figure 32).

FIGURE 31. SEDIMENTATION ANALYSIS.

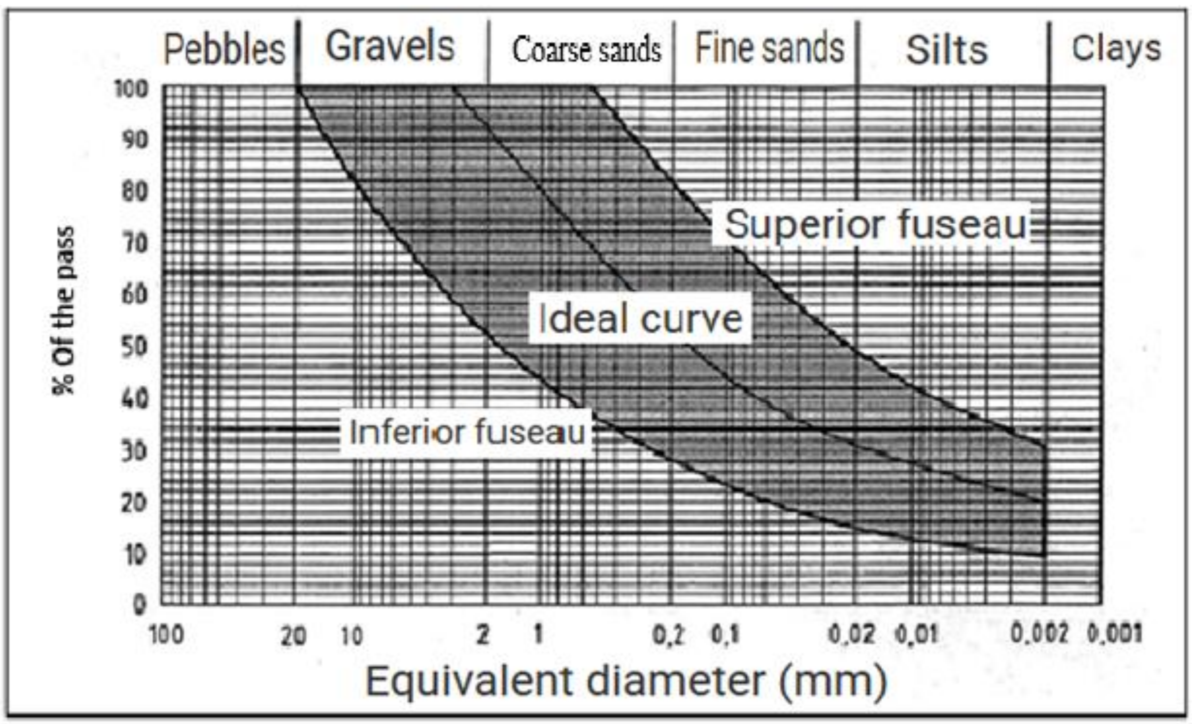


FIGURE 32. DIAGRAM OF GRANULARITY.

c. Plasticity

The moisture content of the soil is one of the characteristics that is most frequently determined. In the case of moist soil, it has various states of consistency: solid, plastic or liquid. The analysis of the plasticity is done on the fine granular fraction clay and serves to determine the variation of consistency and its cohesion. The plasticity of an earth material is evaluated by the calculation of the quantities called Atterberg limits (Consistency Limits). Atterberg Limits testing is a group of tests used to define the properties of cohesive soils at different moisture contents. The following moisture conditions - liquid limit (LL), plastic limit (PL), shrinkage limit (SL) and Plasticity index (PI) are referred to as the "Atterberg Limits". Liquid limit (LL) (Figure 33) is the water content at which soil changes from a plastic to a liquid state. This occurs at very high-water contents when the soil behaves as a viscous liquid in that it flows and will not hold a specific shape. Plastic limit (PL) (Figure 34) is the water content at which it changes from a plastic to a semisolid state. Shrinkage limit (SL) is the water content at which there is no more volume change in the soil due to reduction in water. Plasticity index (PI) is the range of moisture content in which the soil is plastic; the finer the soil the greater is its plasticity index [72], [73].

Plasticity index = liquid limit - plastic limit

$$\mathrm{PI} = \mathrm{LL} - \mathrm{PL} \qquad (\mathrm{II.1})$$

According to CRATerre, the higher the index PI is, the higher swelling by humidification and shrinkage by drying, the earth will be important.

FIGURE 33. LIQUID LIMIT TEST PROCEDURE OF SOIL FEZ.

FIGURE 34. PLASTIC LIMIT TEST PROCEDURE OF SOIL FEZ.

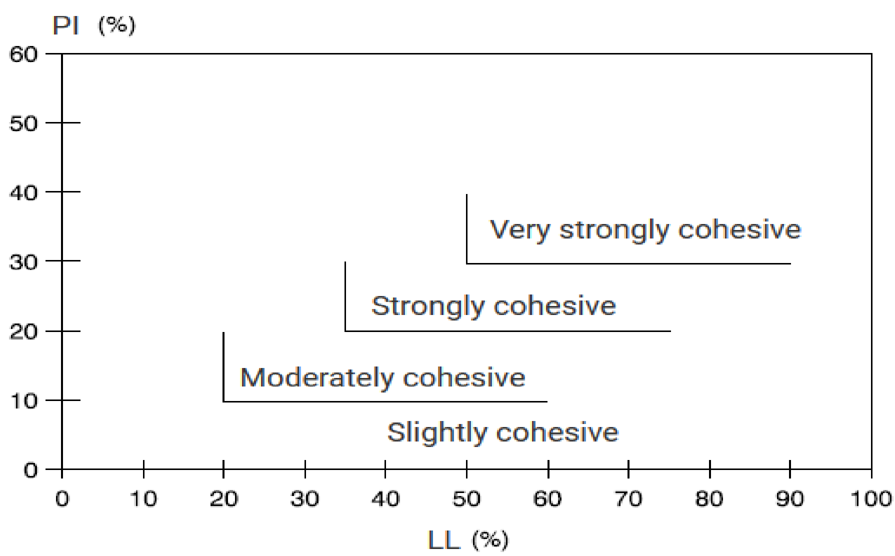


FIGURE 35. COHESION DIAGRAM.

Figure 35 shows the different zones associated with the cohesion of the earth as a function of the liquidity limit and the plasticity index.

d. The coefficient activity

In any particular clay stratum, the ratio of the plasticity index to the clay fraction content is approximately constant and may be defined as the "activity coefficient" of the clay [74], [75], [76]. The activity coefficient gives an indication of the swelling and shrinkage of the material, particularly its clay. It is determined by the ratio of the plasticity index to the percentage of clay in the earth. It is noted by Ca and expressed by:

$$Ca = \frac{PI}{\% \text{ Argile } (\emptyset<2\mu m)} \qquad (II.2)$$

The different zones of activity are described in figure 36.

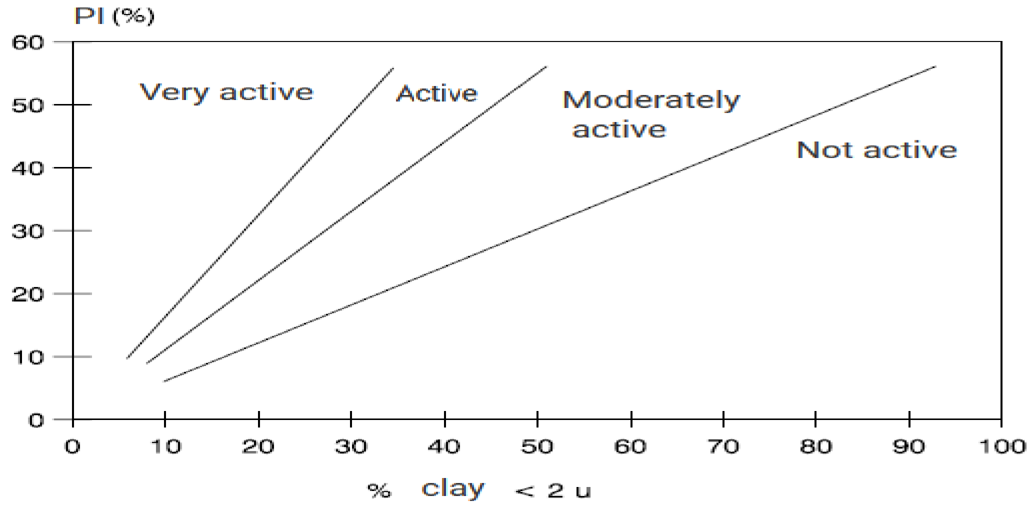


FIGURE 36. ZONES OF ACTIVITY OF THE CLAY FRACTION.

Four classes of clay were recognized, according to their activity levels, namely “inactive”, “normal”, “active” and “very active” as follows (Table 11):

TABLE 10. COEFFICIENT ACTIVITY.

Activity	Inactive clay	Normal clay	Active clay	Very active clay
Ca	< 0,75	0,75 < Ca < 1,25	1,25 < Ca < 2	> 2

f. Methylene blue adsorption test (MBA)

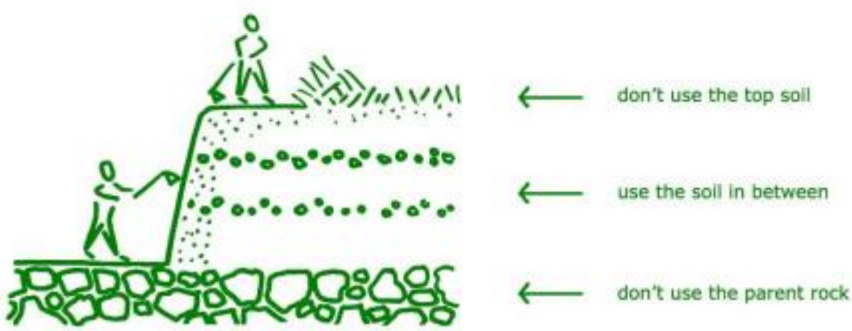
This test evaluates the clay richness of a soil by measuring its adsorption capacity of methylene blue molecules. The purpose of this test is to evaluate the clay overall richness of a soil, which depends both on the nature of the clay and its quantity [77]. This measurement uses the adsorption properties that the clay particles are almost alone to possess in the soil, and because of their surfaces are electrically charged, they adsorb a proportion of methylene blue proportional with the available surfaces, when they are put in the presence of a solution of this dye (Figure 37). The nature of the clay fraction is expressed in this test by the specific surface. For a given soil, the total surface developed depends on the mineralogical nature.

Calculation of the surface area, can be calculated starting with the Blue Value 'BV', and is given by:

$$S_a = 21B_V \qquad (II.3)$$

FIGURE 37. ELECTRIC MIXER USED FOR STIRRING THE SOIL-METHYLENE BLUE SOLUTION.

g. Organic matter



As mentioned previously, there are four main components of soil: mineral matter (sand, silt and clay), organic matter, air and water (Figure 29). Organic matter is any living or dead animal and plant material. It is the top of soil, humus, agricultural soil, and peat, including living plant roots and animals. Plant and animal remains at various stages of decomposition, and microorganisms and their excretions. Most soil organic matter is present near the soil surface, rather than deeper in it. It is generally 25 to 50 centimeters thick, but the depth of this organic top soil rarely exceeds 1 to 2 meters [78], [79]. Organic matter, serving as a reservoir of nutrients and water in the soil, aids in reducing compaction and surface crusting, and increases water infiltration into the soil, due to its tremendous surface area, leads to act like a sponge to store water, but reduces thermal conductivity. It is not recommended to use organic soils for any type of earth construction, because of its low mechanical strength and its high ability to absorb water [80], [81]. According to Gomes, Maria Idália et al [82] earthen buildings, where the percentage of organic matter is significant, are more likely to present anomalies caused by the presence of moisture or biodeterioration processes. This has been deduced by several criteria for organic matter and are reported in table 12 as requirements indicated by different references for the organic content of soils for rammed earth construction. As seen, there is a wide consensus that soils with large quantities of organic matter (either microscopic or macroscopic) should not be used. However, quantitative threshold limits are rarely indicated or accepted.

TABLE 11. REQUIREMENTS FOR ORGANIC MATTER [82].

Reference	Requirements for the content in organic matter
Keable (1996)	"Soil shall be free from organic material"
NZS 4298 (1998)	"Soil shall not be used if contains organic matter prone to rot or breakdown within the wall"
SAZS 724 (2001)	"Soil should be free from organic material"
Walker and Standard Australia (2001)	"A musty aroma indicates an unacceptable quantity of organic matter and the soil should, therefore, be rejected"
Walker et al. (2005)	< 2% by mass
Houben and Guillaud (2006)	< 2 to 4% by mass
New México Code (2006)	"The soil shall be free of all organic matter"
Lehmbau Regeln (2009)	The smell test is sufficient for rejection of a soil

II. 3. 2. 2. Chemical and mineralogic analysis of soil

a. X-ray fluorescence analysis

To analyze the chemical elements and determine the proportions of the mineralogical elements in the F earth, the UATRS laboratory of the CNRST Rabat has carried out the X-ray fluorescence analysis [83]. X-ray fluorescence spectrometry is a technique for the elemental analysis of the chemical elements present in a material and the determination of their respective quantity [84].

b. Determination of the carbonate content (CaCO3)

Calcium carbonate is one of the natural cementing agent which participate in the binding of soil particles together through physico-chemical mechanisms and presumably create a stable soil structure. Soil carbonates play a major role in soil respiration positively or negatively depending on the soil type, the weather conditions, soil texture, soil pH etc. The test method called calcimeter method (Figure 38) is used to determine the presence and quantity of calcium carbonate in our soil sample. The calcium carbonate content of soil is determined by treating 1g dried soil specimen with hydrochloric acid (HCL) in an enclosed reactor vessel. Carbon dioxide gas is then evolving during the reaction between the acid and carbonate fraction of the specimen. The resulting pressure generated in the closed reactor is proportional to the carbonate content of the sample.

The chemical reaction equation used for the measurement of the soil CaCO3 content is the same with the calcimeter method:

$$\mathrm{CaCO_3} + \mathrm{2HCL_2} \rightarrow \mathrm{CaCL_2} + \mathrm{H_2O} + \mathrm{CO_2} \qquad (\mathrm{II.}\,4)$$

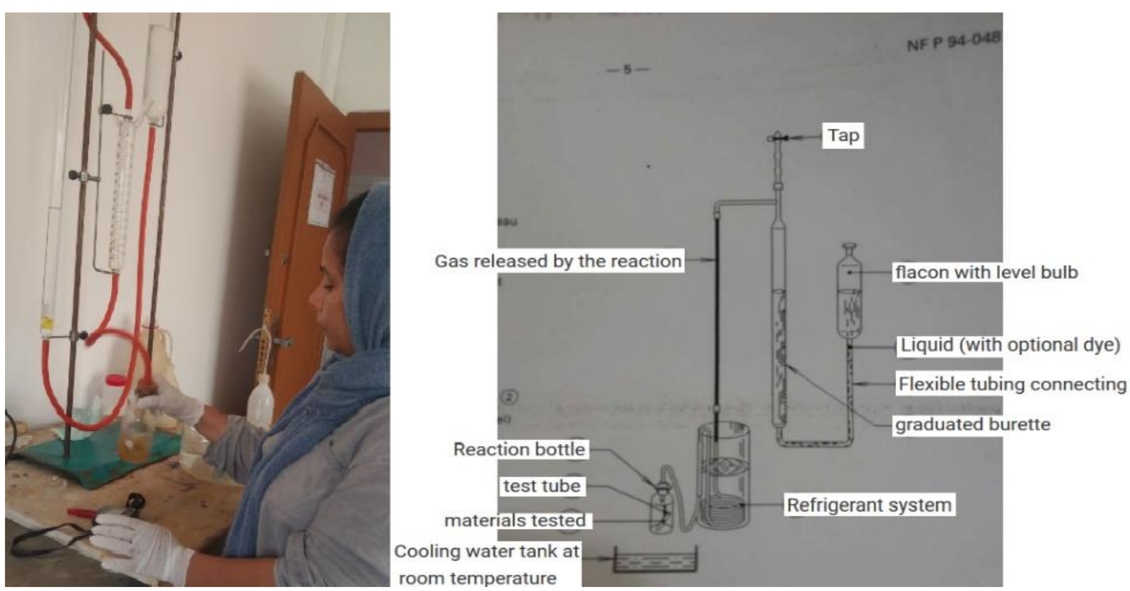


FIGURE 38. CALCIMETER METHOD.

The carbonate content for a sample of material of mass m is, when the atmospheric pressure between the test on that material and the test on the mass reference sample mt has not varied (Eq. II. 5):

$$\text{Carbonate content} = \left(\left({}^{m_t}/_{m} \right) \times \left({}^{V_b}/_{V_t} \right) \times \frac{(\theta t + 273)}{(\theta b + 273)} \right) \times 100 \qquad (II.5)$$

TABLE 12. MASS OF THE TEST SAMPLE ACCORDING TO THE PRESUMED CARBONATE CONTENT [85].

Carbonate content presumed in percent (%)	< 4	4 to 9	10 to 19	20 to 39	40 to 79	≥ 80
Mass of the test sample of dry material in (g)	10	5	2,5	1	0,5	0,25

TABLE 13. CLASSIFICATION OF MATERIALS ACCORDING TO THE CARBONATE MASS PERCENTAGE.

Carbonate content (%)	Classification
< 10	Non- calcareous
10 to 29	little- calcareous
30 to 69	moderately- calcareous
70 to 89	strongly- calcareous
≥ 90	calcareous

II. 3. 3. The stabilization

Stabilization of soil refers to the process of changing soil properties to improve strength and durability. It is a method of transforming a natural soil into a purpose of engineered construction material. The changes in the soil properties are done by changing it physically, chemically, biologically, or combined methods. There are many techniques for stabilization soil, including granulometry, compaction, dewatering and by adding other materials to the soil as a stabilizer [86], [87]. The characteristics of many soil types can be greatly improved by the addition of stabilizers. According to ARS 670, the stabilization additive is the product used in the manufacture, in order to improve the final characteristics of the CEBs or to develop particular characteristics [88], [89].

II. 3. 3. 1. The objectives of stabilization

It is not always possible to find required or specified performance in locally available material; thus, we can apply the soil stabilization methods. So, in this case, the stabilization of soil can be treated in its structure and its texture [90] to [100]:

To avoid surface abrasion and increasing waterproof (swelling, shrinking with moisture content variations, high plasticity and difficulty in compacting). We must reduce the porosity (the volume of voids between the particles) of the material and its sensitivity to water to obtain a better cohesion between the grains of the material.

To improve mechanical properties of the earth by increasing the cohesion through improving the links binding the particles together, affecting its mechanical strength and Young's modulus, that lead to the reinforcement of the soil and increase its durability.

II. 3. 3. 2. Stabilization processes

Stabilization comes in different processes:

- Mechanical stabilization: This is the process of improving the properties of the soil by changing its gradation. It consists of compacting the soil to remove out the maximum of air, this lead to high density and mechanical strength. The water resistance is also increased and the permeability and porosity decreased.

- Physical stabilization: the properties of a soil can be modified by treating its texture, such as sieved the soil to remove the coarse particles. When we have different soil, we can mix them to get a better texture, adding gravel or sand to reinforce the skeleton or adding clay to bind the grains better.

- Chemical stabilization: soil stabilization depends mainly on chemical reactions between stabilizer and soil minerals to achieve the desired effect. There will be either a physicochemical reaction with the grains or the creation of a matrix which binds the coarse grains. The most common stabilizers are cement, lime and bitumen. On one hand, the reaction helps binding the grains of the earth, the water resistance is increased and the permeability and porosity are decreased [101]. On the other hand, these benefits bring significant disadvantages for example increase costs, increase the carbon footprint of construction and complicate recycling of demolition waste.

II. 3. 3. 2. 1. Proctor Soil Compaction Test

The water content of soil used for the production of CEBs is often determined the according to standard Proctor test. The Proctor compaction test is a laboratory geotechnical testing method used to determine the soil compaction properties, specifically, to determine the optimal water content at which soil can reach its maximum dry density (ρ_d max) (Figure 39).

FIGURE 39. PROCTOR SOIL OF FEZ COMPACTION TEST.

This is the ability of a soil to be compressed to its maximum and reduce the porosity within it to a minimum. It is related to the energy of compaction and to the optimum moisture content. The maximum dry density occurs at an optimum water content (Figure 40) [60], [63]. For most soils and for a given compact effort, the density of the soil will increase to a certain point and decrease afterwards, as the moisture content increased [83], [102]. That point is called the maximum density. The moisture content at which maximum density occurs is called the optimum moisture content (OMC), each compact effort for a given soil has its own OMC. As the compact effort increased, the maximum density generally increases and the OMC decreases.

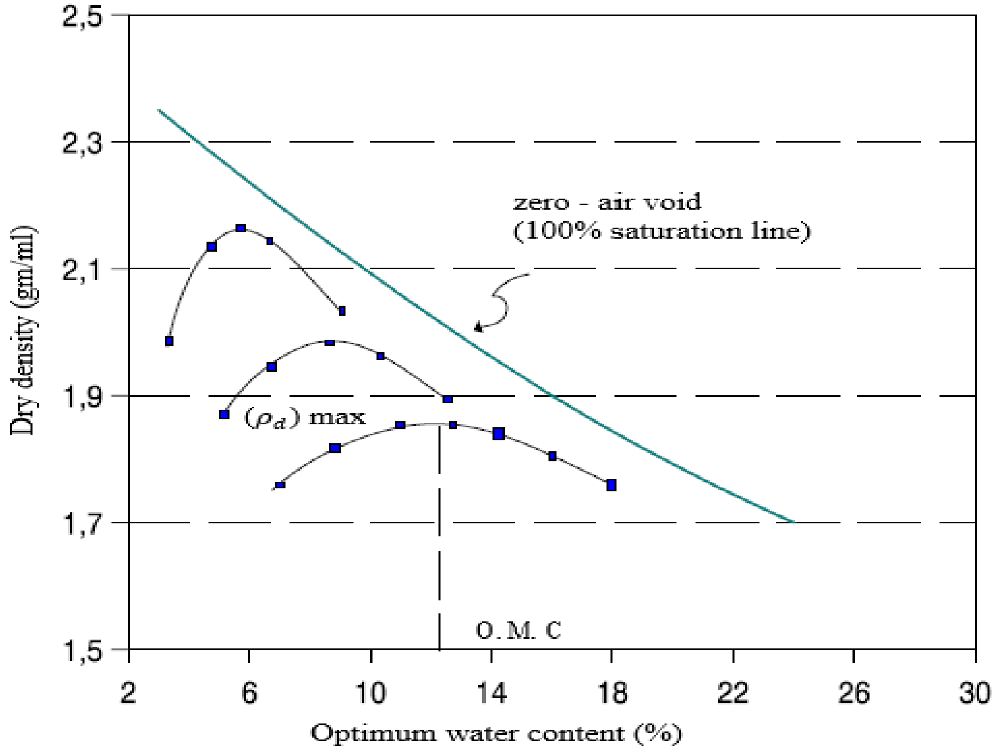


FIGURE 40. SOIL COMPACTION CURVE.

II. 3. 3. 2. 2. Cement Stabilizer

Cement is a soft bind material, a powder-like material. Harden and become stiff when mixed with water, to become able to bind concrete components each other, to form strong building materials, resistant to various environmental influences. The mixture of natural raw materials used in the manufacture of cement consists of (limestone, clay, kaolin, sand and iron ore), so that the limestone forms the highest proportion of the mixture by about 80%. The manufacture of cement starts by burning this mixture at specified rates at high temperatures up to 1400-1500 ° C for the production of molten medium clinker.

Throughout history, cementing materials have played a vital role and were used widely in the ancient world. The Egyptians used calcined gypsum as a cement and the Greeks and Romans used lime made by heating limestone and added sand to make mortar, with coarser stones for concrete. The first cements were from Ancient Egypt. They actually made plaster from gypsum.

The Romans produced lime from calcite. It is an inefficient binder.

$$\underbrace{CaSO_4.2H_2O}_{\text{Gypsum}} \xrightarrow{150°C} \underbrace{CaSO_4.{}^{1}/_{2}\,H_2O}_{\text{Plaster}} \qquad (II.6)$$

The Romans produced lime from calcite. It is an inefficient binder.

$$\underbrace{CaCO_3}_{\text{Calcite}} \xrightarrow{900°C} \underbrace{CaO + CO_2}_{\text{Lime}} \qquad (II.7)$$

Modern cement was invented in XIX° century. It is made from calcite and clay.

$$\underbrace{CaCO_3}_{\text{Calcite}} + \underbrace{SiO_2}_{\text{Clay}} \xrightarrow{1500°C} \text{Siliceous cement (Portland)} \qquad (II.8)$$

$$\underbrace{CaCO_3}_{\text{Calcite}} + \underbrace{Al(OH)_3}_{\text{Bauxite}} \xrightarrow{1500°C} \text{Aluminous cement(Lafarge)}$$

$$(II.9)$$

There are many kinds of cement. In this study, I used Portland cement CPJ 35 and which I have studied its mineralogical composition.

a. Cement (Portland CPJ 35)

Clinker is the main material for the Portland cement and results from the cooking of calciferous rocks, contains between 30 and 40% of clay all this is under temperature ranging between 1000 and 1500 ^{0}C. Since it is not affected by the water, it must be crushed and add 3 to 5% of gypsum before the final cooking. Basic chemical constituents of Portland cement are (CaO, Al2O3, Fe2O3 and SiO2), and there are some secondary chemical constituents for Portland cement such as magnesium oxide and other oxides of other elements that are formed as a low impurity in cement. Generally, Portland cement is the most common type of cement used in building construction. It is a fine powder which is produced by grinding and heating the clinker in a kiln (more than 90%), and by adding 5% calcium sulfate to control the setting time. Portland cement clinker as a hydraulic material, consists of two-thirds of calcium silicates (3CaO.SiO2 and 2CaO.SiO2) by mass, and the other one third consists of alumina, iron and other compounds. Cement is used to improve both of the dry and the wet compressive strengths [103], [104]. Also cement gives the resistance to erosion, rain and abrasion. To have a good quality, it is important that the cement is well-mixed with the soil. Based on the type of the soil, some soils require 3 to 4% original material addition of cement, but normally it ranges from 3 to 15%.

b. Mineralogical composition of cement (Portland CPJ 35)

Portland cement clinker is nodules of sintered material produced by heating a homogeneous mixture of raw materials in a kiln to a sintering temperature of approximately 1500 °C for modern cements. There are 4 major phases in a clinker:

1. Ca_3SiO_5 or C_3S, the alite composing 50 to 70%.
2. Ca_2SiO_4 or C_2S, belite constituting 10 to 30%.
3. $Ca_3Al_2O_6$ or C_3A, the aluminates composing 5 to 12%.
4. $Ca_4Al_2Fe_2O_{10}$ or C_4AF, the ferrites composing 5 to 12%.

To finalize the cement, add to the clinker:

1. $CaSO_4$ or $C\hat{S}$, anhydrite.
2. $CaSO_4 \cdot 2\,H_2O$ or $C\hat{S}H_2$, gypsum.

II. 3. 4. Production of compressed earth block (CEB)

At the beginning, the subsoil is excavated after the removal of the topsoil. Soil for block making has been carefully free from organic matter such as weeds and roots, which may interfere with the setting and hardening of the cement (stabilizer). Then it is crush so that it can pass through a 6mm mesh sieve to have uniform soil. The second stage was to complete all the laboratory tests described previously. To achieve satisfactory mixing, brings the stabilizer and soil into direct contact, homogeneous color is first obtained in mixing the dry components (soil and cement). Mix initially with spade and subsequently with hand [105], [106]. The mixing is completed when the mixture attains a uniform color. This dry mixing of the materials was done repeatedly for about four to five minutes. Wet mixing shall commence by adding a little water at a time to the dry mix, spray gradually over the top of the mixture and the wet mix turned over with a suitable tool and subsequently with hand, until all the water has been mixed. The mixing is completed when the mixture attains a uniform color and be homogeneous. The moisture of the mixture is checked by simple procedure: we press in hand the mass vigorously, which should form a cake with clear imprint of the fingers (Figure 42). If cement is used for stabilization, the mix shall be used for molding quickly because cement starts to hydrate quickly after it is wetted and delays will result in the production of poor quality blocks. For this reason, the quantity of cement- soil mix should not exceed what is needed for one hour of operation. Even though, the blocks produced at the end of one hour may be considerably weaker than those produced immediately after the mixing. After the completion of wet mixing the molding and compaction of the wet mix was performed [107]. It can be compressed using a variety of block making machines, including hydraulic presses, mechanical presses and various combinations. Some mechanical presses are small enough to be operated by hand. The wet mixture of soil (semi-dry mixture) is loaded into the mold cavity [108]. Compaction is attained by pulling the lever down from the suitable height and the compressed block is ejected [109]. The sample is to be removed from the mold and on a leveled ground under plastic sheet to avoid quick loss of moisture. Molding and compacting was done under 2MPa.

After the samples were compacting and molding, the samples of CEB experienced a period of damp curing, where they were kept moist to achieve maximum strength. This process is necessary to avoid rapid loss of moisture which could lead to shrinking and cracking, because of the new samples were still weak and liable to damage [111], [112]. The duration of curing depends on the type of soil and, more significantly, on the type of used stabilizer. The samples require a minimum of two weeks curing time covered to maintain high humidity and temperature. Figure 41 shows the total process of compressed earth block (CEB) production [113], [114], [115].

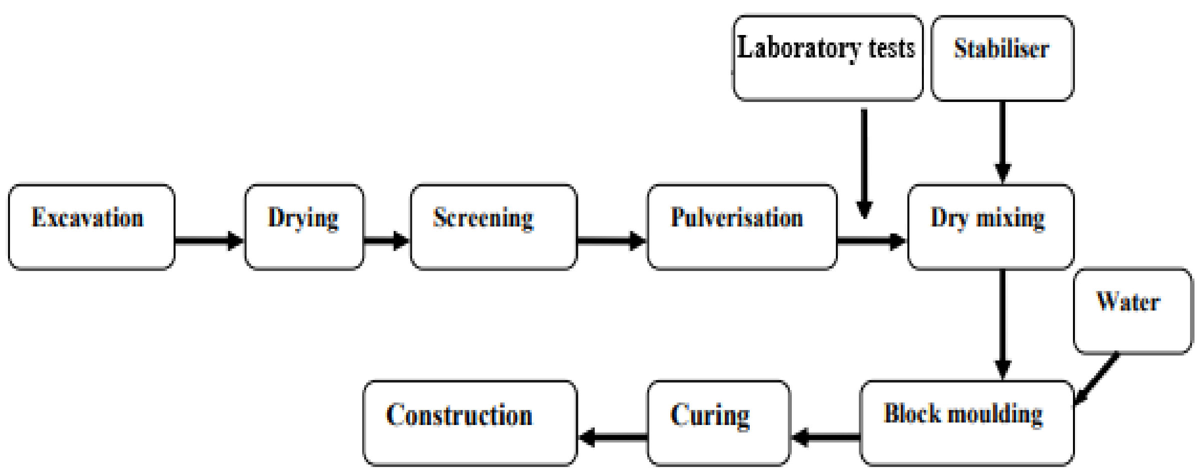


FIGURE 41. PRODUCTION PROCESS OF COMPRESSED EARTH BLOCK [110].

FIGURE 42. THE MOISTURE OF THE MIXTURE [116].

II. 4. Experiments Results of the procedure to manufacture Stabilized Compressed Earth Blocks

The soil chosen to make compressed earth blocks stabilized (CEBs) samples in this research is extracted from the imperial center of the medina of Fez in Morocco at a depth of 100 cm. In fact, Fez is a very famous city in Morocco known for its several historical monuments and old buildings made of earth (Figure 43). For the experimental investigation, the laboratory tests were conducted to determine various engineering and physical properties of the soil. According to CRATerre classification system, the soil was sandy soil (Figure 44).

FIGURE 43. COLLECTED SOIL OF FEZ SAMPLE

Before analyzing the granular components of the studied earth, we considered it interesting to bring the granulometric curve of the earth of Fez in the limit fuseaux recommended by CRATerre (Figure 32). These fuseaux serve as a reference for us in the field of compressed earth block construction. The Fez earth referred to as F is initially sieved to 16 mm. The results of the particle size classification, shown in figure 44, show that the soil F falls into the category of average sized sand.

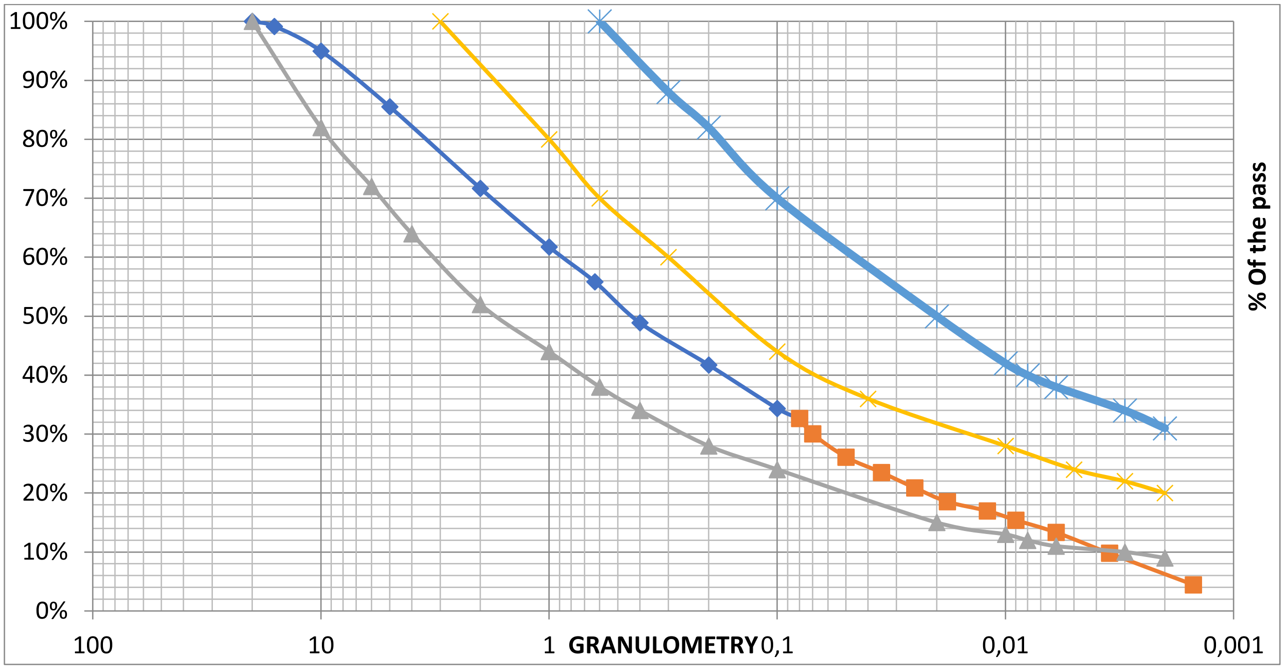


FIGURE 44. GRANULOMETRIC CURVE OF EARTH F

From the curve above, we notice that the grain size curve totally into the limit fuseaux recommended by CRATerre [117]. It is even closer to the ideal curve, except for very fine clay fraction.

We have summarized the granular distribution of the earth F in table 15.

TABLE 14. THE GRANULAR FRACTION OF THE EARTH F.

Granular fraction (%)				
Gravels	Coarse sand	Fine sand	Silt	Clay
28	30	22	12	8

The identification of the earth is completed by the analysis of the clayey part to define its states of consistency (Atterberg limits). These limits, namely: the limit of liquidity and the limit of plasticity were carried out on the very fine mortar on which water acts by modifying its consistency. For the studied soil F, we determined the liquid limit 'LL', the plasticity limit 'PL', the plasticity index 'PI', the activity coefficient 'Ca' and the surface area 'Sa (m2 / g)' of the earth F are reported in table 16.

TABLE 15. CONSISTENCY LIMITS OF EARTH F.

Liquid limit %	Plastic limit %	Plasticity index %	The activity coefficient (Ca)	The surface area (Sa)(m2/g)	Water content %	Dry density (g/cm3)	Color
35,58	25,32	10,26	1,28	48,93	12,5	1,82	Brownis h wheat

According to the classifying presented in table 11, and from the value of Activity Coefficient (Ca) in the table 16 and figures 35 and 36, we can conclude that the F earth is an active material and slightly to moderately cohesive.

The content of organic matter of the analyzed materials is indicated in table 17 according to the standard CRATerre. When these values are compared to the limits (Table 12) recommended by Walker et al. (2005) or Houben and Guillaud (2006), it is seen that the earth F has clearly acceptable organic matter content.

TABLE 16. THE ORGANIC MATTER OF EARTH F.

The Soil	Water Content of the soil of organic matter (%)	Organic Matter (%)
F earth	0,70	1,8

The optimum compaction is obtained by the static compaction test proctor. The compaction effort retained in this study is 2 MPa which is equivalent to that of a manual press. The value of the optimal water content and the dry density of soil F are shown in table 16.

From X-ray fluorescence, we have obtained the chemical elements present in earth F and the proportion of each component separately. In the light of these results of mineralogical in table 18, we concluded with respect to references [83], [84]:

- ✓ The main constituents of the chemical elements of clay of the earth F are calcite $CaCO_3$, with a high SiO_2 content (22.3%) due to the concentration of quartz and dolomite. These constituents are very sensitive to the addition of cement, as performed for the earth F, and of lime CaO (31.8%). The clay of the soil F is composed of a rate of quartz 80% and nearly 12% of aluminum oxide (Al_2O_3), but a very small amount of lime (0.003%).

- ✓ The presence very strong of these constituents amplified the improvement of the behavior of the material by the addition of small amount of cement. Indeed, the high presence of calcite stabilized the clay by cementing quartz (san) and the cement matrix reinforced the bonds between the grains of the earth.

TABLE 17. THE RATE OF CHEMICAL ELEMENTS AND THE MINERALOGICAL

Composition	Earth of F (%)
SiO2	22,3
CaO	31,8
Al2O3	5,96
Fe2O	1,72
MgO	2,13
SO3	1,29
K2O	0,536
TiO2	0,226
MnO	0,0503
P2O5	0,753
Na2O	0,323
SrO	0,0125
L.O.I. = Loss on ignition at 975°C)	32,9

- ✓ According to classifying presented in table 14, and from the value of Calcium carbonate (CaCO3) in the table 19, we conclude that the F earth is moderately calcareous (Figure 45) reported from the calcimeter tests.

TABLE 18. CARBONATE CONTENT PRESUMED IN PERCENT (%) OF EARTH F

The earth	Carbonate content presumed in percent (%)
F	51,323

FIGURE 45. CARBONATE (CACO3) OF SOIL FEZ

- ✓ From X-ray fluorescence, we have obtained the mineralogical and chemical composition of sample (Portland cement CPJ 35), is presented in tables 20 and 21 shows the chemical composition of cement Portland cement CPJ 35 developed and table 21 the mineralogical composition of cement CPJ35. In the light of these results of mineralogical in the tables, it has been concluded that:

The main constituents of the chemical elements of cement CPJ35 are calcite $CaCO_3$, with a high rate of Cao content (57.02%), and of C3S. (50.04). The composed of basis of Portland cement CPJ35 is a mixture of silicates and calcium aluminates resulting from the combination of the lime (CaO) with the silica (SiO_2), the alumina (Al_2O_3) and iron oxide (Fe_2O_3).

C3S high amount (50.04 %) is the active compound of cement, it develops a high initial resistance and its heat of hydration is quite strong. C2S a very small amount (-1.97) is the compound that provides cement with its long-term strength. C3 A small amount (5.79%) which is the compound the most rapid setting and gives off the greatest hydration temperature, it plays an important role in the short-term resistance and in the behavior of cement with water. C4AF small amount (5,75%) which does not participate in the mechanical resistance.

The four cement minerals play very different roles in the hydration process that converts the dry cement into hardened cement paste. The C3S and the C2S contribute virtually all of the beneficial properties by generating the main hydration product, C-S-H gel. However, the C3S hydrates much more quickly than the C2S and thus is responsible for the early strength development. The C3A and C4AF minerals also hydrate, but the products that are formed contribute little to the properties of the cement paste. These minerals are present because pure calcium silicate cements would be virtually impossible to produce economically.

TABLE 19. THE RATE OF CHEMICAL ELEMENTS OF PORTLAND CEMENT CPJ35

Composition	Sample Portland Cement CPJ 35(%)
SiO2	12.46
Cao	57.02
Al2O3	3.39
Fe2O	1.89
MgO	1.35
SO3	1.95
K2O	0.62
TiO2	0.18
MnO	0.03
P2O5	0.11
Na2O	-0.03
SrO	0.015
L.O.I. = Loss on ignition at 975°C)	20.90

TABLE 20. THE RATE OF THE MINERALOGICAL COMPOSITION OF PORTLAND CEMENT CPJ35 CLINKER USED.

Composition	Sample Cement CPJ 35(%)
C_3S	50.04
C_2S	-1.97
C_3A	5.79
C_4AF	5,75
Phliquide	15,77
Cao libre	0.56

After classifying the soil and the stabilization, compressed earth blocks were made from this earth F. The soil is used in its natural state without any addition of other soil constituents or fractions, except the cement stabilizer. We prepared the mixture and divided it into four parts:

The first mixture contains only soil and water and 0% cement.

The second mixture contain soil, water and 4 % of cement.

The third mixture contains soil, water and 7% of cement.

The fourth mixture contains soil, water and 10% of cement.

Once we have obtained the four mixtures well homogeneous, we used it to fill the molds, which take cylindrical form. The dimensions of the mold are 13 cm high × 8 cm diameter. Then, compress the samples in the molds by the compacting machine, to improve their density, that is mean reduction of the porosity in the samples, and therefore improve the mechanical properties of the samples. The compressive strength (the compacting pressure) is 2MPa for each sample, then we removed the samples from the molds to dry 28 days. The samples, with cement stabilizer, had been put in plastic bags to dry for two weeks so that samples do not dry quickly, and the cement can interact with water and soil, after that, we removed the plastic bags from the samples and let the samples dry again for two weeks (total 15 days of drying), all the samples are dried away from direct sunlight. The temperature, humidity, and drying time are the three factors that determine the quality of our samples, the slow drying improves product quality (Figure 46).

FIGURE 46. THE SAMPLES OF CEBS OF EARTH F.

Conclusion

In this chapter explored the possibility of using our local soil (earth of Fez) for making compressed earth blocks for the construction of affordable residential buildings, this was done through several tests carried out on selected soil. The CEBs samples were made with a block press that delivers a high compressive effort 2MPa. CEBs samples were also made from soil with (0%, 4%, 7% and 10 %) of Ordinary Portland cement.

The results of test laboratory of the soil that used for making the compressed earth block stabilized samples gave an average dry density of 1,82 (g/cm3), an average water content 12,5 (%), an average Plasticity index 10,26 (%), an average the activity coefficient 1,28, an average surface area 48,93 (m2/g) and an average organic matter 1,8 (%). These values are comparable to recommended values by CRATerre. And from these values have demonstrated that this soil may be suitable to make compressed earth blocks samples. If the native soil is unsuitable or inadequate for building, it can be blended with or replaced by soil from another source.

Chapter III: Heat Transfer in Stabilized Compressed Earth Block

Introduction

Study how the heat is transfer in building, between the building and the atmosphere, is considered very important in developing measures for regulating building temperature and provide thermal comfort inside the building, and for combating severe climate conditions outside. Heat transfer is closely associated with heat conductivity of materials, which results from gradient the temperature of various material components, and with their heating capacity.

This chapter provides thermal conductivity data for compressed earth block stabilized by cement and with different ratios of water content. The samples of CEBs are stabilized by different ratios of cement: 0%,4%,7% and 10% of weight.

The purpose is to measure and compare the thermal conductivity of CEBs samples with respect of both cement content and water content at temperature room of 22^0C. Hot ring method is adopted because it fits the cylindrical geometry of the samples. This method is non- steady state technique, as a variable heat flux is produced and the time- variant temperature gradient is measured. The method involves the transient heating of the cylindrical shape of samples and formulate the heat transfer equation using a cylindrical coordinate system.

III. 1. Mechanisms of heat transfer

It is first worth explain the different ways heat flows through the materials. This heat flow takes place by three mechanisms either individually or in combination: conduction, convection and radiation [118], [119], [120].

III.1. 1. Convection

Convection is the mechanism of heat transfer through a fluid in the presence of bulk fluid motion. Convection is classified as natural (or free) and forced convection depending on how the fluid motion is initiated. Newton determined that the heat transfer/area, Q/A, is proportional to the fluid solid temperature difference ΔT. The temperature difference usually occurs across a thin layer of fluid adjacent to the solid surface. This thin fluid layer is called a boundary layer. The constant of proportionality is called the heat transfer coefficient, h.

The rate of convection heat transfer is expressed by Newton's law of cooling:

$$Q = h\ A\ \Delta T \qquad (III.1)$$

III. 1. 2. Radiation

Radiation is the mechanism of energy transfer by the emission of electromagnetic waves which carry energy away from the emitting object. The radiation does not require a heat transfer medium and can occur in a vacuum. The heat transfer by radiation is proportional to the fourth power of the absolute material temperature. The proportionality constant σ is the Stefan- Boltzman constant equal to 5.67 x 10^{-8} W/m^2K^4. The radiation heat transfer also depends on the material properties represented by Ɛ, the emissivity of the material.

The rate of radiation heat transfer is expressed by:

$$Q = \sigma.\varepsilon.T^4 \qquad (III.2)$$

III. 1. 3. Conduction

Conduction is the mechanism of heat transfer through the molecules of the material due to molecular motion and interaction, without causing a chemical change in its composition. Fourier determined that Q/A, the heat transfer per unit area (W/m2) is proportional to the temperature gradient dT/dx. The constant of proportionality is called the material thermal conductivity k. The rate of conduction heat transfer is expressed:

$$Q = -k\ A\ \frac{\partial T}{\partial x} \qquad (III.3)$$

Equation (Eq. III. 3) is called Fourier's law of heat conduction, for one-dimensional heat conduction (x axis). It is this mechanism that occurs and dominates in compressed earth block. We will describe it in detail in the following sections.

III. 1. 3. 1. Conduction heat transfer equation

Heat transfer problems are classified as being one- dimensional as (Eq. III. 3), two-dimensional, or three-dimensional, depending on the relative magnitudes of heat transfer rates in different directions and the level of accuracy desired. In my study, an axisymmetric heat conduction model in two-dimensional is adopted, where the z-axis is the axis of symmetry. Then it is convenient to formulate the problem using a cylindrical coordinates system. Since all coefficients are independent of θ, the temperature distribution is a function of (r, z). Transient heat transfer through the compressed earth block is governed by the following differential equation [121], [122]:

$$\rho C_p \frac{\partial T}{\partial t} = k \frac{1}{r}\left(\frac{\partial}{\partial r}\left(r \frac{\partial T}{\partial r}\right)\right) + k \frac{\partial^2 T}{\partial z^2} + \dot{q} \qquad \text{(III. 4)}$$

Where ρ is the mass density of the material in (kg/m3), Cp is the specific heat capacity in (J/kg. k), k is the thermal conductivity in (W/m. k), T is the temperature in (Kelvin), t is the time in (second), and r, z is the cylindrical coordinate in meter.

CEBs is a heterogeneous, and permeable solid material. The heat transfer in CEBs building material at normal temperatures is mainly by conduction. The properties of CEBs are influenced by the spatial spreading and volume ratio of its elements, such as aggregate, water content, cement content and voids.

In my work, the samples of CEBs to be characterized was considered as an infinite medium, homogeneous and isotropic (K is the same in the three directions).

III. 1. 3. 2. Thermal conductivity

Thermal conductivity (K) (also called heat conduction) is the ability of a material to conduct heat. It is a thermophysical property of the materials, related to heat transfer phenomena in which the energy is transferred from one location to another due to the vibration of molecules accompanied by changes in the temperature of the material from one location to another. The lower this value K, the more insulating the material. Equation III. 3 is the defining equation for thermal conductivity, it is primarily in Fourier's Law for heat conduction. Thermal conductivity unit are Watt per kelvin-meter ($W \cdot K^{-1} \cdot m^{-1}$, i.e. W/ (K. m) in IS.

III. 1. 3. 3. Some values of thermal conductivity for common materials in building

The ability of materials to transfer heat depends on the degree of thermal conductivity. Dense solid materials tend to have high levels of conductivity, whereas materials with very small amount of solid matter and large proportion of voids (gas or air, not large enough to carry heat by convection) have the lowest thermal conductivities. The table 22 shows the thermal conductivity at 25◦C of some common materials in W /m. k:

TABLE 21. THERMAL CONDUCTIVITY OF VARIOUS MATERIALS AT 25◦C [123].

Material	Thermal Conductivity W/ (m. K) at 25 oC	Material	Thermal Conductivity W/ (m. K) at 25 oC
Air, atmosphere (gas)	0.0262	Fiber hardboard	0.2
Asbestos-cement board	0.744	Fire-clay brick 500oC	1.4
Asbestos-cement sheets	0.166	Gravel	0.7
Asbestos-cement	2.07	Ground or soil, dry area	0.5
Breeze block	0.10 - 0.20	Ground or soil, very dry area	0.33
Brick dense	1.31	Gypsum board	0.17
Brick, fire	0.47	Limestone	1.26 - 1.33
Brick, insulating	0.15	Plaster, sand	0.71
Brickwork, common (Building Brick)	0.6 -1.0	Plaster, wood lath	0.28
Brickwork, dense	1.6	Sand, dry	0.15 - 0.25
Cement, Portland	0.29	Sand, moist	0.25 - 2
Cement, mortar	1.73	Sand, saturated	02-avr
Clay, dry to moist	0.15 - 1.8	Sandstone	1.7
Clay, saturated	0.6 - 2.5	Sawdust	0.08
Concrete, lightweight	0.1 - 0.3	Soil, clay	1.1
Concrete, medium	0.4 - 0.7	Soil, with organic matter	0.15 - 2

Concrete, dense	1.0 - 1.8	Soil, saturated	0.6 - 4
Concrete, stone	1.7	Straw slab insulation, compressed	0.09
Earth, dry	1.5	Water	0.606
Fiber insulating board	0.048		

III. 1. 3. 4. Thermal mass for various materials

Thermal mass is the ability of the fabric of a building to absorb and store heat. For an ideal thermal mass of material, it is sought the combination of three basic characteristics: (i) A high specific heat capacity; so, the heat squeezed into every kg is maximized, (ii) A high density; the heavier the material, the more heat it can store by volume. (iii) Moderate thermal conductivity, so the rate heat flows in and out of the material is roughly in step with the daily heating and cooling cycle of the building [124]. A lot of heat energy is required to change the temperature of high density materials. A material that has high thermal mass is one that has the capacity to absorb, store and release the sun's heat energy. Its density and levels of conductivity help to keep the internal temperature of a building stable [125]. The materials that have thermal mass have inherent qualities for both heating and cooling.

In winter, thermal mass will increase thermal comfort in a building when solar heat stored in the materials during the day is released as internal temperatures fall. When thermal mass is used for its heating capacity, when exposed to sunlight, the thermal mass absorbs the sun's heat energy. Because objects with thermal mass are typically dense, they have the ability to store heat. Because of this, all of the thermal mass does not need to be exposed to the direct sunlight, but a large portion of it should be. The heat energy that is absorbed will slowly spread (conductivity) through the mass and then radiate or release the heat energy throughout the evening and night.

Heavyweight construction materials such as compressed earth block masonry and concrete have these characteristics. They combine a high storage capacity with moderate thermal conductivity [126]. This means that heat moves between the material's surface and its interior at a rate that roughly matches the building's daily heating and cooling cycle. For example, Wood has a high heat capacity, but its thermal conductivity is relatively low, limiting the rate at which heat can be absorbed during the day and released at night (Table 23).

Thermal mass elements in buildings assists in the reduction of energy consumed in heating and cooling in most climate zones and can significantly reduce the ecological impacts of burning fossil fuels due to energy production as well as reduce costs, improve thermal comfort and reduce or eliminate the need for air conditioning.

TABLE 22. THERMAL MASS FOR SOME BUILDING MATERIALS [127]

Material	Thermal mass (volumetric heat capacity, KJ/m³. k)
Water	4186
Concrete	2060
Sandstone	1800
Compressed earth blocks	1740
Rammed earth	1673
Fibre cement sheet (compressed)	1530
Brick	1360
Earth wall (adobe)	1300
Autoclaved aerated concrete	550
Wood	862

III. 1. 3. 5. Factors affecting thermal conductivity

The thermal conductivity (k) value of earth-based construction building materials like CEBs is an important factor when considering the amount of heat transfer through conduction. The amount of heat loss through walls and roofs has a direct effect on the energy consumption of buildings [128], [129]. The thermal conductivity is not always constant. The flow of heat is not measured by how much energy is transferred, but by the rate it is transferred. Thermal conductivity in materials depends on the following factors according to the Fourier’s law:

$$\frac{\Delta Q}{\Delta t} = -kA\left(\frac{\Delta T}{L}\right) \qquad (III.5)$$

Where:

$\frac{\Delta Q}{\Delta t}$: The rate of heat conduction $\left({}^{kJ}/_{s}\right)$.

ΔT : Temperature difference across the material (temperature gradient).

L : Thickness of the layer (m).

A : Area of the material (m^2).

k : Thermal conductivity of the material $\left({}^{W}/_{m.k}\right)$.

The symbol Δ (delta) means "change in." It could also be written as follows:

$$\frac{\Delta Q}{\Delta t} = \frac{(Q_2 - Q_1)}{(t_2 - t_1)} \qquad (III.6)$$

$$\Delta T = (T_2 - T_1) \qquad (III.7)$$

$\frac{\Delta Q}{\Delta t}$ is the rate of heat flow by conduction, that is how fast it flows through the material. The amount of heat flow is ΔQ.

Several factors affect thermal conductivity and the rate in which energy is transferred. The water content, temperature, type of aggregate, type of cementitious material, porosity, density and age of CEBs are influential factors on the thermal conductivity. The main aim of my thesis is to study how both water content and cement content affect thermal conductivity of CEBs. The water content and cement content in the samples appeared to be the main effective factors and the most effective factors that affect the thermal conductivity of CEBs.

III. 2. Methods of measuring thermal conductivity of CEBs as function of water content and cement content

There are a number of possibilities to measure thermal conductivity, well developed and very accurate in their measurement, do not take long time during the measurement, and designed according to the international standards of measurement such as: hot ring method, hot iron method, hot wire method, flash method and guarded hot plate method, the Twin Climate Chamber, and some of which have been mentioned in the literature review (in chapter. I). Each of them is however suitable for limited range of materials, depending on the thermal properties, the medium temperature and the geometric shape of the sample [130], [131].

Some of these methods measure thermal conductivity in steady state and others measure thermal conductivity in unsteady state. In steady state techniques, equilibrium heat flux and temperature gradient are measured. In unsteady state techniques, a variable heat flux is produced and the time-variant temperature gradient is measured [132].

In this work, the thermal conductivity of compressed earth blocks (CEBs), influenced by cement content and water content, has been investigated by using hot ring method. This method measures thermal conductivity in non-steady state because the temperature depends on the time. Hot ring it also very suitable for the CEBs sample which of a cylindrical shape.

The hot ring method allows to measure the thermal conductivity of all the isolation materials such as compressed earth block (Figure 47). The system is composed of: a thermal shock sensor (or the probe with shocks) the sensor consisting of the resistive ring and the thermocouple in an insulating support in slab Kapton, an electronic acquisition system, and a software for testing guidance and data processing. This sensor and device principle has been developed by the CSTB (Technical and Scientific Center for Building). This device is in compliance with the standards ASTM D5930-97 and AAC 11-3 RILEM Recommendation. The mechanical characteristics of the probe or sensor (Thickness = 0,2 mm, Dimensions = 60 × 90 mm, Diameter = 30 mm, Radius = 15 mm) [133], [134].

Figure1. Hot Ring sensor

Figure2. Hot ring method

FIGURE 47. HOT RING METHOD.

III. 2. 1. Thermal conductivity measurement

The method of hot ring uses the principle of thermal shock probes, it allows to create a thermal excitement of the material (the samples of CEBs). The response to this excitement is being dependent of thermal properties of our samples. The thermal parameters for the method of hot ring that we used in our experience were heating power, measuring time, heating time, and resistance of the probe. The thermal parameters were constant for all samples throughout the experiment (Figure 47).

The principle of the shock sensor consists on placing the sensor between two pieces of the same sample of CEB (in the middle of the sample) (Figure 48), and then inject current into the ring by shock sensor to generate a heat flow (few degrees above ambient temperature) [135]. Low heating dissipates in the sample and arrives after a certain time (temperature rise in time (few minutes)) in the center of this ring, where the measurement is made, to estimate the thermal conductivity of a CEBs from the evolution of the temperature measured by a thermocouple placed near a resistive ring. By a mathematical treatment of this signal integrated into the supplied software, the identification of the thermal conductivity is realized after, a thermal excitation is produced on the surface of the samples [136], [137].

FIGURE 48. THERMAL CONDUCTIVITY MEASUREMENTS BY HOT RING METHOD.

The heating source (the probe) is inserted into the middle of a sample and is heated with constant power while recording the temperature rise with time inside the source. The slower the source temperature rises, the higher is the thermal conductivity of the sample material. The thermal conductivity of the sample is calculated from the temperature rise with time registered by the probe.

The evolution of the temperature of ring at the center is the same as that of a point located at a distance R_r from a continuous point source and can be obtained analytically by relation:

$$\Delta T_c = \frac{\dot{Q}}{4\pi K_C R_r} \operatorname{erfc}\left(\frac{R_r\sqrt{\rho C_p}}{\sqrt{4K_C t}}\right) \qquad (III.8)$$

Where R_r the radius immersed of thin circular ring in the sample, $\dot{Q}$ the heating power of the ring, and C_p specific heat of the porous medium of the sample. From the formula (Eq. III. 8) we can calculate the thermal conductivity kc of the material from the variation of temperature (ΔT_c) T_1 and T_2 measured at time t_1 and t_2 at the center of the ring [133]. In practice, as the function erfc could not be inverted analytically, it is necessary to use an identification procedure computing the

value of K_C, which permits to best fit the temperature rise at the center of the ring.

The error function of x variable is defined as:

$$\operatorname{erf}(x) = \frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2}\,dt \quad \text{For} \quad x \geq 0 \qquad (III.9)$$

And the complementary error function can be written as:

$$\operatorname{erfc}(x) = 1 - \operatorname{erf}(x) = \frac{2}{\sqrt{\pi}} \int_{x}^{\infty} \mathrm{e}^{-\mathrm{t}^2}\, \mathrm{dt} \qquad \text{For} \quad x \geq 0 \qquad \text{(III. 10)}$$

The error function erf(x) is involved in the expression of the solutions of the heat equation or the diffusion equation. According to this formula (Eq. III. 8), it is possible to determine the thermal conductivity kc of the samples CEBs from the variation temperature ΔT measured at time t at the center of the ring. The method for finding this value for a set of measurement points of the function ΔT, where kc is the optimization parameter, is called curve fitting or 'fit'. Curve fitting is a technique of analyzing an experimental curve, consisting of constructing a curve from mathematical functions and adjusting the parameters of these functions to approximate the measured curve - so we also talk about adjusting parameters. Since, the solution could not be obtained analytically, we chose to implement the equation in MATLAB in which we build a program for the specific purpose.

III. 2. 2. Drying of test samples

Before starting thermal measurements of the samples (CEBs), all samples must be completely dried by putting the samples in a laboratory oven at 60 ° C for 72 hours until their masses are stabilized (Figure 49). The reason for this is to obtain accurate measurements of values thermal conductivity of the samples in the dry state and compared it with the values of thermal conductivity of the samples in humidity states and know the impact of humidity on the thermal conductivity. After taking out the samples from the laboratory oven, we have covered them by a very thin plastic bag, in order not to be affected by surrounding humidity and to get accurate values of the thermal conductivity in the dry state.

FIGURE 49. DRYING OF TEST SAMPLES.

III. 2. 3. Water content

Water content of compressed earth block is expressed as the percentage of water that fills the voids or pores inside the block. And this percentage depends on the size and distribution of granules of earth materials involved in the formation and manufacture of compressed earth blocks.

After the measurement of thermal conductivity of dried sample, in each time we add water to this sample, its mass and its thermal conductivity are measured, and repeated so on until reaches the saturation state. I didn't soak the samples in the water, I followed a new method, spraying samples with water, and let the water spread in the sample for a period of time approximately 30 minutes to be homogeneous water within sample (Figure 50). The water content in the samples is expressed as a percentage:

$$\mathrm{w} = \left(\frac{\mathrm{m_h} - \mathrm{m_d}}{\mathrm{m_d}}\right) * 100 \qquad \text{(III. 11)}$$

m_h and m_d are respectively the humid and dry masses of the sample.

The mass of the humid sample consists of the mass of the dry sample plus the mass of the water within it. This water content test was intended to find out the thermal behavior of CEBs with water.

FIGURE 50. THERMAL TESTS OF THE SAMPLES CEBS.

III. 2. 4. Initial conditions and boundary conditions for thermal measurement

Equation III. 4 of heat transfer was subjected to the following initial condition:

$$\text{For } \forall r \text{ and } \forall z \text{ when } t \leq 0,\ T(r,z,t) = T_{int} \qquad (III.12)$$

The thermal conductivity of compressed earth block with water content and cement does not have a unique value because it depends on the boundary conditions, which may cause humidity redistribution into the samples and the interaction between water and cement inside the sample. The description of a heat transfer problem in a medium is not complete without a full description of the thermal conditions at the bounding surface of the medium of the samples [138], [139]. Boundary conditions is the mathematical expressions of the thermal conditions at the boundaries, (space coordinates) in our experiment situation:

$$\text{For } r \to \infty \text{, or } z \to \infty \text{ , } T(r,z,t) = T_{init} \quad \text{(Initial temperature),}$$
$$(III.13)$$

$$r = 0, \quad \forall z \quad k\frac{\partial T}{\partial r} = 0,$$

$$z = +\frac{H}{2} \quad \text{and} \quad z = -\frac{H}{2},$$

$$\forall z \text{ and } r = R, \; T = T_{\infty}. \qquad \text{(III.14)}$$

III. 3. Experimental results of thermal behaviour of CEBs as function of water content and cement content

All the samples CEBs on which thermal tests were conducted in a dry state. Figures (51 to 54) present the thermal behavior records collected from two CEBs samples (the sample 1 containing 7 % of cement content with mass 1,14465 Kg, and the sample 2 containing 4 % of cement content with mass 1,11216 Kg) both in the dry state. The heat is generated in the middle of the samples just in dry state at a different rate of parameters of hot ring method (heating power, measuring time and heating time according to the table 24, at resistance of the probe = 2,5 Ω are under an ambient temperature recorded in the laboratory at the beginning of the test was T = 22°C). For the samples with (the high (h)= 0,13 m, the radius (r) = 0,04 m and diameter (D)= 0.08).

The data was drawn as curves using the Origin software. Figure 51 and figure 52 represent each the thermal conductivity as function of power, and figure 53 and figure 54 represent the temperature as function of time. Four different parameters of heating power (0.5W, 1W, 1.5W and 2 W), correspond to four different parameters of heating time (60s, 120s, 240s and 400s) respectively, and corresponds to four different parameters of measure time (120s, 500s, 500s and 500s).

Figure 51 and Figure 52 reported the thermal conductivity of the samples CEBs as a function of heating power depending on ratios of cement content. We found that positive and nonlinear relationship between thermal conductivity and heating power. The thermal conductivity of CEBs is being affected by heating power and cement content. This can be explained by the gradual increase of the values of thermal conductivities with increase the percentage of cement, as seen previously in table 22, and the heating power (Table 24), because higher heating power leads to increase kinetic energy of solid particle.

TABLE 23. THERMAL CONDUCTIVITY OF CEBS (WITH 7% AND 4% CEMENT CONTENT) AND WITH DIFFERENT PARAMETERS OF HOT RING METHOD AT 22◦C

			Sample 1 with 7 % cement content	Sample 2 with 4 % cement content
Heating power (W)	Heating time (s)	Measuring time (s)	Thermal conductivity (W/m. K)	Thermal conductivity (W/m. K)
0,5	60	120	0 ,676	0,646
1	120	500	0 ,72	0 ,708
1,5	240	500	1,042	0,808
2	400	500	1,154	1,011

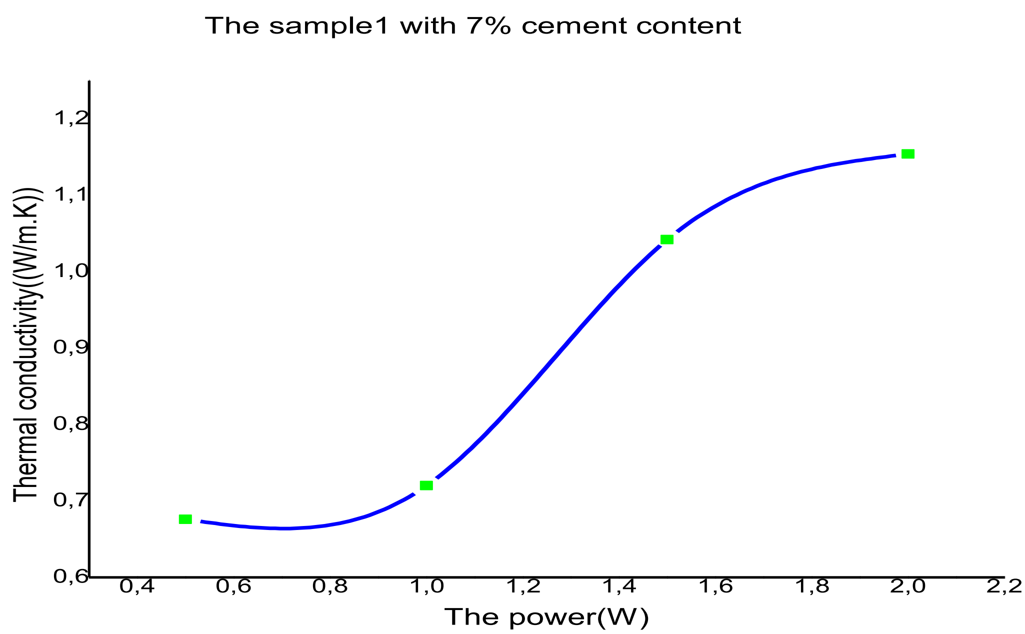


FIGURE 51. THE EXPERIMENTAL RESULTS OF THE THERMAL CONDUCTIVITY WITH DIFFERENT VALUES OF HEATING POWER FOR SAMPLE 1 (7% CEMENT CONTENT).

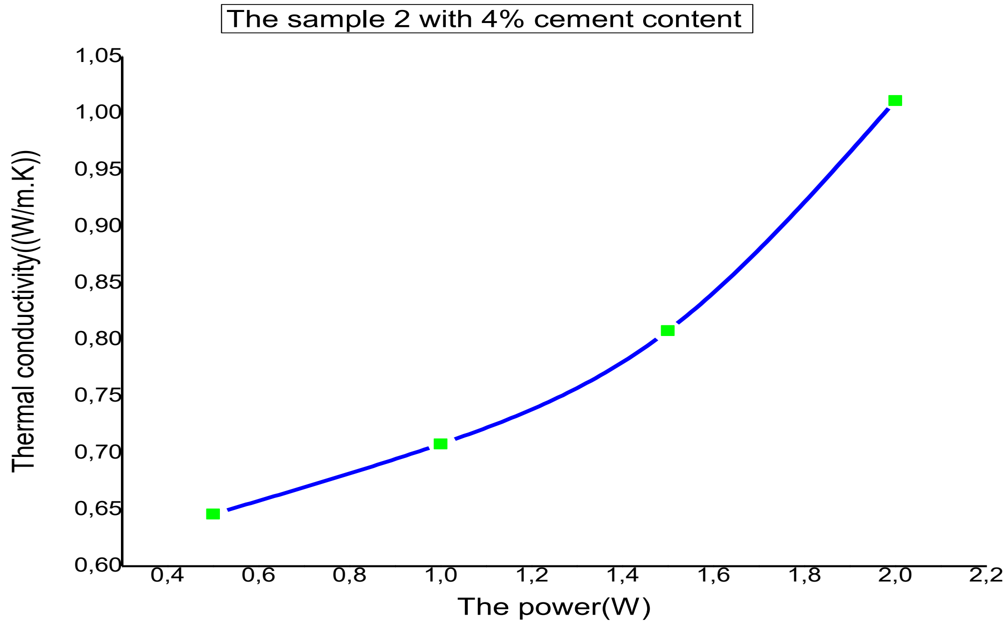


FIGURE 52. THE EXPERIMENTAL RESULTS OF THE THERMAL CONDUCTIVITY WITH DIFFERENT VALUES OF HEATING POWER FOR SAMPLE 2 (4% CEMENT CONTENT).

One could note from Figure 53 and Figure 54 that the evolution of temperatures in CEBs is also depending on the percentage of cement in the sample and on the heating power.

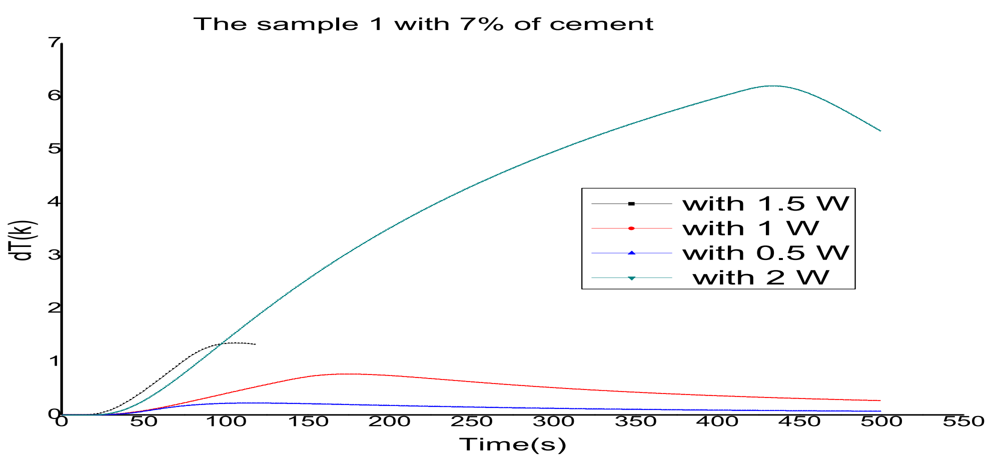


FIGURE 53. THE VARIATION OF TEMPERATURE AS FUNCTION OF TIME, OF THE SAMPLE1 DEPENDS ON 7 % OF CEMENT CONTENT AND ON DIFFERENT HEATING POWER.

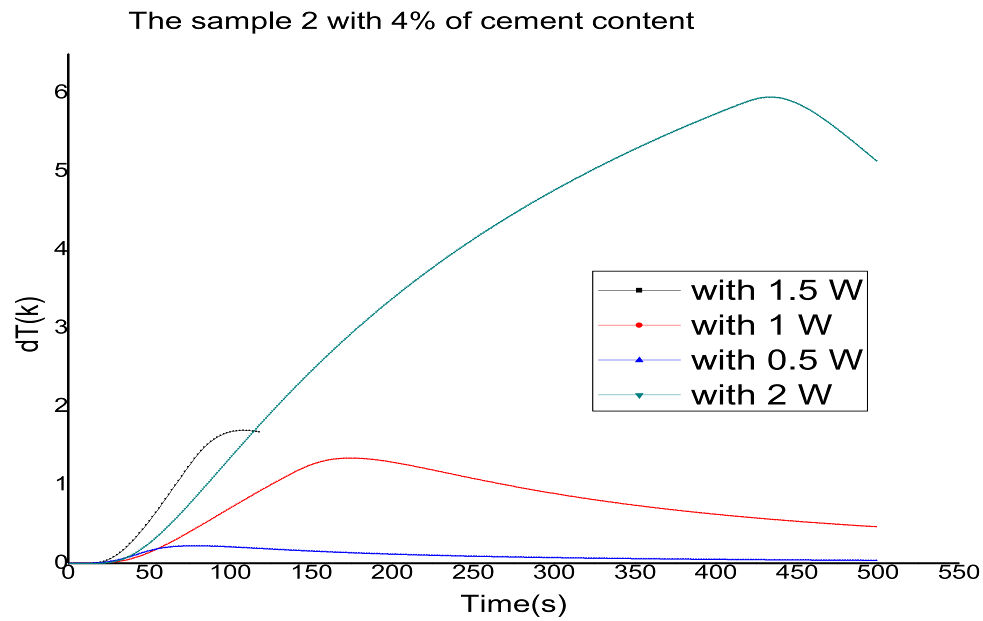


FIGURE 54. THE VARIATION OF TEMPERATURE AS FUNCTION OF TIME, OF THE SAMPLE2 DEPENDS ON 4 % OF CEMENT CONTENT AND ON DIFFERENT HEATING POWER.

III. 3. 1. The effects of water content on thermal conductivity of the samples CEBs

The heat transfer can occur through a number of mechanisms as we mentioned. The heat conduction, which occurs primarily through the material's granular structure, which in the case of CEBs consists of hydraulically-bound mineral aggregate particles and clays. Heat transfer will be enhanced by the introduction of water and cement stabilizer into the voids between particles as the thermal conductivity of water and cement is an order of magnitude higher than air. Figures 55 to 59 present the thermal behavior for samples 1,2,3, and 4 corresponding respectively to 0, 4, 7 and 10% of cement. The heat is generated in the middle of the samples at a constant rate of parameters of hot ring method were (heating power= 2 W, measuring time= 500 s, heating time = 400 s, resistance of the probe = 2,5 Ω are under an ambient temperature recorded in the laboratory at the beginning of the test was T = 22°C). For all the samples with the height (h)= 0,13 m, the radius (r) = 0,04 m and diameter (D)= 0.08.

The thermal conductivity of the CEBs is significantly affected by water content. Thus, as the humidity increases, the thermal conductivity increases. Figure 55 shows a non- linear variation of thermal conductivity of the samples CEBs, with different ratios of cement, as a function of water content. The humid state of sample CEBs conducts heat more than its dry state. Water increases thermal contact between grains, due to the fact that the soil has a porous medium and air pores which could be filled by water. From the table 22 thermal conductivity of the air is 0.026 W/m. K, cement Portland is (depending on the amount and the type of aggregates) in the range of 0.29 W/m. K, the thermal conductivity of soil in the range of 0.15 - 2 W/m. K, and thermal conductivity of water is 0.606 W/m. K. We can clearly observe that the thermal conductivity of water is higher than soil and cement and is much greater than that of air at the same temperature. Therefore, the water content leads to increasing thermal conductivity of the samples.

The water content in the samples increases their density which in turn leads to increase thermal conductivity of the samples. What happens in the heat transfer process in the samples CEBs is, that the heat is transferred to the sample of CEBs by heating (by the probe of hot ring method). The CEBs particles gain energy, its particles are only vibrating, but they vibrate faster after being heated. Particles are close together in the solid state, so they are likely to hit each other and transfer heat. heat is transferred through the samples slowly, so the temperature of the block goes up which leads to increase the thermal conductivity.

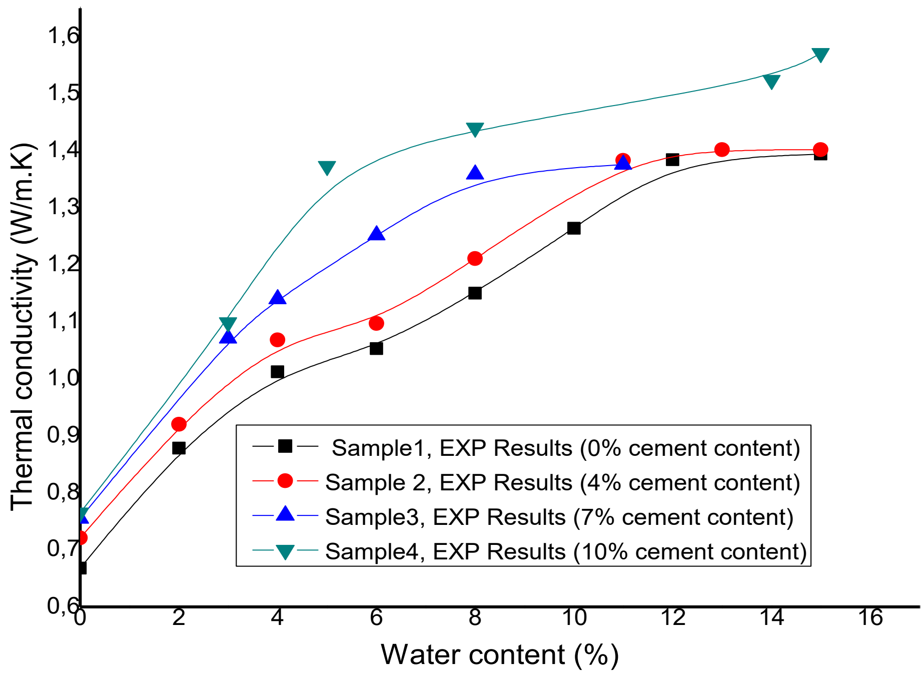


FIGURE 55. THE EXPERIMENTAL RESULTS OF THERMAL CONDUCTIVITY OF THE SAMPLES CEBS WITH DIFFERENT PERCENTAGES OF CEMENT AS A FUNCTION OF THE WATER CONTENT.

Thermal parameters are affected by material composition and structure. Heat capacity and thermal diffusivity are greatly affected by water content because of the high heat capacity of water compared to air and solids (Table 25). The specific heat which is defined as property that describes how much heat must be added to a particular substance to raise its temperature one-degree Kelvin. For instance, the specific heat capacity of water is about three times greater than that of soil and five times greater than that of cement (Table 25). The soil cools faster than the water once the temperature goes down. The figure 56 demonstrates the specific heat of the samples CEBs as a function of water content depending on different ratios of cement. We found nonlinear relation of specific heat as function of water content.

TABLE 24. SOME VALUES OF SPECIFIC HEAT OF MATERIALS.

Materials	Specific Heat (J/kg. K)

Water	4187
Soil	1810
Air	1004
Cement	920

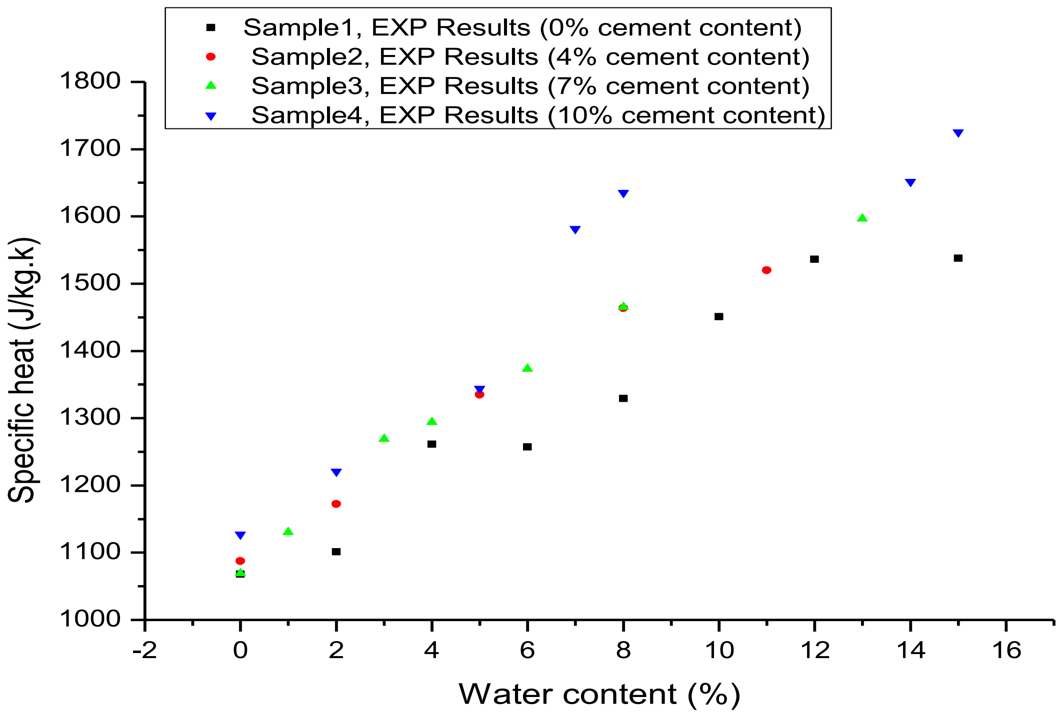


FIGURE 56. EXPERIMENTAL RESULTS OF SPECIFIC HEAT OF THE SAMPLES CEBS AS A FUNCTION OF THE WATER CONTENT WITH DIFFERENT PERCENTAGES OF CEMENT.

The figure 57 plotted the thermal diffusivity of the samples CEBs as a function of water content depending on ratios of cement content. We also found there a nonlinear relation of specific heat as function of water content. Thermal diffusivity of CEBs increased with the increasing density, heat capacity. The thermal diffusivity of soil with increasing moisture content and cement content since K, ρ and Cp all increase with it. The results obtained for the thermal diffusivity (Figure 57) are qualitatively very similar to those for thermal conductivity. Experimental values of density (ρ) and heat capacity were used together to obtain specific heat (Cp). Then, the experimental values of density, thermal conductivity (K) and heat specific of each sample, were used together to obtain thermal diffusivity (α). The latter can be understood as the ability of a material to conduct heat relative to the heat stored per unit volume. It also can be defined as the thermal conductivity divided by the product of specific heat and density. Analytical calculate are used to determine specific heat and thermal diffusivity (α) by the relation:

$$\alpha = \frac{k}{\rho C_P} \qquad \text{(III. 15)}$$

From this equation (Eq. III. 15) we can conclude the relationship between the thermal conductivity and thermal diffusivity.

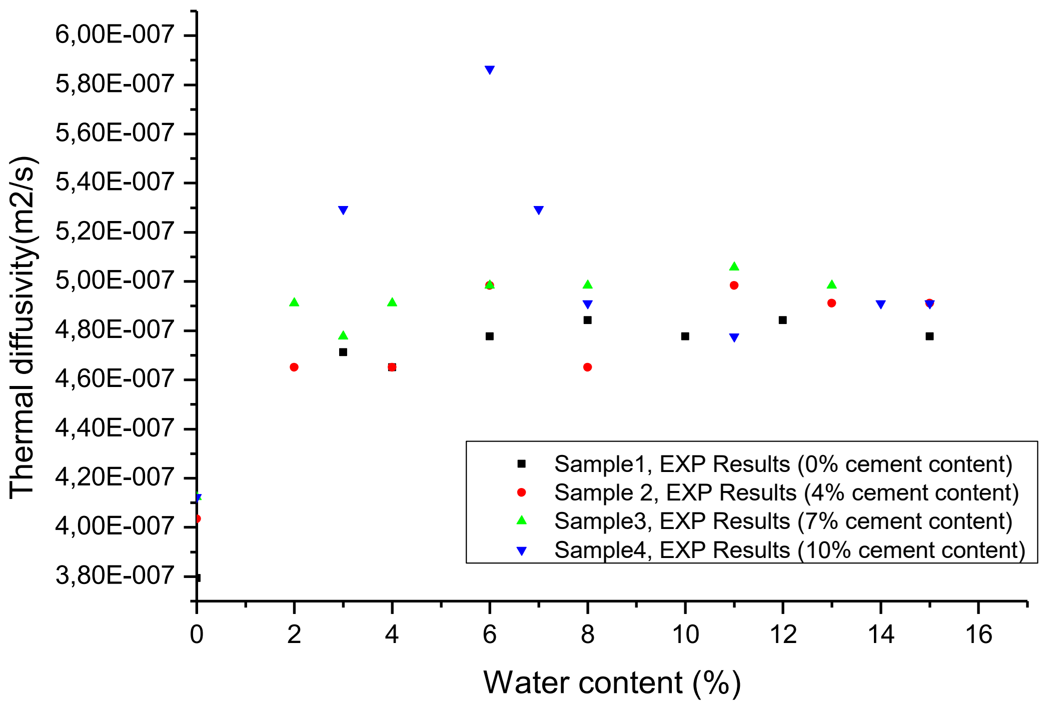


FIGURE 57. EXPERIMENTAL RESULTS OF THERMAL DIFFUSIVITY OF THE SAMPLES CEBS AS A FUNCTION OF THE WATER CONTENT WITH DIFFERENT PERCENTAGES OF CEMENT.

According to this formula (Eq. III. 8), and from the experimental points for each of the sample (variation of temperature ΔT, specific heat CP, heating time t, heating power, volume density and the radius of thin circular ring), we got numerical values of Kc using MATLAB software. The results are reported in table (Table 26). MATLAB contains toolboxes containing functions that make data fit e.g.:

$$f_0 = fit\left(x, T, \ '2 \times erfc\left(\frac{0.015 \times \sqrt{1013.173 \times 1656.61}}{\sqrt{4 \times K \times x /_{4 \times \pi \times K \times 0.015}}} \right) \right)$$

The function fit in the previous MATLAB command will calculate the optimal value of kc. We determine both the numerical points of the variation temperature as function of time, and the numerical values of thermal conductivity. The figure 58 shows the comparison of experimental and numerical data of the variation temperature as function of time, and the experimental and numerical values of thermal conductivity of CEBs with different cement dosages (0%, 4%, 7% and 10%).

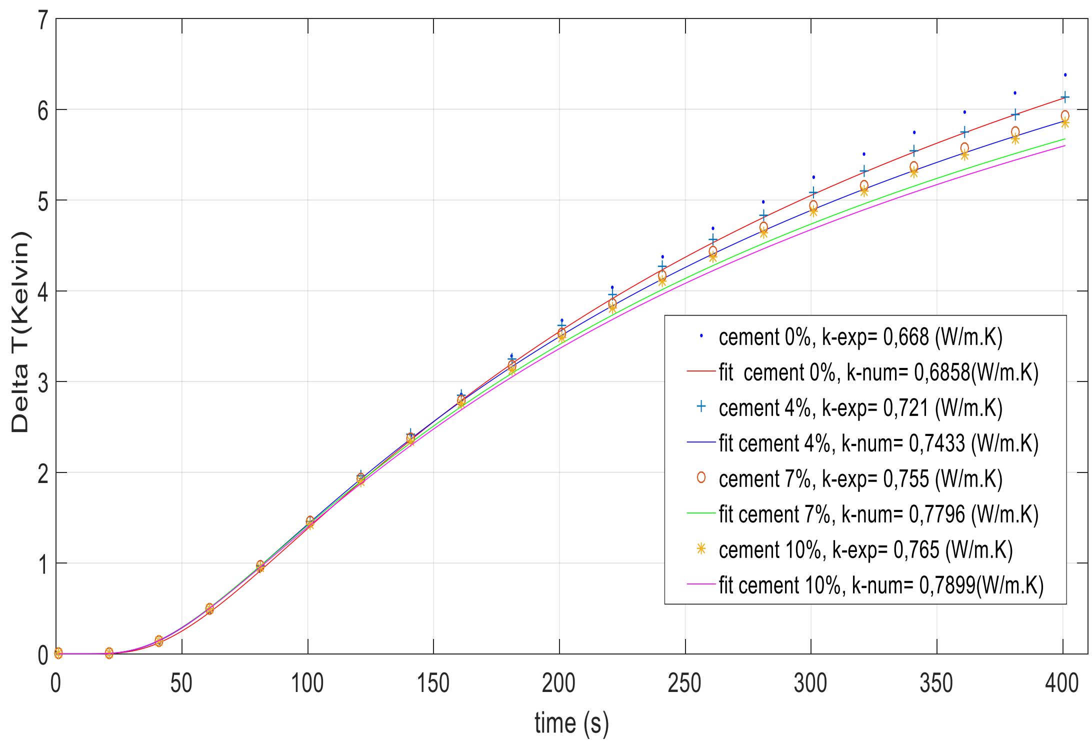


FIGURE 58. EXPERIMENTAL AND NUMERICAL DATA OF THE TEMPERATURE VARIATION AS FUNCTION OF TIME, AND THE VALUES OF THERMAL CONDUCTIVITY.

TABLE 25. EXP AND NUM THERMAL CONDUCTIVITY VALUES OF CEBS (WITH 0% ,4%,7% AND 10% CEMENT CONTENT).

Cement content (%)	EXP Thermal conductivity (W/m. K)	NUM Thermal conductivity (W/m. K)	Error (%)
0	0.668	0.6858	2.66
4	0.721	0.7433	3.09
7	0.755	0.7796	3.25
10	0.765	0.7899	3.25

III. 3. 2. The effects of cement content on thermal conductivity of the samples CEBs

The cement stabilizer is considered as chemical stabilization. Experiments results in figure 59 indicate that the CEBs samples with cement contents have a higher thermal conductivity. We observed a strong and a non- linear relationship between thermal conductivity as function of cement for four samples of CEBs irrespectively of water content. While cement content is proved to improve the mechanical properties, the thermal properties is not. From the figure 59, the effect of incorporating cement in samples is to increase the thermal conductivity resulting from increasing density. The presence of cement causes a decreasing of porosity within the samples. In fact, the increase in cement content corresponds to an increase in the amount of bonds. This can be explained by the formation of cement hydrates in the pores that allow the creation of rigid bridges between clay, lime and sand particles. These bridges between the particles allow heat to pass through the particles of samples, and thus increase the heat energy, which lead in turn to increase their thermal conductivity.

Figure 59 shows also that for small ratios of water content doesn't affect significantly the thermal conductivity. Indeed, the presence of water in small quantity in the sample is almost totally absorbed by cement which results in almost no change in the heat transfer and thermal conductivity.

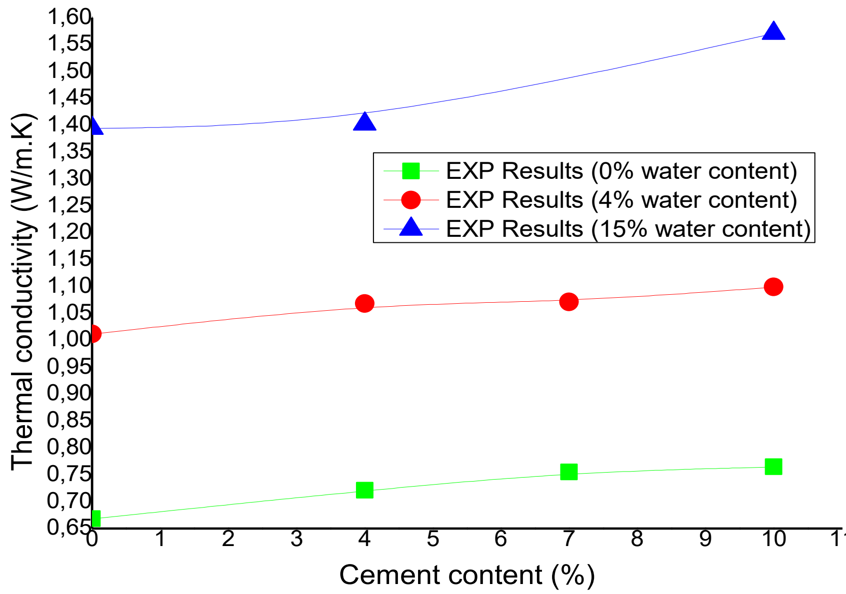


FIGURE 59. THE EXPERIMENTAL RESULTS OF THERMAL CONDUCTIVITY OF THE SAMPLES CEBS WITH DIFFERENT PERCENTAGES OF WATER AS A FUNCTION OF THE CEMENT CONTENT

III. 3. 3. The effect interaction between cement content and water content on thermal conductivity inside the samples of CEBs

From the Figures (55 and 59) the results are indicated that the analyses show that the thermal properties of CEBs are not only controlled by cement content, but also by interaction of cement with the cement water content process. These ratios of cement and water directly impact the ultimate porosity, density, and thermal properties of samples CEBs. The interaction of cement with water is an exothermic interaction, thus a lot of heat is liberated.

Conclusion

The thermal analysis of the CEBs is important for thermal insulation purposes, is one of the fundamental materials to establish the design of earth building materials. The heat transfer through the samples CEBs depends on many different variables, including the particle size of soil, it is considered the main component of samples, mineral composition of soil, the temperature of the samples, density, compression, water content and cement content. In this chapter is an experimental study were carried out on the thermal properties of compressed earth blocks with two variables which effect on their thermal behaviour are water content and cement content. The investigated samples include samples of CEBs with four different ratios of cement (0%, 4%, 7% and 10%). The purpose of the thermal conductivity test is to determine the thermal behavior of the samples CEBs at low temperatures. The main objective of this work was to study the influence of water content and cement content on the thermal properties of compressed earth block stabilized (CEBs). Fundamental thermal properties of various high-water content and cement content CEBs samples were determined. Thermal conductivity, heat capacity, and thermal diffusivity were determined. A transient hot ring method technique is used in the experiments, in order to measure the thermal conductivity of CEBs. The results show the thermal conductivity, specific heat and thermal diffusivity of CEBs were strongly influenced by water content, an increased water content is as a substantial negative factor affecting both thermal properties of samples. Also, the effect of cement content is the increase of their thermal conductivity. The cement has been added to the samples in order to increase their durability and to limit water absorption. Although the addition of cement stabilizer enhances the engineering properties of samples CEBs, it is not the case for their hygrothermal properties. The heat will flow faster through the samples when add the cement content and water content that lead to increase their thermal properties. From the presented results above, that with increasing water content and cement content the thermal insulation properties of the samples of CEBs significantly decreased.

Chapter IV: Numerical Solution of the Heat Transfer Equation in Stabilized Compressed Earth Block

Introduction

The majority of physical problems are, in general, described by coupled and strongly non-linear equations. Regardless of linear differential equations with variables constant or low order, in general, we are unable to solve a differential equation analytically [140], [141], except in very particular cases. This is why, numerical resolution methods are always needed to solve these equations [142]. This method of resolution uses numerical schemes, which are computational algorithms for numerically solving a differential equation (i, e, calculating an approximate solution) [143], [144]. To enable differential equations to be solved, it is necessary that they be approximated. There are three prominent strategies for approximating partial differential equations that are used at present: (i) Finite Element Method (FEM); (ii) Finite Difference Method (FDM); (iii) Finite Volume Method (FVM),

Each method of numerical resolution of a continuous problem includes a discretization phase and a resolution phase. The discretization phase transforms the continuous problem into a discrete one [145].

In the present study, we opted for use of the finite volume method of implicit type which is the easiest to use for simple geometry problems. The choice of this method is essentially based on reasons of stability and saving time of calculation. The modeling is based on the heat transfer through samples of CEBs with different ratios of cement content and water content. Temperature measurements were already performed experimentally to validate the model [146], [147].

In this chapter we will present the model and compare the results obtained experimentally with the results obtained by the numerical model.

IV. 1. The finite volume method

IV. 1. 1. General principles of the method

The method includes two important steps:

- The mesh: it consists of dividing the domain into several intervals (regular or not), it is called control volumes (VC).

- Discretization: this step involves the integration of the equation into the volumes of control.

The finite volume method is a discretization technique that converts the equations of partial derivative equations into algebraic equations that can be solved numerically [148] and [149].

IV. 1. 2. Study problem of two-dimensional heat transfer in cylindrical coordinates in unsteady case

a. The mesh

An axisymmetric heat conduction model is adopted, where the z-axis is the axis of symmetry. It is convenient to formulate the problem using a cylindrical coordinate system with regard to the cylindrical geometry of the CEB samples. Since all coefficients are independent of θ ($\theta = 0$), the temperature distribution is a function of (r, z). The general differential equation which governs the unsteady conduction of heat across a two dimensional solid in cylindrical coordinates is written as the following equation [150]:

$$\rho C_p \frac{\partial T}{\partial t} = k\frac{1}{r}\left(\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)\right) + k\frac{\partial^2 T}{\partial z^2} + \dot{q} \qquad \text{(IV.1)}$$

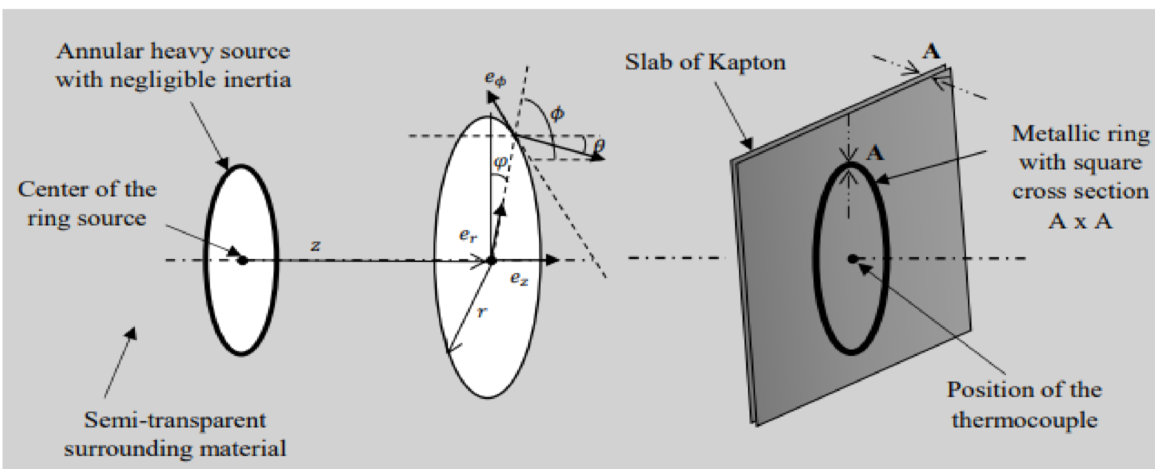


FIGURE 60. ILLUSTRATION OF THE CYLINDRICAL COORDINATE SYSTEM AROUND THE RING [133].

According to the equation IV.1 and figure 60, where $T = T(z, r, t)$ is the temperature in K, r and z are the cylindrical coordinates in the direction of the radius and cylinder length respectively, while it is neglected in angular direction θ due to symmetry boundary conditions, t is the time in [s]. And the thermo-physical parameters k the thermal conductivity in [W/m. K], C_p

the specific heat in $[J/kg.k]$, $\dot{q}$ the energy generation in $[k/s]$, and ρ the density of the sample CEB in $[g/cm^3]$ are assumed to be constant for the sake of simplicity in the analytical solution.

In two dimensions, the domain of calculation is subdivided into a finite number of control volumes which consist of regular surface elements. The mesh takes the following form shown in Figure 61:

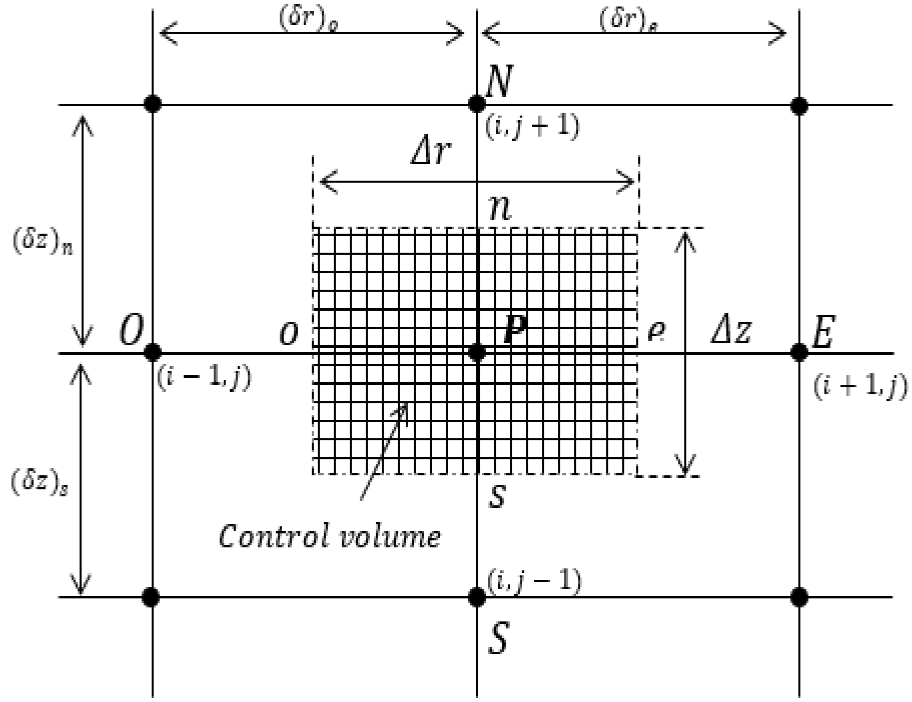


FIGURE 61. TWO-DIMENSIONAL CONTROL VOLUME IN CYLINDRICAL COORDINATES [140].

"East" (E) and "West" (W) of the point P are added the neighbors "North" (N) and "South" (S). The hatched rectangle represents a control volume element. The segments [PE] and [PN] are respectively Δr and Δz. P is the main node, $''\,i\,''$ the index of discretization along the axis of $''\,r\,''$, $''\,j\,''$: the index of discretization along the $''\,z\,''$ axis, the time will be indexed by the index $''\,k\,''$ [140].

Following the axis of $''\,r\,''$:

$$i = 1,2,3,\ldots,,\text{imax},\ \ r(i) = (i-1).\Delta r \ \text{ with } \Delta r = \frac{R}{(i_{max}-1)}$$

Following the axis of " z ":

$$j = 1,2,3,\ldots,,\text{jmax},\ \ r(j) = (j-1).\Delta z \ \text{ with } \Delta z = \frac{h/2}{(j_{max}-1)}$$

For the time $''\,t\,''$:

$t(k) = (k-1).\Delta t \quad$ with $\quad \Delta t = \frac{t_{max}}{k_{max}-1}$

Where:

$$\begin{cases} 2 \le i \le i_{max}-1 \\ 2 \le j \le j_{max}-1 \\ 2 \le k \le k_{max} \end{cases}$$

b. Discretization

In the following, we will apply the finite volume method on the heat transfer equation obtained in the previous chapter (Chapter III) as well as at the boundary conditions. The spatial domain of the problem is represented by Vc, with r being the radial coordinate and z, the axial one. The time interval of integration is represented by $T = [t, t+\Delta t]$. For simplicity, the medium is considered orthotropic. The methodology consists of integrating equation on the control volume of center P:

$$\int_{Vc}\int_{t}^{t+\Delta t}\rho C_p \frac{\partial T}{\partial t} dv.dt = \int_{vc}\int_{t}^{t+\Delta t}\frac{1}{r}\frac{\partial}{\partial r}\left(r.k\frac{\partial T}{\partial r}\right) dv.dt + \int_{vc}\int_{t}^{t+\Delta t}\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) dv.dt + \int_{vc}\int_{t}^{t+\Delta t}\dot{q}.dv.dt \qquad \text{(IV.2)}$$

Where: $\quad dv = r\, dr\, dz$, and replacing in the equation IV.2, we get:

$$\int_{vc}\int_{t}^{t+\Delta t}\rho C_p \frac{\partial T}{\partial t} r.dr.dz.dt = \int_{vc}\int_{t}^{t+\Delta t}\frac{\partial}{\partial r}\left(r.k\frac{\partial T}{\partial r}\right) dr.dz.dt + \int_{vc}\int_{t}^{t+\Delta t}\frac{\partial}{\partial z}\left(r.k\frac{\partial T}{\partial z}\right) rdr.dz.dt + \int_{vc}\int_{t}^{t+\Delta t}\dot{q}.rdr.dz.dt \qquad \text{(IV.3)}$$

By replacing the temperature gradients, we obtain:

$$\rho C_p\left(T_p{}_-T_p^o\right)r_p\Delta r\Delta z = k\left\{\left[r\frac{\partial T}{\partial r}\right]_e - \left[r\frac{\partial T}{\partial r}\right]_o\right\}\Delta z\Delta t + k\left\{\left[\frac{\partial T}{\partial z}\right]_n - \left[\frac{\partial T}{\partial z}\right]_s\right\} r_p\Delta r\Delta t + \dot{q} r_p\Delta r\Delta z\Delta t \qquad \text{(V.4)}$$

$$\rho C_P\left(T_p{}_-T_p^o\right)r_p\Delta r\Delta z = \left\{\frac{(r_E+r_p)}{2}\frac{(T_E-T_p)}{\Delta r} - \frac{(r_p+r_O)}{2}\frac{(T_p-T_O)}{\Delta r}\right\}\Delta z\Delta t + k\left\{\left[\frac{T_N-T_p}{\Delta z}\right]_n - \left[\frac{T_p-T_S}{\Delta z}\right]_s\right\} r_p\Delta r\Delta t + \dot{q} r_p\Delta r\Delta z\Delta t \qquad \text{(IV.5)}$$

$$T_p\left(\rho C_p r_p \Delta r\Delta z + \frac{k}{2\Delta r}\Delta z\Delta t\left(r_E + 2r_p + r_O\right) + \frac{2k}{\Delta z}\Delta r\Delta t r_p\right) = T_E\left(k\frac{(r_E+r_p)}{2\Delta r}\Delta z\Delta t\right) +$$

$$T_O\left(k\frac{(r_p+r_O)}{2\Delta r}\Delta z\Delta t\right) + T_N\left(\frac{k}{\Delta z}\Delta r\Delta t r_p\right) + T_S\left(\frac{k}{\Delta z}\Delta r\Delta t r_p\right) + \dot{q} r_p \Delta r\Delta z\Delta t \qquad \text{(IV.6)}$$

The final algebraic equation given by the following expression:

$$a_p T_P = a_E T_E + a_O T_O + a_N T_N + a_S T_S + b_o \qquad \text{(IV.7)}$$

With: $a_E = \frac{k}{2\Delta r}\Delta z\, \Delta t\left(r_E + r_p\right)$

$$a_O = \frac{k}{2\Delta r}\Delta z\Delta t\left(r_p + r_O\right)$$

$a_N = \frac{k}{\Delta z}\Delta r\Delta t r_p$

$$a_S = \frac{k}{\Delta z}\Delta r\Delta t r_p$$

$$a_p = a_p^o + a_E + a_O + a_N + a_S$$

With: $a_p^o = \rho C_p r_p \Delta r\Delta z$

$$b_o = a_p^o T_p^o + \dot{q} r_p \Delta r\Delta z\Delta t$$

This system of algebraic equations is applied only to areas not influenced by the boundary conditions.

Where: $r_p = \Delta r(i-1) \Rightarrow r_E = i\Delta r,$

$r_O = \Delta r(i-2)$

$$\Rightarrow a_E = k\Delta z\Delta t\left(i-\frac{1}{2}\right)$$

$$a_O = k\Delta z\Delta t\left(i-\frac{3}{2}\right)$$

$$a_N = \frac{k\Delta r^2\Delta t}{\Delta z}(i-1)$$

$$a_S = \frac{k\Delta r^2\Delta t}{\Delta z}(i-1)$$

$$a_p^o = \rho c_p \Delta r^2 \Delta z (i-1)$$

$$b_0 = a_p^0 T_P^0 + \dot{q} \Delta r^2 \Delta z \Delta t (i-1)$$

Axial symmetry boundary conditions:

We integrate the heat equation IV. 1 on the half- control volume hatched presented in the following figure:

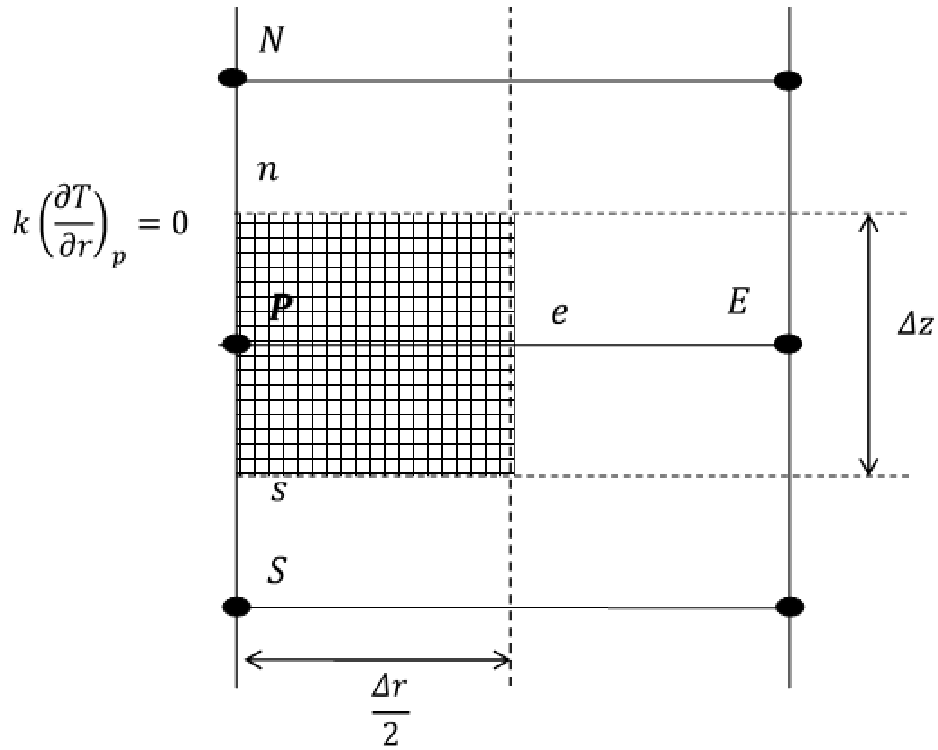


FIGURE 62. HALF VOLUME CONTROL ON THE WEST BORDER [140].

$$\rho c_P (T_P - T_P^0) r_p' \frac{\Delta r}{2} \Delta z = k \left\{ \frac{(r_E + r_p)}{2} \frac{(T_E - T_P)}{\Delta r} \right\} \Delta z \Delta t + k \left\{ \frac{T_N - T_P}{\Delta z} - \frac{T_P - T_S}{\Delta z} \right\} r_p' \frac{\Delta r}{2} \Delta t + \dot{q} \frac{\Delta r}{2} \Delta z \Delta t r_p'$$

(V.8)

$$T_P \left(\rho c_p r_p' \frac{\Delta r}{2} \Delta z + \frac{k}{2\Delta r} (r_E + r_P) \Delta z \Delta t + \frac{2k\Delta r}{2\Delta z} r_p' \Delta t \right) = T_E \frac{k\Delta z \Delta t}{2\Delta r} (r_E + r_P) + T_N \left(\frac{k\Delta r \Delta t}{2\Delta z} r_p' \right) + T_S \left(\frac{k\Delta r \Delta t}{2\Delta z} r_p' \right) + \dot{q} \frac{\Delta r}{2} \Delta z \Delta t r_p' \qquad \text{(IV.9)}$$

By grouping the terms in Equation IV.9, we obtain the general form of the discretized equation:

$$a_p T_p = a_E T_E + a_N T_N + a_S T_S + b_o \qquad \text{(IV.10)}$$

With:

$$a_E = \frac{k\Delta z\Delta t}{2\Delta r}(r_E + r_P), \qquad a_N = \frac{k\Delta r\Delta t}{2\Delta z} r_p^{\backslash}, \qquad a_s = \frac{k\Delta r\Delta t}{2\Delta z} r_p^{\backslash}$$

$$a_p = a_p^o + a_E + a_N + a_S,$$

$$a_p^o = \rho c_p r_p^{\backslash} \frac{\Delta r}{2} \Delta z,$$

$$b_0 = a_p^0 T_p^0 + \dot{q} r_p^{\backslash} \frac{\Delta r}{2} \Delta z \Delta t$$

Solution of systems of discretization equations by scanning method:

The direct resolution of the system of algebraic equations is complicated and to fix it, we use a method of iterative scanning resolution in the r and z directions respectively.

$$a(i,j) = a_p(i,j)$$

$$b(i,j) = a_e(i,j)$$

$$c(i,j) = a_o(i,j)$$

We consider the following algebraic equation can represent by:

$$d(i,j) = b_o(i,j) + a_n(i,j) * t(i,j+1) + a_s(i,j) * t(i,j-1) \qquad \text{(IV.11)}$$

$$\alpha(1,j) = b(1,j)/a(1,j)$$
$$\beta(1,j) = d(1,j)/a(1,j)$$
$$\alpha(i,j) = b(i,j)/\big(a(i,j) - c(i,j) * \alpha(i-1,j)\big) \qquad \text{(IV.12)}$$
$$\beta(i,j) = \big(d(i,j) + c(i,j) * \beta(i-1,j)\big)/\big(a(i,j) - c(i,j) * \alpha(i-1,j)\big) \qquad \text{(IV.13)}$$

The recurrence formulas (IV. 12) and (IV. 13) are calculated using the data of α (i,j) and β (i,j) resulting from the boundary conditions.

$$T(i,j) = \alpha(i,j) * T(i+1,j) + \beta(i,j) \qquad \text{(IV.14)}$$

IV. 1. 3. Organizational chart for resolution

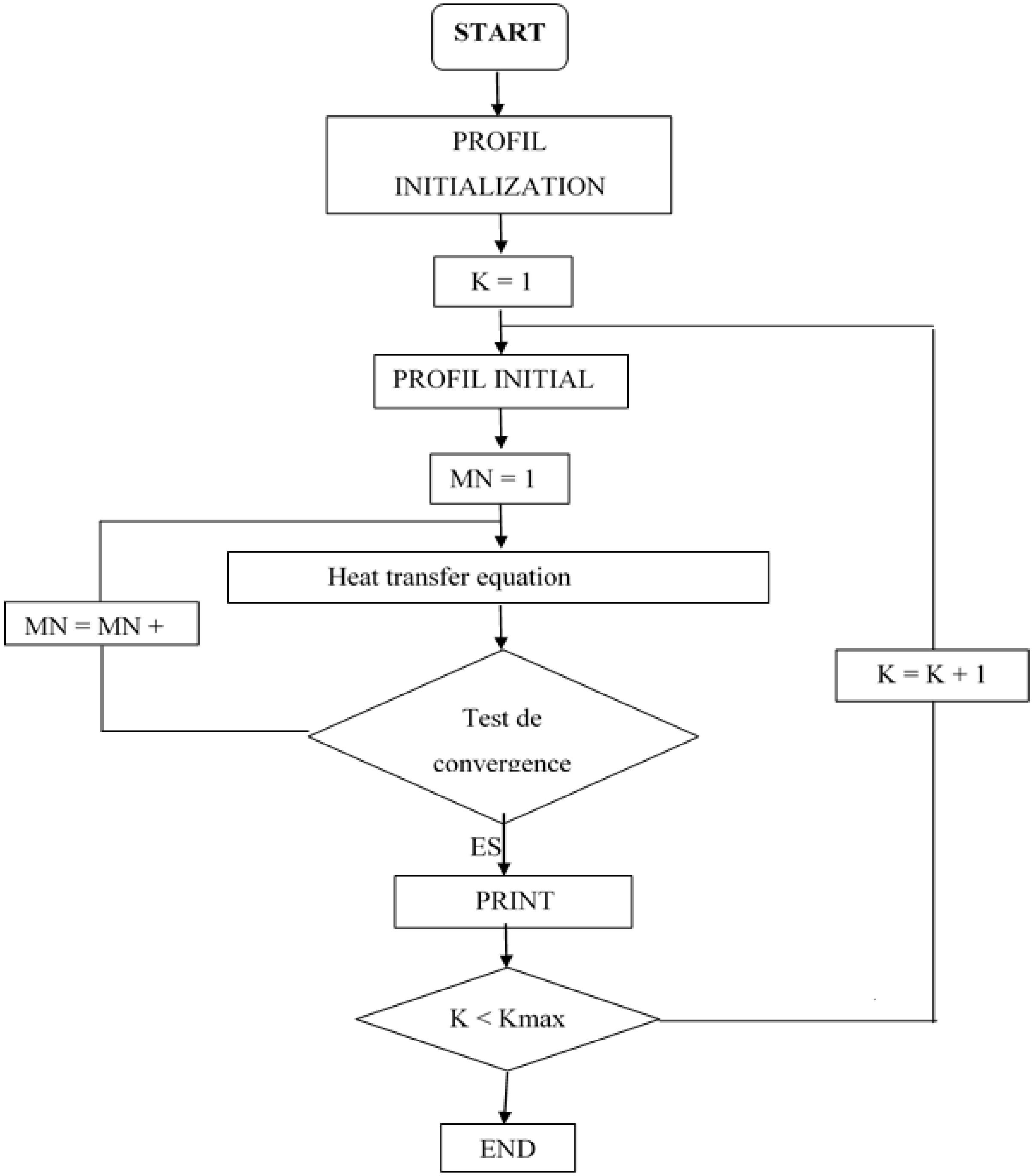


FIGURE 63. ORGANIZATIONAL CHART OF THE PROGRAM USED.

IV. 2. Numerical results of the Heat Transfer Equation in Stabilized Compressed Earth Block

All unsteady- state solutions were obtained using the implicit transient algorithm, when the time derivative of the temperature is changing. From the numerical investigation it is found that heat exchange between the particles of the sample of CEBs depends on the parameters such as cement content, water content and boundaries condition.

Once the model is validated, we used it to calculate the temperature profile through the sample surface. The results are obtained by the program developed in this work with Fortran software. Figures 64, 65, 66 and 67 show the evolution of the temperature along the surface of the sample for each period of time during heating which lasted 400 s. From the curves in these figures, it is possible to observe the differences variation of temperature the with cement content and with different ratios of water content for each sample. Also, illustrate comparison of the temperature rise with time obtained experimentally and numerically for the four samples with 0%, 4%, 7% and 10% cement content and with three ratios of water content. It is worth remind that the program allows us to calculate the temperature variation and thermal conductivity for any value of cement and water contents. There is an inverse relation between the variation of temperature and water content. There is good agreement between experimental measurements and numerical calculations. The variations of temperature as function of time for all the samples are not linear whether numerical or experimental.

According to the formula (Eq. IV.1) there is an inverse relation between thermal conductivity and the temperature variation: $\frac{q_x}{K} = -A\frac{\partial T}{\partial x}$. As the temperature increases the thermal conductivity decreases and the heat diffusion also decreases, resulting in the accumulation of heat in the ring heating zone.

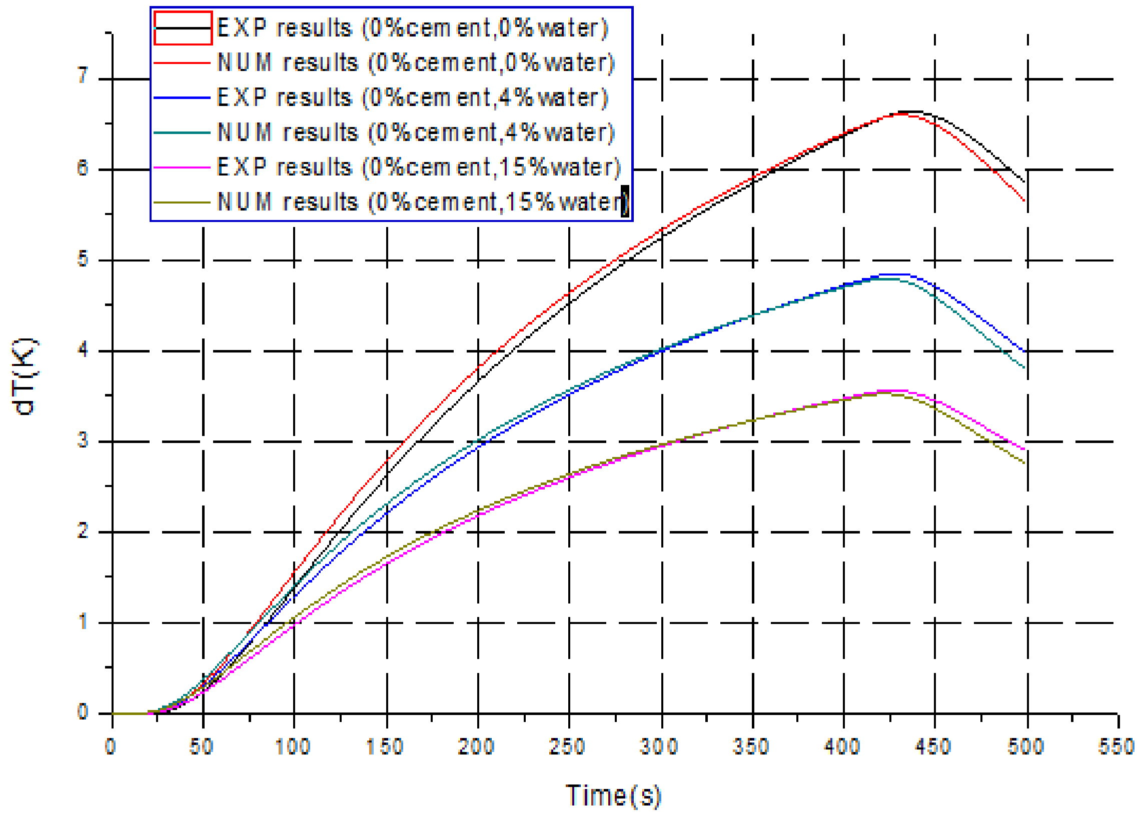


FIGURE 64. THE VARIATION OF TEMPERATURE AS FUNCTION OF TIME OBTAINED EXPERIMENTALLY AND NUMERICALLY, FOR THE SAMPLE 1 WITH 0% CEMENT CONTENT AND WITH THREE RATIOS OF WATER CONTENT

For the hot ring method's power of 2W, heating time 400s and measuring time 500s, the variation temperature of sample1 (0% cement) in 0% water content hardly reach 6,63k after 436 second of exposure. In 4% water content the variation temperature reaches 4,85k after 427 second and in 15% water content the variation temperature reaches 3,56k after 426 second (Figure 64). After these measurements the variation of temperature values, the temperature gradually begins to decrease.

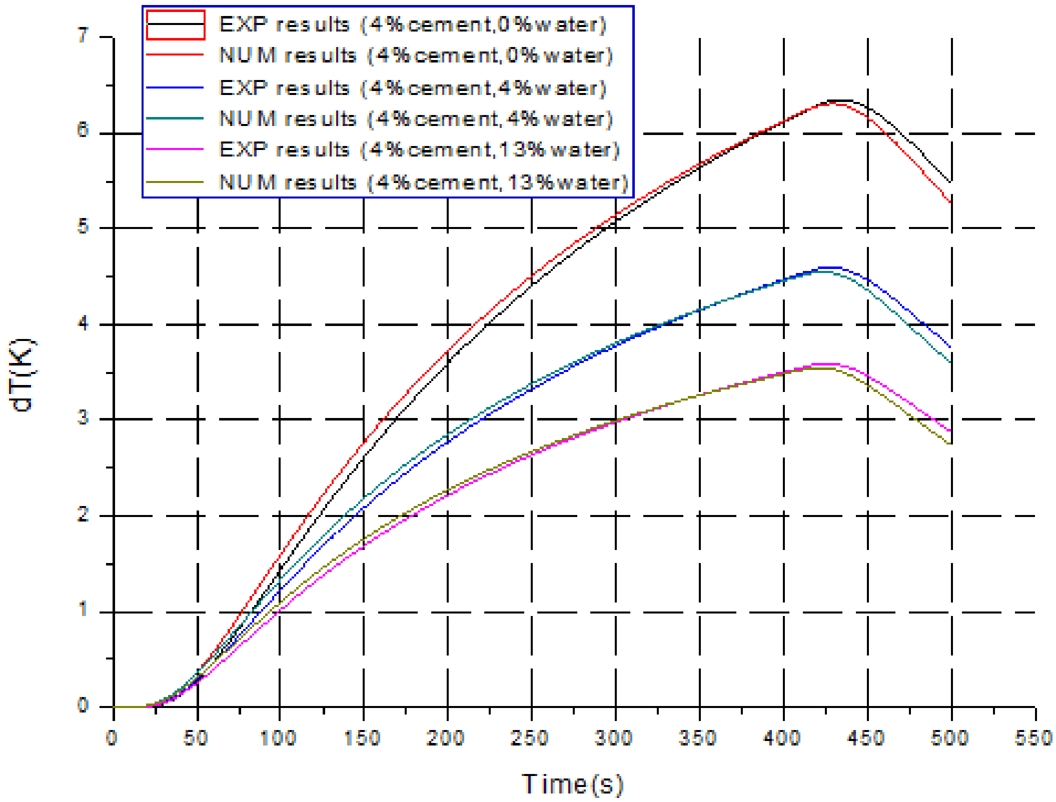


FIGURE 65. THE VARIATION OF TEMPERATURE AS FUNCTION OF TIME OBTAINED EXPERIMENTALLY AND NUMERICALLY, FOR THE SAMPLE 2 WITH 4% CEMENT CONTENT AND WITH THREE RATIOS OF WATER CONTENT

The variation temperature of sample 2 (4% cement) in 0% water content hardly reach 6,35k after 432 second of exposure. In 4% water content, the variation temperature reaches 4,59k after 427 second and in 13% water content the variation temperature reaches 3,59k after 428 second (Figure 65). After these measurements the variation of temperature values, the temperature gradually begins to decrease.

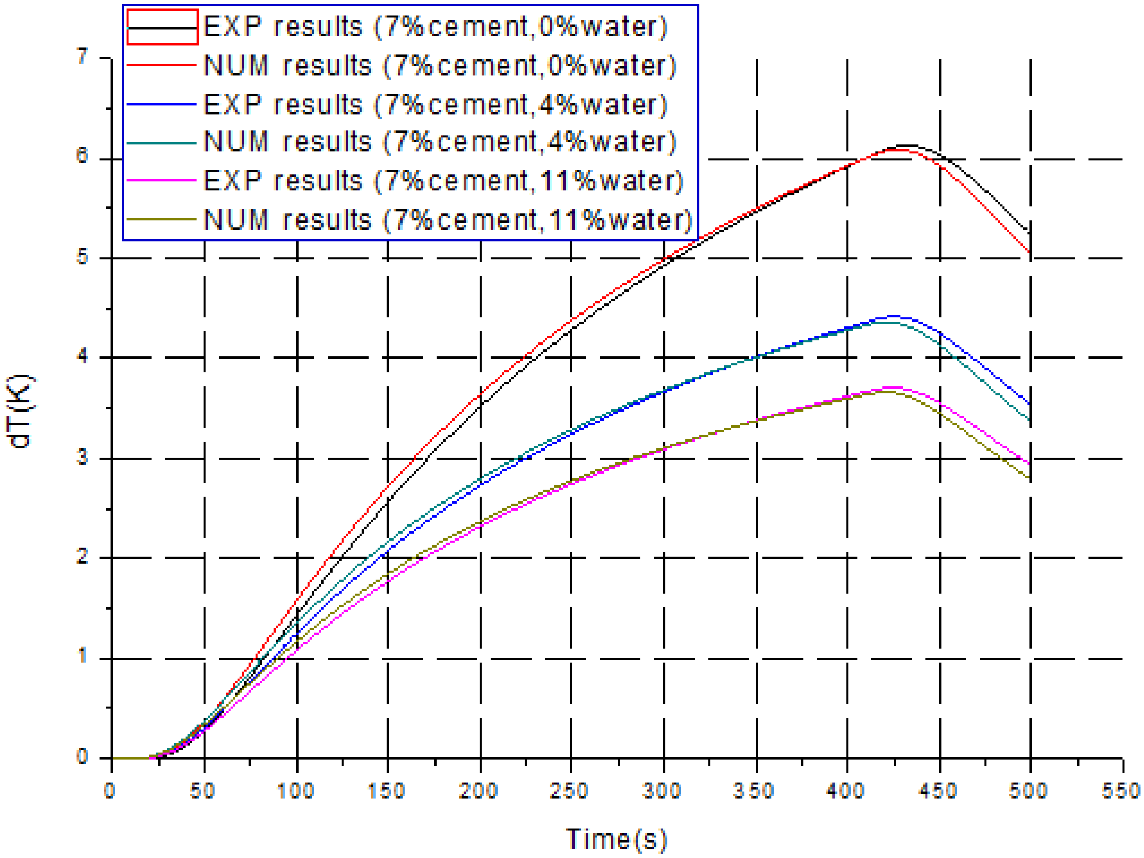


FIGURE 66. THE VARIATION OF TEMPERATURE AS FUNCTION OF TIME OBTAINED EXPERIMENTALLY AND NUMERICALLY, FOR THE SAMPLE 3 WITH 7% CEMENT CONTENT AND WITH THREE RATIOS OF WATER CONTENT

The variation temperature of sample 3 (7% cement) in 0% water content hardly reach 6,13k after 432 second of exposure. In 4% water content the variation temperature reaches 4,41k after 425 second and in 11% water content the variation temperature reaches 3,71 k after 423 second (Figure 66). After these measurements the variation of temperature values, the temperature gradually begins to decrease.

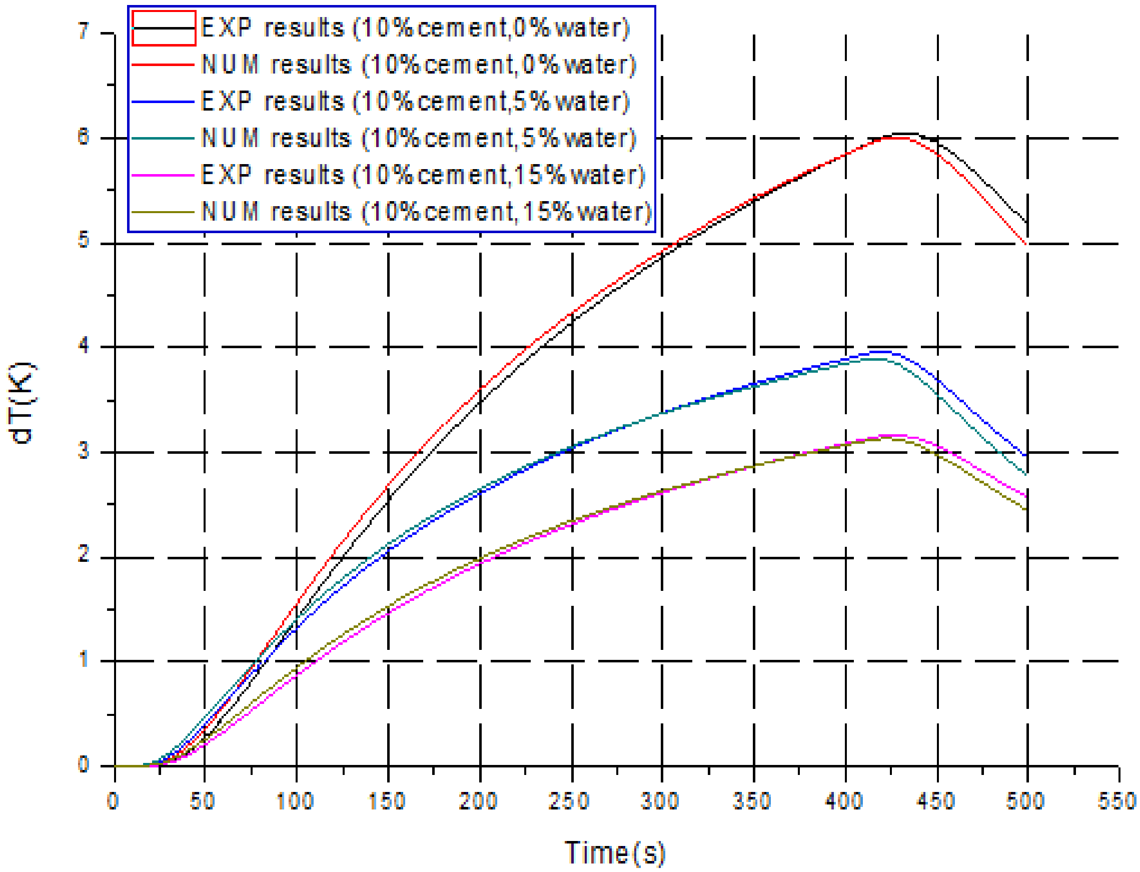


FIGURE 67. THE VARIATION OF TEMPERATURE AS FUNCTION OF TIME OBTAINED EXPERIMENTALLY AND NUMERICALLY, FOR THE SAMPLE 4 WITH 10% CEMENT CONTENT AND WITH THREE RATIOS OF WATER CONTENT

The variation temperature of sample 4 (10% cement) in 0% water content hardly reach 6,05k after 432 second of exposure. In 4% water content the variation temperature reaches 3,96k after 420 second and in 15% water content the variation temperature reaches 3,16 k after 426 second (Figure 67). After these measurements the variation of temperature values, the temperature gradually begins to decrease.

To validate the numerical model, the values of the temperatures measured experimentally are compared with those calculated by the program. The results are presented in tables 27, 28, 29, and 30 using the variation of temperature as function of time curves. Tables give the values of the temperatures (on CEBs) measured experimentally and calculated by the model in two dimensions gives close solutions with an error.

TABLE 26. THE VARIATION OF TEMPERATURE WITH TIME VALUES MEASURED EXPERIMENTALLY AND NUMERICALLY CALCULATED OF SAMPLE1(CEBS) WITH (0% CEMENT) AND DIFFERENT WATER CONTENT

	0% Cement	0% Cement	0% Cement	0% Cement	0% Cement	0% Cement
	0% Water	0% Water	4% Water	4% Water	15% Water	15% Water
	EXP	NUM	EXP	NUM	EXP	NUM
Time (s)	ΔT(K)	ΔT(K)	ΔT(K)	ΔT(K)	ΔT(K)	ΔT(K)
20	1,9353232 E-3	0,00844	5,458173 E-3	0,01496	4,7048584 E-3	0,01236
40	0,105958	0,1618	0,150362	0,20387	0,119529	0,16024
60	0,428923	0,53724	0,482195	0,57058	0,372947	0,43888
80	0,886921	1,03108	0,886094	0,99311	0,675872	0,7548
100	1,3921	1,55654	1,294526	1,4084	0,979075	1,06237
120	1,897563	2,07078	1,68112	1,79437	1,264196	1,3465
140	2,382114	2,55618	2,03774	2,14576	1,526028	1,6041
160	2,837487	3,00706	2,36357	2,46366	1,764475	1,83644
180	3,261566	3,42313	2,66055	2,75115	1,981251	2,04608
200	3,65503	3,80634	2,93146	3,01177	2,1786	2,23575
220	4,019795	4,15942	3,17917	3,24883	2,358769	2,40804
240	4,358187	4,48528	3,40638	3,46528	2,523808	2,56515
260	4,672596	4,78671	3,6155	3,6637	2,675525	2,70904
280	4,965311	5,06626	3,8086	3,84628	2,815497	2,84133
300	5,238415	5,32618	3,98752	4,0149	2,945079	2,9634
320	5,493806	5,56849	4,15381	4,17114	3,065436	3,07643
340	5,733167	5,79494	4,30885	4,31631	3,177566	3,18136
360	5,958014	6,00709	4,45378	4,4516	3,282338	3,27911
380	6,169657	6,20625	4,58963	4,578	3,380498	3,37035
400	6,369281	6,39365	4,7173	4,69633	3,47269	3,45573
420	6,556024	6,56166	4,83207	4,79195	3,554785	3,52313
440	6,630639	6,57398	4,80066	4,7061	3,521865	3,44956
460	6,47711	6,35546	4,57617	4,43695	3,34588	3,24127
480	6,180086	6,01076	4,27399	4,10684	3,116316	2,99196
Error	1,90%		0,90%		0,80%	

TABLEAU 27. THE VARIATION OF TEMPERATURE WITH TIME VALUES MEASURED EXPERIMENTALLY AND NUMERICALLY CALCULATED OF SAMPLE2 (CEBS) WITH (4% CEMENT) AND DIFFERENT WATER CONTENT

	4% Cement	4% Cement	4% Cement	4% Cement	4% Cement	4% Cement
	0% Water	0% Water	4% Water	4% Water	13% Water	13% Water
	EXP	NUM	EXP	NUM	EXP	NUM
Time (s)	ΔT(K)	ΔT(K)	ΔT(K)	ΔT(K)	ΔT(K)	ΔT(K)
20	2,8618549 E-3	0,01072	0,00517	0,01427	5,568591 E-3	0,01406
40	0,125542	0,18423	0,14248	0,19348	0,130315	0,17279
60	0,471398	0,57953	0,45691	0,54119	0,395463	0,46284
80	0,938378	1,07816	0,83963	0,94178	0,706637	0,78631
100	1,439226	1,59542	1,22665	1,33551	1,014889	1,09823
120	1,931448	2,09328	1,59297	1,70142	1,302845	1,38457
140	2,397484	2,55779	1,93089	2,03458	1,56608	1,6431
160	2,831487	2,9856	2,23964	2,33602	1,804995	1,87552
180	3,232856	3,37783	2,52105	2,60863	2,021651	2,08473
200	3,603221	3,73722	2,77775	2,85575	2,218491	2,27367
220	3,945041	4,06699	3,01247	3,08054	2,397895	2,44501
240	4,260999	4,3703	3,22777	3,28581	2,562019	2,60108
260	4,553656	4,65005	3,42592	3,474	2,712723	2,74384
280	4,825401	4,90886	3,6089	3,64717	2,85163	2,87496
300	5,078376	5,14898	3,77844	3,8071	2,980116	2,99585
320	5,31447	5,37243	3,93601	3,95529	3,099367	3,10769
340	5,53537	5,58088	4,08292	4,093	3,210399	3,21145
360	5,742548	5,77584	4,22025	4,22133	3,314083	3,30802
380	5,937305	5,95863	4,34898	4,34123	3,411179	3,39811
400	6,12078	6,13035	4,46995	4,4535	3,502333	3,48235
420	6,291126	6,2811	4,5787	4,54424	3,582551	3,54699
440	6,332276	6,2589	4,54894	4,46301	3,538713	3,4615
460	6,141666	6,00686	4,33622	4,20808	3,350044	3,2408
480	5,822065	5,6443	4,04988	3,8954	3,111303	2,98291
Error	1,60%		0,97%		0,80%	

TABLE 28. THE VARIATION OF TEMPERATURE WITH TIME VALUES MEASURED EXPERIMENTALLY AND NUMERICALLY CALCULATED OF SAMPLE3 (CEBS) WITH (7% CEMENT) AND DIFFERENT WATER CONTENT

	7% Cement	7% Cement	7% Cement	7% Cement	7% Cement	7% Cement
	0% Water	0% Water	4% Water	4% Water	11% Water	11% Water
	EXP	NUM	EXP	NUM	EXP	NUM
Time (s)	ΔT(K)	ΔT(K)	ΔT(K)	ΔT(K)	ΔT(K)	ΔT(K)
20	3,2049434 E-3	0,01138	0,00685	0,01721	6,7709946 E-3	0,01628
40	0,130378	0,18879	0,16026	0,21236	0,145803	0,19096
60	0,477196	0,583	0,48635	0,56902	0,430171	0,50036
80	0,937697	1,07312	0,86904	0,96678	0,757739	0,83971
100	1,426912	1,57718	1,24814	1,35033	1,078834	1,16376
120	1,904782	2,05958	1,60227	1,70245	1,37679	1,45937
140	2,355321	2,50788	1,926	2,02033	1,647907	1,72511
160	2,7736	2,9196	2,21983	2,30612	1,893145	1,96327
180	3,159512	3,29624	2,48628	2,56337	2,114954	2,17714
200	3,51495	3,64076	2,72835	2,79569	2,316072	2,36989
220	3,842495	3,95643	2,94899	3,00637	2,49907	2,54443
240	4,144882	4,24643	3,15083	3,19827	2,66625	2,7032
260	4,424677	4,51368	3,33617	3,37383	2,819593	2,84828
280	4,684247	4,7607	3,507	3,53506	2,960786	2,98139
300	4,925701	4,98972	3,66502	3,68371	3,091282	3,10401
320	5,150901	5,20268	3,81168	3,8212	3,212305	3,21735
340	5,361478	5,40127	3,94823	3,94881	3,324923	3,32244
360	5,558877	5,58689	4,07574	4,06754	3,430019	3,42014
380	5,744338	5,76084	4,19515	4,1783	3,52839	3,51123
400	5,918994	5,92417	4,30725	4,28187	3,620704	3,59632
420	6,080612	6,06625	4,40591	4,36137	3,700766	3,65944
440	6,109286	6,03257	4,352	4,25623	3,643609	3,55861
460	5,910112	5,77446	4,11997	3,98479	3,436603	3,31909
480	5,589717	5,41356	3,82636	3,66764	3,182277	3,04584
Error	1,50%		0,72%		0,60%	

TABLE 29. THE VARIATION OF TEMPERATURE WITH TIME VALUES MEASURED EXPERIMENTALLY AND NUMERICALLY CALCULATED OF SAMPLE4 (CEBS) WITH (10% CEMENT) AND DIFFERENT WATER CONTENT

	10% Cement	10% Cement	10% Cement	10% Cement	10% Cement	10% Cement
	0% Water	0% Water	5% Water	5% Water	15% Water	15% Water
	EXP	NUM	EXP	NUM	EXP	NUM
Time (s)	ΔT(K)	ΔT(K)	ΔT(K)	ΔT(K)	ΔT(K)	ΔT(K)
20	3,1630486 E-3	0,01114	0,01557	0,03044	4,1747758 E-3	0,01091
40	0,128674	0,186100	0,227210	0,282180	0,106062	0,142140
60	0,470958	0,575070	0,587410	0,664740	0,330928	0,389420
80	0,925440	1,058710	0,967460	1,052150	0,599723	0,669790
100	1,408260	1,556080	1,322110	1,405520	0,868765	0,942760
120	1,879883	2,032130	1,641040	1,718550	1,121762	1,194900
140	2,324533	2,474520	1,925030	1,994310	1,354095	1,423530
160	2,737344	2,880790	2,177870	2,237810	1,565677	1,629740
180	3,118211	3,252440	2,403800	2,453980	1,758029	1,815790
200	3,469003	3,592390	2,606710	2,647100	1,933144	1,984140
220	3,792266	3,903900	2,789920	2,820660	2,093013	2,137030
240	4,090700	4,190080	2,956230	2,977570	2,239458	2,276480
260	4,366838	4,453770	3,107950	3,120170	2,374081	2,404170
280	4,623015	4,697520	3,247030	3,250350	2,498283	2,521560
300	4,861313	4,923520	3,375060	3,369710	2,613265	2,629900
320	5,083568	5,133670	3,493390	3,479540	2,720063	2,730200
340	5,291393	5,329600	3,603170	3,580920	2,819559	2,823340
360	5,486211	5,512770	3,705360	3,674760	2,912526	2,910070
380	5,669249	5,684410	3,800770	3,761880	2,999627	2,991060
400	5,841622	5,845580	3,890110	3,842910	3,081432	3,066820
420	6,001126	5,985740	3,958430	3,887400	3,154278	3,126650
440	6,029426	5,952500	3,825740	3,705140	3,125067	3,061380
460	5,832856	5,697730	3,540040	3,388330	2,968910	2,876560
480	5,516648	5,341520	3,230400	3,062810	2,765210	2,655350
Error	1,50%		0,02%		0,90%	

Conclusion

Heat transfer in CEBs flow is investigated numerically and experimentally. In this chapter we have developed a numerical model that calculates the temperature through the CEBs with different ratios of cement content and water content, the numerical computations are carried out using finite volume method approach. Validated by the experimental measurements carried out on the hot ring method, this model made it possible to calculate the profile of the temperatures in the CEBs with different ratios of cement content and water content. Indeed, the cement content in the samples of CEBs do not alone effect on behavior of temperature, but also the water content effect on behavior of temperature. The numerical and experimental results have shown a good agreement for the temperature of the contact area.

Chapter V: Technico- Economic Optimum of thermal conductivity of stabilized compressed earth block

Introduction

The importance of energy saving and low energy consumption is linked to energy prices, emissions, etc. Thermal characteristic of building materials is necessary to evaluate the energy consumption in building, since it raises now particularly difficult issues. The importance of earth buildings consists of hydrothermal properties of the material. Compressed earth block is growing in many countries because of their low impact on the environment and low consumption of energy. While the stabilization of compressed earth block is a common approach used to maintain and improve its use for construction, it must not be systematic since it causes thermal conductivity increase. Thus, its addition must be controlled so that it is effective as economic.

In this chapter, a technico- economic Optimum (TEO) model is proposed and tested. This optimum is determined by using the evolution of the properties of the compressed earth block according to the stabilization (cement content) and water content, proposed in this chapter, by means of physical interpretations. It is borrowed from Bouabid and Cherraj models [60] and [63] on mechanical properties behavior with respect to cement and compaction effects. The comparison is made between experimental and analytical methods used to determine thermal parameters proved high agreement between them.

As seen in the previous chapters, thermal conductivity presents a nonlinear increase for an increasing cement content and water content in CEBs. Decreasing the thermal conductivity of the CEB is very important factor to increase its insulation capability and to achieving thermal comfort for its occupants. Insulation reduces unwanted heat loss or gain and then decreases the energy demands of heating and cooling systems. In contrast, the other additives increase the thermal conductivity of the CEB. This might happen due to the reaction between the additives and the components of the CEB.

The point corresponding to the best rate of cement content or water content will be considered technico-economic optimum (TEO) if the economic contribution of the cement (more cement) content or water content (low humidity) is proportionally compensated and justified by a technical gain of the material properties, in this case thermal conductivity. Experimentally, even with a large series of tests varying the cement content and the water content, it is less probable to quantify the TEO but with certainty. Overestimation will certainly generate additional costs, especially on a wide range, while the minimization would lead to relatively low performance.

V. 1. Modelling

We have proved in chapter III from the experimental results that the thermal properties of the compressed earth block evolve as a non- linear function of both cement content and water content. Nevertheless, the way in which these properties evolve is unknown. From the analysis of experimental results an understanding of the phenomena which it occurring by the modes of stabilization and humidity, and adapting Bouabid and Cherraj models [60], [63], [151], we proposed a model that allow to give the thermal conductivity, specific heat and thermal diffusivity of the compressed earth block stabilized as function of the cement content and the water content.

V. 1. 1. Hypotheses

In order to simplify the mathematical development, we adopt the variable Kc to refer to thermal conductivity. Its magnitude is assumed to continue as a function of cement content $'\mathrm{D}'$ and water content $'\mathrm{W}'$. The quantification of Kc is carried out in from the following hypotheses:

I. When $\mathrm{D} = 0$ and $\mathrm{W} = 0$, the magnitude Kc is null, $\mathrm{Kc} = \mathrm{Kc}_0$ $\quad (\mathrm{V}.1)$

II. When $\mathrm{D} \to \infty$ and $\mathrm{W} \to \infty$, then Kc is constant, $\mathrm{Kc} = \mathrm{Kc}_\infty$ $\quad (\mathrm{V}.2)$

$'\mathrm{D}'$ is the cement content, and $'\mathrm{W}'$ is the water content applied to the compressed earth block stabilized.

V. 1. 1. 1. Analysis of the effect of the cement content

From previous studies, the effect of stabilization by cement on the improvement material characteristics such as strength, density, durability, shrinkage and swelling has been demonstrated for a long time. This improvement is provided by the creation of cohesion bonds, more or less stable, between the grains of the material (Figure 68). This induces thermal properties to increase thermal properties. Moreover, the degree of this effect depends on the granular composition of the material, the proportion and type of clay, etc [152], [153]. When the clay fraction represents more than 30% of the material, it is very difficult to acquire stabilization an economically justified. In general, the amount of cement needed increases with the percentage clay [154].

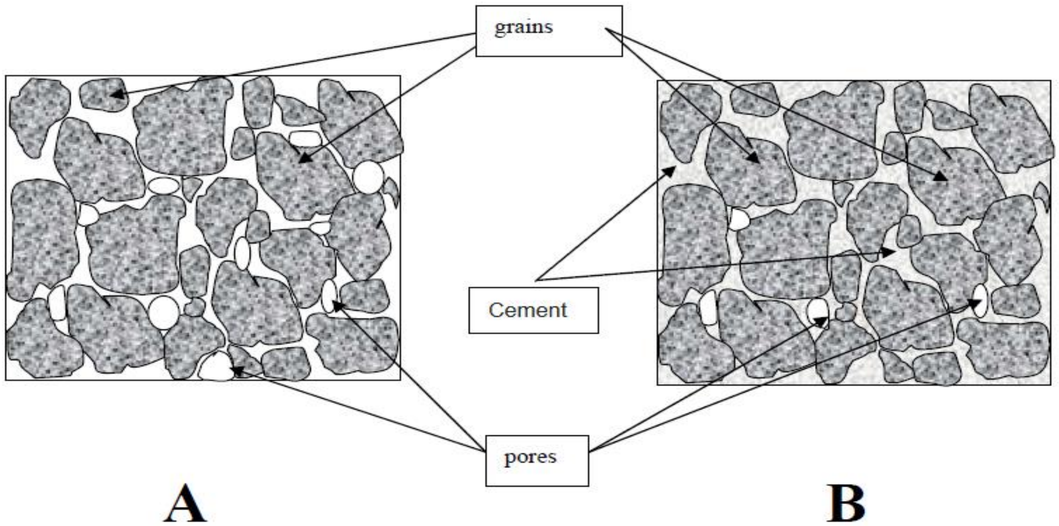


FIGURE 68. SATURATION PHASE BY ADDING CEMENT: (A) RAW MATERIAL, (B) CEMENTED MATERIAL [60]

The contribution of cement in the material, starting from a certain low value, does not bring a substantive change in the magnitude Kc_D with respect to the dosage. At high rate of cement content, Kc seems to not change. This is the saturation phase. Practically all bonds are masonry and almost all pores are eliminated (Figure 68 (B)). Thus, almost all heat vectors are built. From equation V. 2, this translates as:

When $D \to \infty$, Kc_D is constant. $(V.3)$

In equation V. 3, the constant is none other than the saturation limit. Actually, this limit is approximated by inferior value. It depends on the granular composition of the material, the clay fraction, the nature of the clay, etc. The magnitude Kc_D is proportional to D^n . Moreover, to satisfy mathematically the condition V. 3, are posed for Kc_D a variation in D^n in numerator and denominator under the following formula:

$$Kc_D = \frac{a_D * D^n}{b_D + D^n} + Kc_{D0} \qquad (V.4)$$

With:

a_D : Saturation limit in cementation;

n: Degree of variation;

b_D : Constant introduced to approach the limit (asymptote) by inferior value.

Kc_{D0} : Value of the Kc when $D = 0$.

Starting with the formula V.4, deduce that for $D = 0$ we have $Kc_D \neq 0$.

As for D $\rightarrow\ \infty$ then we have $\mathrm{Kc} = \mathrm{a_D}$.

V. 1. 1. 2. Analysis of the effect of the water content

The water and high humidity can have many different effects on building materials, including that on thermal comfort. This effect is negative while the thermal properties increasing with water content as mentioned in chapter III (Figures 55, 56 and 57). Frist, the water content increases thermal contact between grains, by substituting of the air (with very low conductivity) in pores by water (with higher conductivity) and filling the hollow spaces inside dry pores. Secondly, the cement content will be hydrate with water which allows the creation of humidified rigid bridges between clay and sand particles (Figure 69). The degree of this effect depends on the granular composition of the material, the proportion and type of clay, and the ratios of cement content, etc. So, it is important to determine the rate of water content of the samples to control of humidity in the building [155].

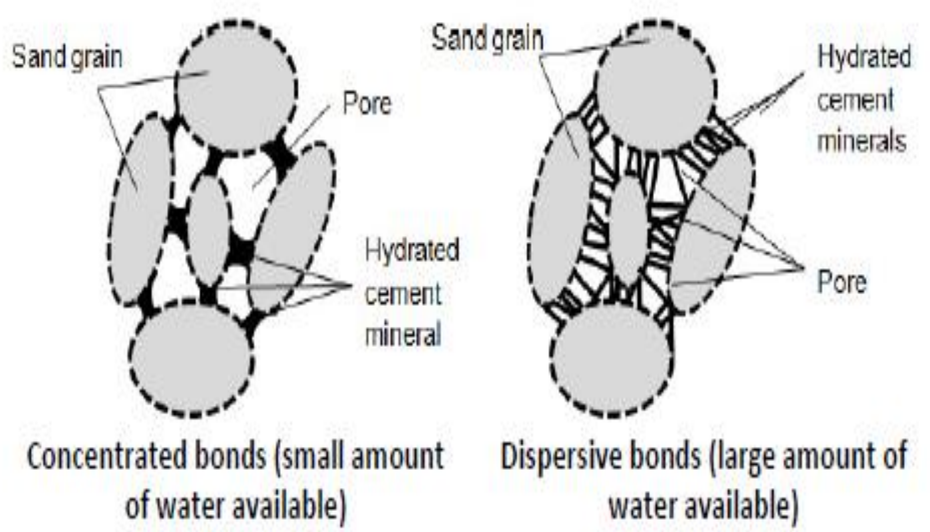


FIGURE 69. EXPECTED GEOMETRIES FOR THE BONDS CONSIDERING THE AMOUNT OF WATER AVAILABLE IN THE SOIL MIXTURE [155].

Similarity of stabilization effects led to propose the same function of variation V. 4 of the magnitude Kc as a function of W:

$$\mathrm{Kc_W} = \frac{\mathrm{a_W} \times \mathrm{W^m}}{\mathrm{b_W} + \mathrm{W^m}} + \mathrm{Kc_{W0}} \qquad (\mathrm{V.5})$$

With:

a_W : Saturation limit in water content;

m : Degree of variation;

b_W : Constant introduced to approach the limit (asymptote) by inferior value.

Kc_{W0} : Value of the magnitude when $W = 0$.

In equation V. 5 find $Kc_V \neq 0$ for $W = 0$, that is the hypothesis I, and $Kc = a_W$ when $'W'$ is infinite.

The evolution of the magnitude Kc as a function of $'D'$ and $'W'$ is deduced from the equations V. 4 and V.5, as follows:

$$Kc(W, D) = \frac{a_D \times D^m}{b_D + D^m} + \frac{a_W \times W^n}{b_W + W^n} + Kc_0 \qquad (V.6)$$

From equation V. 6 models 1, we have $Kc(0,0) = 0$, this is the hypothesis I. As $D \to \infty$ and $W \to \infty$ so $Kc_\infty = a_D + a_W$, this is the hypothesis II.

The graphical representation of the function V. 4 or V. 5 is shown in Figure 70.

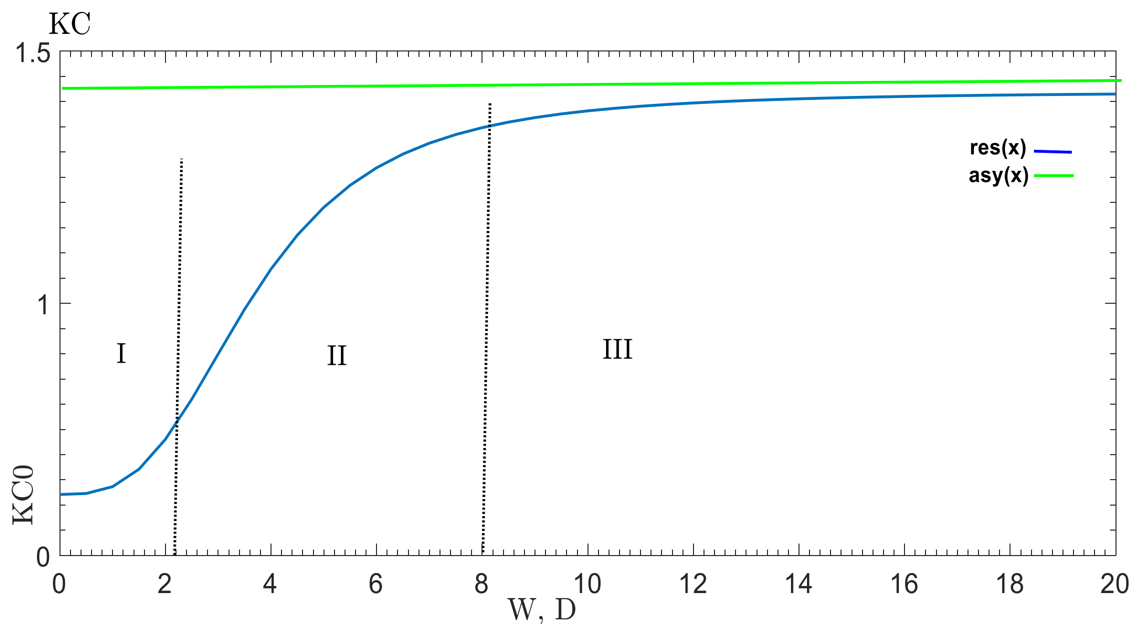


FIGURE 70. SCHEMA OF THE EVOLUTION OF KC AS A FUNCTION OF D OR W [60].

From figure 70 there are 3 zones:

I: induction zone; zone in which the stabilization variable is still low, and therefore does not lead to a significant improvement to the Kc magnitude;

II: effect zone; once stabilization reaches a certain level, its effect begins to significantly interact with the material. In this zone there is a marked improvement in the Kc magnitude as a function of stabilization;

III: saturation zone; this zone outside the threshold where the magnitude Kc is less sensitive to the increasing in the stabilization variable. The contribution of the stabilization is not economically compensated by a gain on the Kc magnitude.

V. 1. 1. 3. Coupled effect of the cement content and the water content (model 2)

In reality, each of the phenomena of cement content and water content contributes to accentuate or amplify the other. This amplification is more felt when these two phenomena are both within the "effect zone". This amplification results from the interaction between these two effects. The association of the effects of cement content and water content induces a physical interaction between them, that increase their effect each time the cement content and water content increase. Therefore, Mr. Bouabid and Mr. Cherraj proposed to add each term correction term which refers to the physical interaction. Moreover, including this interaction term leads to improve the accuracy of the model to fit experimental results which did not include the coupling effect.

In view of the above, a correction term added to the expression Kc such that:

$$\mathrm{Kc}(\mathrm{W},\mathrm{D}) = \frac{a_W \times W^n}{b_W + W^n} + \frac{a_D \times D^m}{b_D + D^m} + \mathrm{Kc}_{D_0 W_0} + \mathrm{Kc}_{int} \qquad (\mathrm{V}.7)$$

The search for the form of the Kc_{int} correction term supposes the following physical hypotheses:

III. When $D = 0$ or $W = 0$ so $\mathrm{Kc}_{int} = 0$. $(\mathrm{V}.8)$

IV. When $D \to \infty$ and $W \to \infty$ we have $\mathrm{Kc}_{int} = \text{constant}$.

$(\mathrm{V}.9)$

The interaction supposes the existence of at least two interacting effects, this is hypothesis III. As for hypothesis IV, it finds its reason in the fact that if the addition of the cement in the material does not bring a gain for Kc which reaches its saturation limit (Eq. V. 4) from a certain value, it will be even saturated to interact with water content and vice versa. On the other hand, for a given value of an effect, the interaction component reaches a relative limit for large values of the other effect. Mathematically this translates into:

$$\text{When } D = D_0 \text{ and } W \to \infty \text{ so } Kc_{int} \to Kc_{int}^{D_0}. \qquad (V.10)$$

$$\text{When } W = W_0 \text{ and } D \to \infty \text{ so } Kc_{int} \to Kc_{int}^{W_0}. \qquad (V.11)$$

For large values of the two effects, the interaction term converges but this time towards an absolute limit. Otherwise written:

$$\text{When } D \to \infty \text{ and } W \to \infty \text{ so } Kc_{int} \to Kc_{int}^{\infty}. \qquad (V.12)$$

$$\text{With } Kc_{int}^{D_0} < Kc_{int}^{\infty} \ \forall \ D_0 \text{ and } Kc_{int}^{W_0} < Kc_{int}^{\infty} \ \forall \ W_0.$$

To satisfy these conditions, Mr. Bouabid and Mr. Cherraj used a model to represent the interaction component between the cement content $'D'$ and the water content $'W'$ the following form:

$$Kc_{int}(D, W) = \frac{a_{DW} \times D^{n'} \times W^{m'}}{(D^{n'} + b_{DW})(W^{m'} + b_{DW})} \qquad (V.13)$$

With a_{DW} the absolute saturation limit of the cement / water interaction, $'n'$ and $'m'$ the degrees of variation and b_{DW} the trend constant towards the saturation limit (asymptote).

It should be noted that when D is equal to D_0 , the relative saturation limit $Kc_{int}^{D_0}$ in equation V.10 is $Kc_{int}^{D_0} = a_{D_0W} = \frac{a_{DW} \times D_0^n}{(D_0^n + b_{DW})}$, with $a_{D_0W} < a_{DW}$ Whatever D_0. In the case where W 'is equal to W_0, we get $Kc_{int}^{W_0} = a_{DW_0} = \frac{a_{DW} \times W_0^m}{(W_0^m + b_{DW})}$, with $a_{DW_0} < a_{DW}$.

From the equations V. 7 and V. 13, the evolution of the Kc magnitude according to the variables $'D'$ and $'W'$ is in the following form:

$$Kc(D, W) = \frac{a_D * D^n}{b_D + D^n} + \frac{a_W * W^m}{b_W + W^m} + \frac{a_{DW} * D^{n'} * W^{m'}}{\left(D^{n'} + b_{DW}\right) * \left(W^{m'} + b_{DW}\right)} + Kc_0 \qquad (V.14)$$

V. 1. 2. Technico- Economic Optimum (TEO) of stabilized compressed earth block

V. 1. 2. 1. Determination of the TEO

Determining the TEO relies on two technical and economic analyzes. The technical analysis relates to the technical gain provided to the mechanical and/ or thermal characteristics of the CEB. Economic analysis allows to do an estimate of the stabilization (cement, water) cost of the investment related to the technical gain [60], [156].

V. 1. 2. 2. Technical analysis

This analysis is done using the evolution, already established, of the thermal conductivity as function to the cement content and water content. It is conducted according to the following sequences:

- Locate the zone where this point could be located (Figure 70);
- Give TEO a physical particularity;
- Finally, determine the corresponding mathematical particularity.

A simple analysis of the evolution of Kc from Figure 70 excludes zones I and III. In these two zones, there is no appreciable improvement in Kc as a function of cement content or water content. In other words, the zone II is likely to shelter the TEO.

Then, the physical particularity of the TEO will be related to the gain in Kc magnitude. It designates the ratio between the variation of Kc and the variation of the cement content or water content. The interpretation is thus done through the gradient of Kc given by:

$$\Delta \mathrm{Kc} = \left(\frac{\partial \mathrm{Kc}}{\partial \mathrm{D}}, \frac{\partial \mathrm{Kc}}{\partial \mathrm{W}}\right) \qquad (\mathrm{V}.15)$$

With:

$$\mathrm{dKc} = \Delta \mathrm{Kc}.(\mathrm{dD}, \mathrm{dW})^{\mathrm{T}} \qquad (\mathrm{V}.16)$$

The figure 71 illustrates the evolution of the Kc gradient.

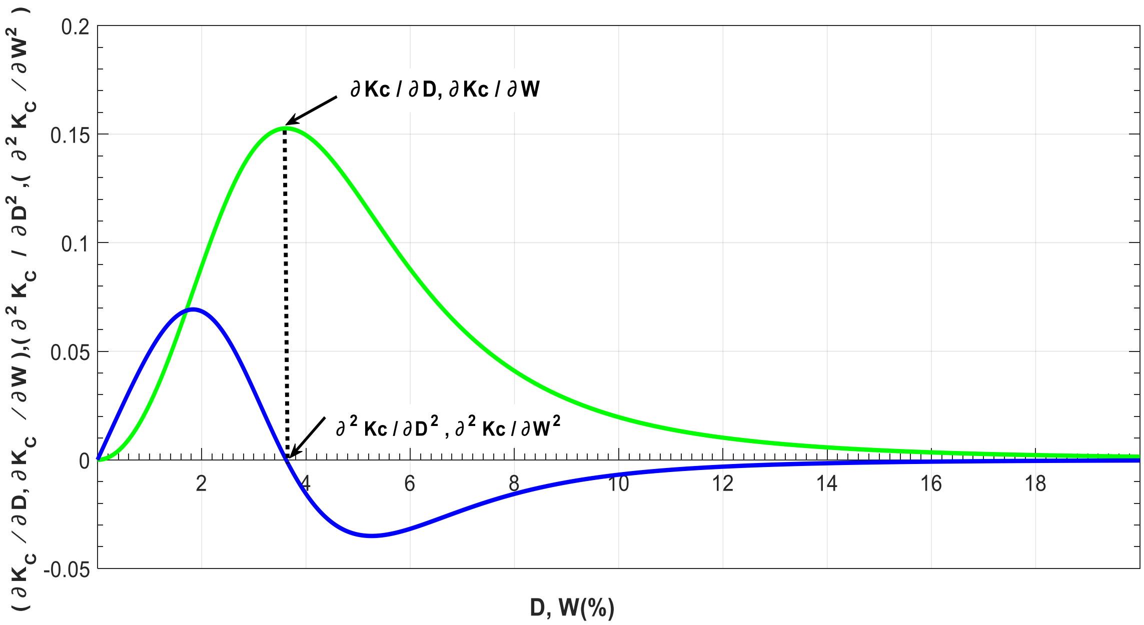


FIGURE 71. EVOLUTION OF THE GRADIENT OF KC AS A FUNCTION OF D OR W.

Finally, the mathematical particularity of the gradient is the extrema. This is the point that corresponds to the greatest gain, the maximum of the gradient of Kc. This point is the inflection point of the function Kc (D, W) (Figure 71). Then, we have the equation:

$$\Delta^2 \mathrm{Kc} = 0 \qquad (V.17)$$

With:

$$\Delta^2 \mathrm{Kc} = \begin{pmatrix} \frac{\partial^2 \mathrm{Kc}}{\partial \mathrm{D}^2} & \frac{\partial^2 \mathrm{Kc}}{\partial \mathrm{D}\, \partial \mathrm{W}} \\ \frac{\partial^2 \mathrm{Kc}}{\partial \mathrm{W}\, \partial \mathrm{D}} & \frac{\partial^2 \mathrm{Kc}}{\partial \mathrm{W}^2} \end{pmatrix} \qquad (V.18)$$

The determination of the optimum from equation V. 17 is done numerically. If the variables D and W were separated (without interaction), we will have:

$$\frac{\partial^2 \mathrm{Kc}}{\partial \mathrm{D}\, \partial \mathrm{W}} = \frac{\partial^2 \mathrm{Kc}}{\partial \mathrm{W}\, \partial \mathrm{D}} = 0 \qquad (V.19)$$

In this particular case and given the equations V. 18 and V. 19, the inflection point corresponding to equation V. 17 satisfies the verse:

$$\left(\frac{\partial^2 \mathrm{Kc}}{\partial \mathrm{D}^2} = 0, \frac{\partial^2 \mathrm{Kc}}{\partial \mathrm{W}^2} = 0 \right) \qquad (V.20)$$

After calculation, the cement content and water content corresponding to the TEO when there is no interaction and the variables are separated are obtained:

$$D_{TEO} = \sqrt[n]{\frac{b_D(n-1)}{(n+1)}} \quad , \quad W_{TEO} = \sqrt[m]{\frac{b_W(m-1)}{(m+1)}} \qquad (V.21)$$

V. 1. 2. 3. Study the effect of the interaction on the TEO

Taking into consideration that the interaction leads to shape fairly and accurately the Kc magnitude with regard to the cement content and water content, figure 72 shows the evolution of the thermal conductivity as a function of the cement content or water content, with and without the interaction. Experimental results are also plotted in the figure. The cement content or water content being fixed equal to D_0 or W_0 respectively.

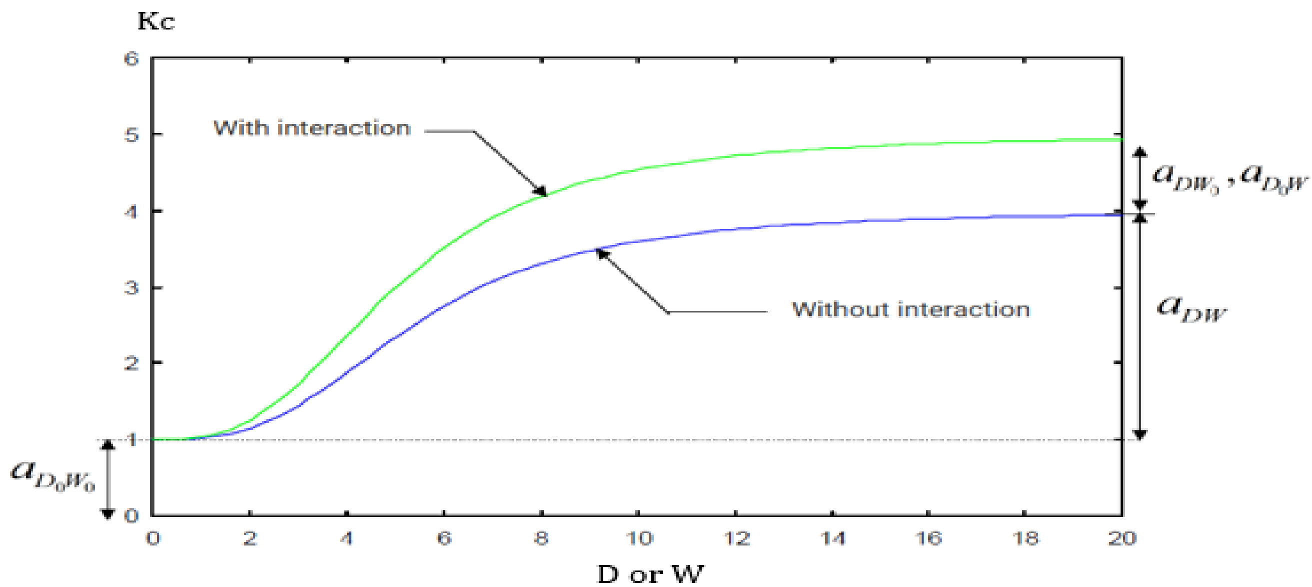


FIGURE 72. EFFECT OF THE INTERACTION ON THE EVOLUTION OF THE THERMAL CONDUCTIVITY AS FUNCTION OF CEMENT CONTENT OR WATER CONTENT.

Figure 72 shows that the interaction not only leads to fit more the thermal conductivity curve, but it also endures a displacement of the optimum towards low or high values of the cement or water variable, which is economically good.

In Figure 73, it is noted that the gain with interaction effect is greater than that without interaction. We also note the displacement of the optimum induced by the interaction. And in Figure 74, it is noted that the gain without interaction effect is greater than that with interaction.

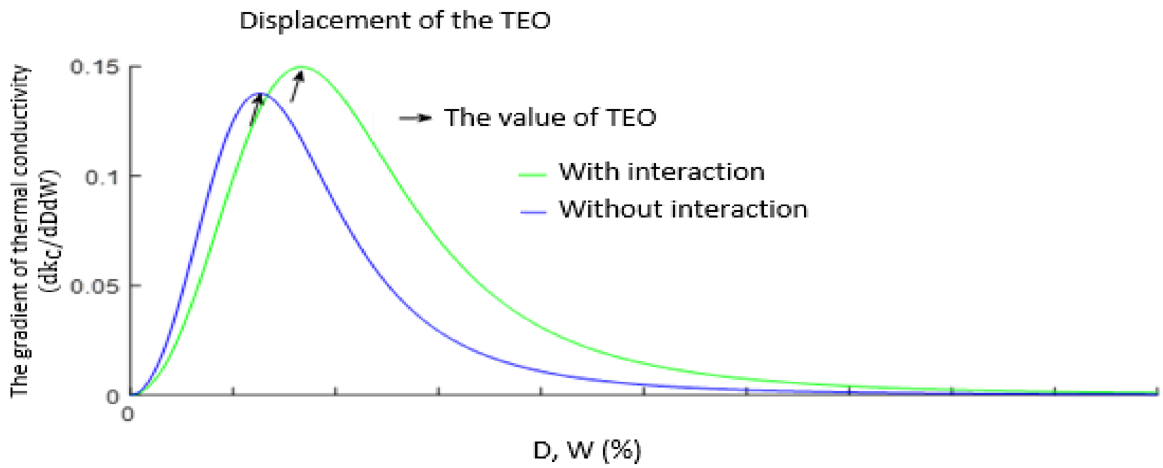


FIGURE 73. EFFECT OF THE INTERACTION ON THE EVOLUTION OF THE THERMAL CONDUCTIVITY GRADIENT (∂KC/∂D, ∂KC/∂W) AS A FUNCTION OF THE CEMENT CONTENT OR WATER CONTENT.

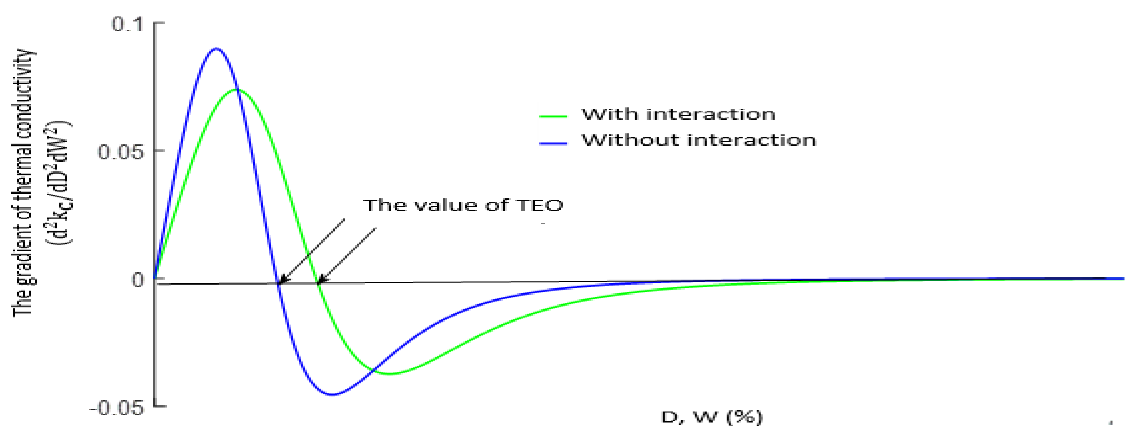


FIGURE 74. EFFECT OF THE INTERACTION ON THE EVOLUTION OF THE THERMAL CONDUCTIVITY GRADIENT ((∂^2 KC)/〖∂D〗^2, (∂^2 KC)/〖∂W〗^2) AS A FUNCTION OF THE CEMENT CONTENT OR WATER CONTENT.

Indeed, the displacement of the TEO induced by the interaction can be done in both directions. Without interaction, TEO essentially depends on the constant b_X, where X is equal to D or W (Figure 73). Taking into consideration the interaction acts on the optimum through the constant b_{XY}. Then, two cases appear:

$b_X > b_{XY}$ $\quad X = D, W$ and $Y = D, W$.

1. $b_X < b_{XY}$ $\quad X = D, W$ and $Y = D, W$.

In case 1, the displacement of optimum is towards the low values of the cement content or water content variable X (Figure 73), which is observed for the cement content or water content. On the other hand, in case 2, the displacement is towards the higher values of the cement content or water content variable X.

V. 2. Numerical results of Technico- Economic Optimum of thermal conductivity of stabilized compressed earth block

We can apply the two models (without interaction in Eq. V. 6 and with interaction in Eq. V. 14 on the experimental results of specific heat, thermal diffusivity and thermal conductivity. We applied these two models to thermal conductivity according to experimental results that we obtained in Figure 55 in chapter III. We used three samples with three different ratios of cement are (0%, 4% and 10% of cement content).

TABLE 30. MODELED PARAMETERS WITHOUT INTERACTION OF THERMAL CONDUCTIVITY AS FUNCTION OF CEMENT CONTENT OF THE CEBS FEZ.

Water content (%)	Kc_0 (W/ m.K)	a_D (W/ m.K)	b_D
0	0,668	0.1028376	60.181
4	1.012	0.0904226	39.3401
15	1.394	0.39825	3250

Without interaction term, the application of the model 1(V. 6) to experimental results presented in chapter III was satisfactory. From five (5) experimental points, the constants a_D, b_D, a_W, b_W and Kc_0 of the model 1 of equation V. 6 are determined (Table 31 and Table 33). Through determining the values of these constants, we obtained numerical thermal conductivity values with cement content and water content (Table 32 and Table 34). We fixed the degrees of variation in the equation (V. 6): $n = m = 3$.

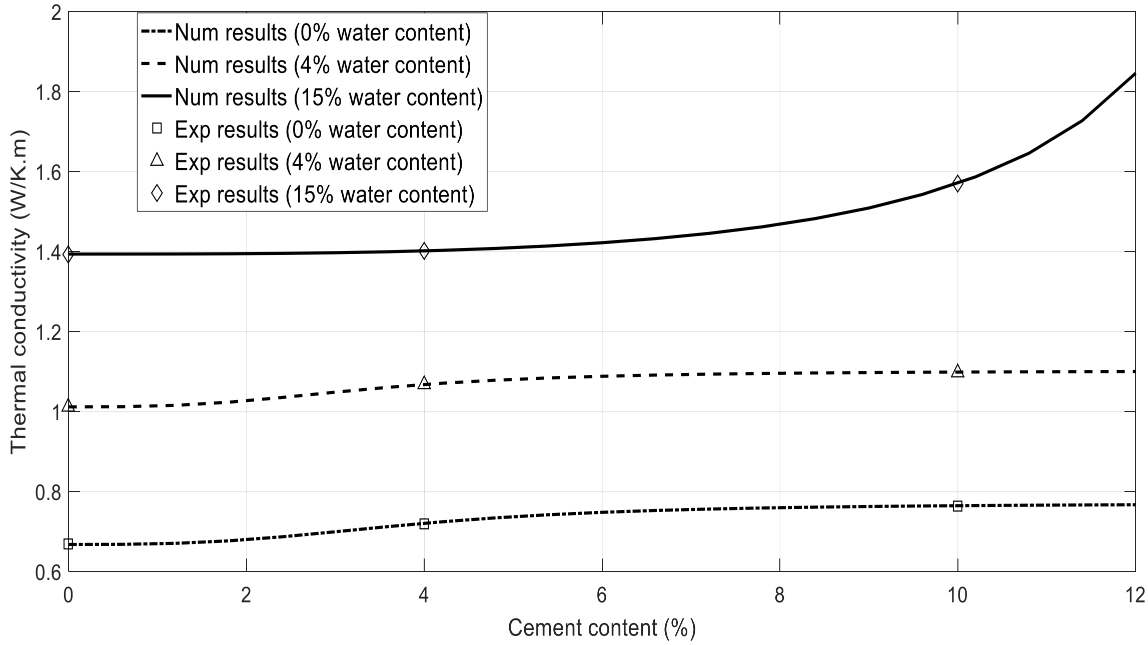


FIGURE 75. EXPERIMENTAL AND NUMERICAL MODEL 1 WITHOUT INTERACTION RESULTS OF THERMAL CONDUCTIVITY AS FUNCTION OF THE VARIATION OF CEMENT CONTENT OF CEBS, USING S CHOSEN EXPERIMENTAL RESULTS.

The modeling of the thermal conductivity of CEBs as a function of the cement content and the water content is represented in Figures 75 and 76 without interaction. If we consider only the two expressions V. 4 and V. 5 to represent the evolution of the magnitude Kc as of function of the cement and the water, it can be observed from figures 75 and 76. Figures 55 and 59 (chapter III), show that the variation curves of the magnitude Kc move further away from each other each time the cement and water increase.

TABLE 31. THE VALUES OF EXPERIMENTAL AND NUMERICAL RESULTS OF THERMAL CONDUCTIVITY AS FUNCTION OF CEMENT CONTENT OF CEBS MODEL 1, USING S CHOSEN EXPERIMENTAL RESULTS.

The results obtained using the model 1:					
$Kc(W,D) = \frac{a_D \times D^3}{b_D + D^3} + \frac{a_W \times W^3}{b_W + W^3} + Kc_0$					
W(%)	D (%)	Kc_{Exp} (W/ m.K)	Kc_{Num} (W/ m.K)	Error (%)	The approximation residue of Kc (Exp and Num) for each ratios of water content
0	0	0.668	0. 668	0.00	0
0	4	0.721	0.721	0.00	
0	10	0.765	0.765	0.00	
4	0	1.012	1.012	0.00	0
4	4	1.068	1.068	0.00	
4	10	1.099	1,099	0.00	
15	0	1.394	1.394	0.00	0
15	4	1.402	1.402	0.00	
15	10	1.571	1.571	0.00	
The approximation residue of Kc (Exp and Num) for all ratios of water content:				0.00	

TABLE 32. MODELED PARAMETERS FOR THERMAL CONDUCTIVITY AS FUNCTION OF WATER CONTENT OF THE CEBS FEZ.

Cement (%)	Kc_0 (W/ m.K)	a_W (W/ m.K)	b_W
0	0.668	0.742	74. 033
4	0.721	0.7013	65.34
10	0.765	0.829	94.78

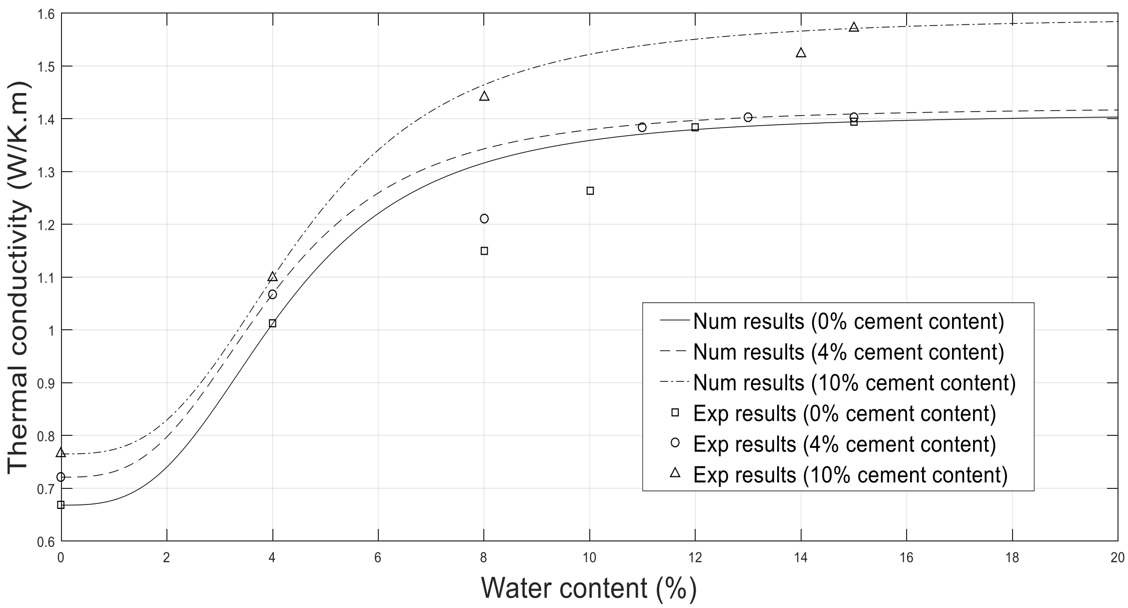


FIGURE 76. EXPERIMENTAL AND NUMERICAL RESULTS USING MODEL 1 (WITHOUT INTERACTION) FOR THERMAL CONDUCTIVITY AS FUNCTION OF THE VARIATION OF WATER CONTENT OF CEBS

In the following tables 32 and 34 and according the figures 75 and 76 we present the numerical results, obtained by the model 1 without interaction term. Compared to the experimental values of the thermal conductivity as function of cement content associated with the CEBs, the error between the numerical results and the experimental results of thermal conductivity (Kc) as function of cement content (D) for all the points is 0%, and the approximation residue of Kc (Exp and Num) for each ratios of constant water content are 0% for each ratio (Table 32). And compared to the experimental values of the thermal conductivity as function of water content associated with the CEBs, the error between the numerical results and the experimental results of thermal conductivity (Kc) as function of water content (W) for all the points does not exceed 14.43%, and the approximation residue of Kc (Exp and Num) for each ratios of constant cement content are 3.7 for 0% cement content, 1.82% for 4% cement content and 0.885% for 10 % cement content (Table 34). This error is justified by the fact that this model doesn’t represent the effect of mutual interaction between the two phenomena of cement content and water content. We assume that the coupled effect of water content on thermal conductivity is greater than the effect of cement taken alone on thermal conductivity. In fact, that the combination of the two effects is accompanied by an amplified interaction between these two effects.

TABLE 33. THE VALUES OF EXPERIMENTAL AND NUMERICAL RESULTS OF THERMAL CONDUCTIVITY AS FUNCTION OF WATER CONTENT OF CEBS MODEL 1, CONSIDERING ALL EXPERIMENTAL RESULTS.

<table>
<tr><td colspan="6">The results obtained using the model 1:</td></tr>
<tr><td colspan="6">$$\mathrm{Kc}(\mathrm{W},\mathrm{D}) = \frac{a_D \times D^3}{b_D + D^3} + \frac{a_W \times W^3}{b_W + W^3} + \mathrm{Kc}_0$$</td></tr>
<tr><td>D
(%)</td><td>W
(%)</td><td>Kc_{Exp}
$(W/m.K)$</td><td>Kc_{Num}
$(W/m.K)$</td><td>Error
(%)</td><td>The approximation residue of Kc (Exp and Num) for each ratios of cement content</td></tr>
<tr><td>0</td><td>0</td><td>0.668</td><td>0.668</td><td>0.00</td><td rowspan="6">3.658</td></tr>
<tr><td>0</td><td>4</td><td>1.012</td><td>1.012</td><td>0.00</td></tr>
<tr><td>0</td><td>8</td><td>1.15</td><td>1.316</td><td>14.43</td></tr>
<tr><td>0</td><td>10</td><td>1.264</td><td>1.359</td><td>7.52</td></tr>
<tr><td>0</td><td>12</td><td>1.384</td><td>1.384</td><td>0.00</td></tr>
<tr><td>0</td><td>15</td><td>1.394</td><td>1.394</td><td>0.00</td></tr>
<tr><td>4</td><td>0</td><td>0.721</td><td>0.721</td><td>0.00</td><td rowspan="6">1.817</td></tr>
<tr><td>4</td><td>4</td><td>1.068</td><td>1.068</td><td>0.00</td></tr>
<tr><td>4</td><td>8</td><td>1.211</td><td>1.343</td><td>10.90</td></tr>
<tr><td>4</td><td>11</td><td>1.383</td><td>1.383</td><td>0.00</td></tr>
<tr><td>4</td><td>13</td><td>1.402</td><td>1.402</td><td>0.00</td></tr>
<tr><td>4</td><td>15</td><td>1.402</td><td>1.402</td><td>0.00</td></tr>
<tr><td>10</td><td>0</td><td>0.765</td><td>0.765</td><td>0.00</td><td rowspan="5">0.885</td></tr>
<tr><td>10</td><td>4</td><td>1.099</td><td>1.099</td><td>0.00</td></tr>
<tr><td>10</td><td>8</td><td>1.44</td><td>1.464</td><td>1.67</td></tr>
<tr><td>10</td><td>14</td><td>1.524</td><td>1.566</td><td>2.76</td></tr>
<tr><td>10</td><td>15</td><td>1.571</td><td>1.571</td><td>0.00</td></tr>
<tr><td colspan="2">The approximation residue of Kc (Exp and Num) for all ratios of cement content:</td><td colspan="4">2.19</td></tr>
</table>

For the model 2, from seven experimental points, the constants a_D, b_D, a_W, b_W, a_{DW}, b_{DW} and Kc_0 in equation V.14 are determined (Table 35). We fix the degrees of variation in the equation V.14: $n = m = n' = m' = 3$. Through determining the values of these constants, we obtained numerical thermal conductivity values with cement content and water content (Table 36 and Table 37).

Table 35 shows that the gain which has been achieved for the thermal conductivity by the cement content is equivalent to the amount of water content. Moreover, the interaction contributes to amplify this gain.

TABLE 34. MODELED PARAMETERS FOR THERMAL CONDUCTIVITY AS FUNCTION OF WATER CONTENT AND CEMENT CONTENT OF THE CEBS.

Cement (%)	Water (%)	Kc_0 (W / m.K)	a_W (W / m.K)	b_W	a_D (W/ m.K)	b_D	a_{DW} (W / m.K)	b_{DW}
0	0	0.668	0.741	74.03	0.102	60.18	0.0001	7.02
4	4							
10	15							

The modeling of the thermal conductivity of CEBs as a function of the cement content and the water content is represented in Figures 77 and 78 with interaction. We consider only the expression V. 14 to represent the evolution of the magnitude Kc.

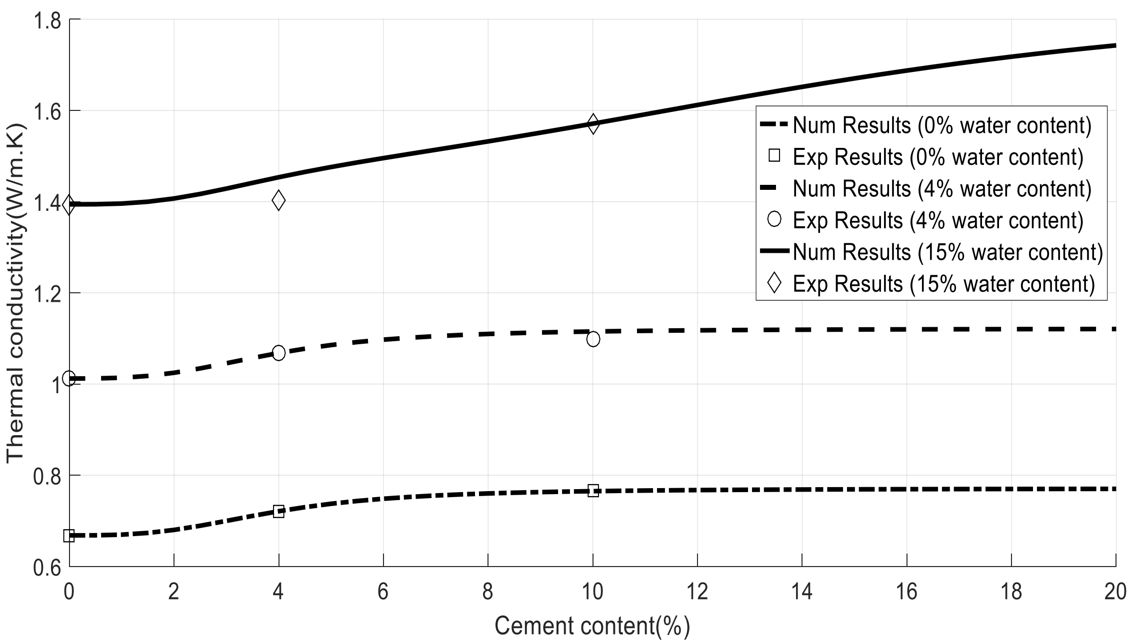


FIGURE 77. EXPERIMENTAL AND NUMERICAL RESULTS OF THERMAL CONDUCTIVITY AS FUNCTION OF THE VARIATION OF CEMENT CONTENT OF CEBS, USING MODEL 2.

As, we mentioned each of the phenomena of cement content and water content contributes to accentuate or amplify each other. From the error in tables 32 and 34 is justified by the fact that the model 1 (Eq. V.6) is not represented the effect of mutual interaction between the two phenomena of cement content and water content.

Because of the interaction contributes to increasing the error between the curves representing the evolution of ′Kc′ as a function of 'D′ and ′W′, the term additive will be positive (tables 36 and 37). From the tables 36 and 37 and according the figures 77 and 78 we present the numerical results, obtained by the model 2 with interaction term. Compared to the experimental values of the thermal conductivity as function of cement content associated with the CEBs, the error between the numerical results and the experimental results of thermal conductivity ′Kc′ as function of cement content 'D′ for all the points does not exceed 3.71%, and the approximation residue of Kc (exp and num) for each ratios of constant water content for each ratio are 0% for 0 % water content, 0.49% for 4% water content and 1.24% for 15% water content(Table 36).

And compared to the experimental values of the thermal conductivity as function of water content associated with the CEBs, the error between the numerical results and the experimental results of thermal conductivity ′Kc′ as function of water content ′W′ for all the points does not exceed 14.43%, and the approximation residue of Kc (exp and num) for each ratios of constant cement content are 3.66 for 0% cement content, 3.95% for 4% cement content and 0.914% for 10 % cement content (Table 34).

From the error in tables 36 and 37 is justified by the fact that the model 2 (Eq. V. 14) is represented the effect of mutual interaction between the two phenomena of cement content and water content.

TABLE 35. THE VALUES OF EXPERIMENTAL AND NUMERICAL RESULTS OF THERMAL CONDUCTIVITY AS FUNCTION OF CEMENT CONTENT OF CEBS MODEL 2.

<table>
<tr><td colspan="6">The results obtained using the model 2:</td></tr>
<tr><td colspan="6">$$Kc(D,W) = \frac{a_D * D^3}{b_D + D^3} + \frac{a_W * W^3}{b_W + W^3} + \frac{a_{DW} * D^3 * W^3}{(D^3 + b_{DW}) * (W^3 + b_{DW})} + Kc_0$$</td></tr>
<tr><td>W (%)</td><td>D (%)</td><td>Kc_{Exp} (W/ m.K)</td><td>Kc_{Num} (W/ m.K)</td><td>Error (%)</td><td>The approximation residue of Kc (exp and num) for each ratios of water content</td></tr>
<tr><td>0</td><td>0</td><td>0.668</td><td>0.668</td><td>0.00</td><td rowspan="3">0</td></tr>
<tr><td>0</td><td>4</td><td>0.721</td><td>0.721</td><td>0.00</td></tr>
<tr><td>0</td><td>10</td><td>0.765</td><td>0.765</td><td>0.00</td></tr>
<tr><td>4</td><td>0</td><td>1.012</td><td>1.012</td><td>0.00</td><td rowspan="3">0.48529</td></tr>
<tr><td>4</td><td>4</td><td>1.068</td><td>1.068</td><td>0.00</td></tr>
<tr><td>4</td><td>10</td><td>1.099</td><td>1.115</td><td>1.46</td></tr>
<tr><td>15</td><td>0</td><td>1.394</td><td>1.394</td><td>0.00</td><td rowspan="3">1.236329</td></tr>
<tr><td>15</td><td>4</td><td>1.402</td><td>1.454</td><td>3.71</td></tr>
<tr><td>15</td><td>10</td><td>1.571</td><td>1.571</td><td>0.00</td></tr>
<tr><td colspan="2">The approximation residue of Kc (exp and num) for all ratios of water content:</td><td colspan="4">0.57</td></tr>
</table>

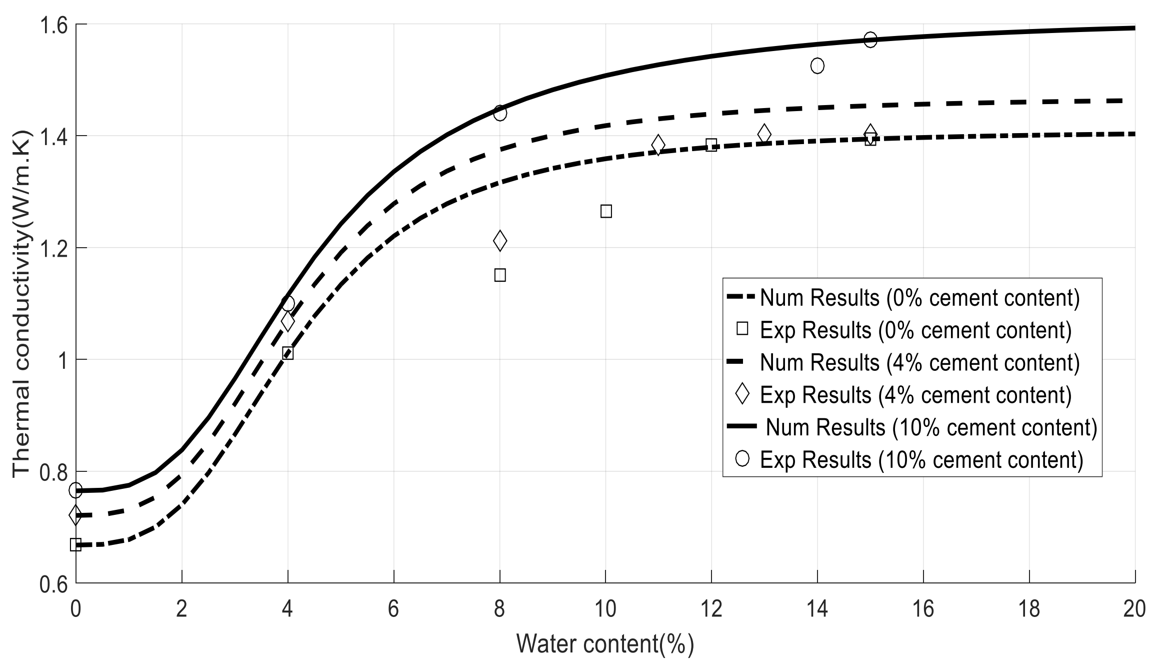
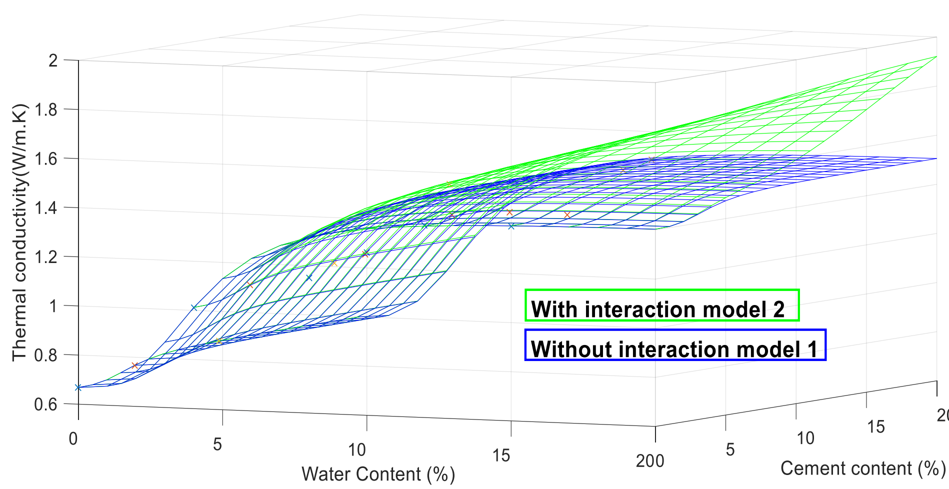


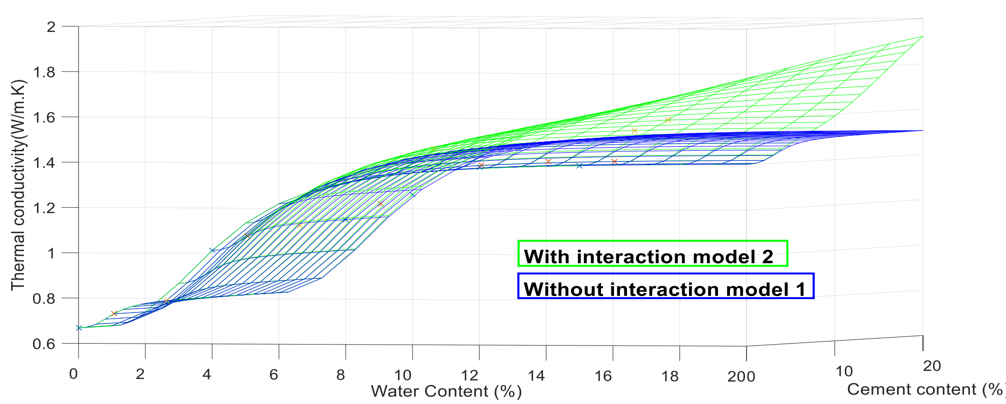
FIGURE 78. EXPERIMENTAL AND NUMERICAL MODEL 2 WITH INTERACTION RESULTS OF THERMAL CONDUCTIVITY AS FUNCTION OF THE VARIATION OF WATER CONTENT OF CEBS (CEMENT CONTENT IS CONSTANT IN EACH CURVE).

TABLE 36. THE VALUES OF EXPERIMENTAL AND NUMERICAL RESULTS OF THERMAL CONDUCTIVITY AS FUNCTION OF WATER CONTENT OF CEBS MODEL 2

<table>
<tr><td colspan="6">The results obtained using the model 2:</td></tr>
<tr><td colspan="6">$$\mathrm{Kc}\,(\mathrm{D},\mathrm{W}) = \frac{a_D * D^3}{b_D + D^3} + \frac{a_W * W^3}{b_W + W^3} + \frac{a_{DW} * D^3 * W^3}{(D^3 + b_{DW}) * (W^3 + b_{DW})} + Kc_0$$</td></tr>
<tr><td>D (%)</td><td>W (%)</td><td>Kc_{Exp} (W/ m.K)</td><td>Kc_{Num} (W/ m.K)</td><td>Error (%)</td><td>The approximation residue of Kc (exp and num) for each ratios of cement content</td></tr>
<tr><td>0</td><td>0</td><td>0.668</td><td>0.668</td><td>0.00</td><td rowspan="6">3.658</td></tr>
<tr><td>0</td><td>4</td><td>1.012</td><td>1.012</td><td>0.00</td></tr>
<tr><td>0</td><td>8</td><td>1.15</td><td>1.316</td><td>14.43</td></tr>
<tr><td>0</td><td>10</td><td>1.264</td><td>1.359</td><td>7.52</td></tr>
<tr><td>0</td><td>12</td><td>1.384</td><td>1.384</td><td>0.00</td></tr>
<tr><td>0</td><td>15</td><td>1.394</td><td>1.394</td><td>0.00</td></tr>
<tr><td>4</td><td>0</td><td>0.721</td><td>0.721</td><td>0.00</td><td rowspan="6">3.953</td></tr>
<tr><td>4</td><td>4</td><td>1.068</td><td>1.068</td><td>0.00</td></tr>
<tr><td>4</td><td>8</td><td>1.211</td><td>1.375</td><td>13.54</td></tr>
<tr><td>4</td><td>11</td><td>1.383</td><td>1.43</td><td>3.40</td></tr>
<tr><td>4</td><td>13</td><td>1.402</td><td>1.445</td><td>3.07</td></tr>
<tr><td>4</td><td>15</td><td>1.402</td><td>1.454</td><td>3.71</td></tr>
<tr><td>10</td><td>0</td><td>0.765</td><td>0.765</td><td>0.00</td><td rowspan="5">0.914</td></tr>
<tr><td>10</td><td>4</td><td>1.099</td><td>1.115</td><td>1.46</td></tr>
<tr><td>10</td><td>8</td><td>1.44</td><td>1.448</td><td>0.56</td></tr>
<tr><td>10</td><td>14</td><td>1.524</td><td>1.563</td><td>2.56</td></tr>
<tr><td>10</td><td>15</td><td>1.571</td><td>1.571</td><td>0.00</td></tr>
<tr><td colspan="2">The approximation residue of Kc (exp and num) for all ratios of cement content:</td><td colspan="4">2.96</td></tr>
</table>

Figure 79 shown the thermal conductivity modeled as a function of cement content and water content. The three-dimensional representation (3D) of this evolution illustrates the iso-curves of thermal conductivity values as a function of cement content for fixed values of water content and vice versa. For low values of cement content and water content, we note that the two models have curves almost confused. This is justified by the fact that the effect of the interaction is weak and the both models have an identical mathematical expression. From the error in tables 32, 34, 36 and 37, we can conclude the approximation residue of Kc as a function of cement content and water content. For the model 1 without interaction. The approximation residue of Kc (exp and num) as function of cement content for all ratios of water content is 0%. And, the approximation residue of Kc (exp and num) as function of water content for all ratios of cement content is 2.19%. And for the model 2 with interaction. The approximation residue of Kc (exp and num) as function of cement content for all ratios of water content is 0.57%. And, the approximation residue of Kc (exp and num) as function of water content for all ratios of cement content is 2.96%. We observed from the approximation residues of the model 2 with interaction term that cement content and water content contributes to accentuate or amplify the other, this indicating that the combination of the two effects of cement and water are accompanied by an interaction between these two effects.





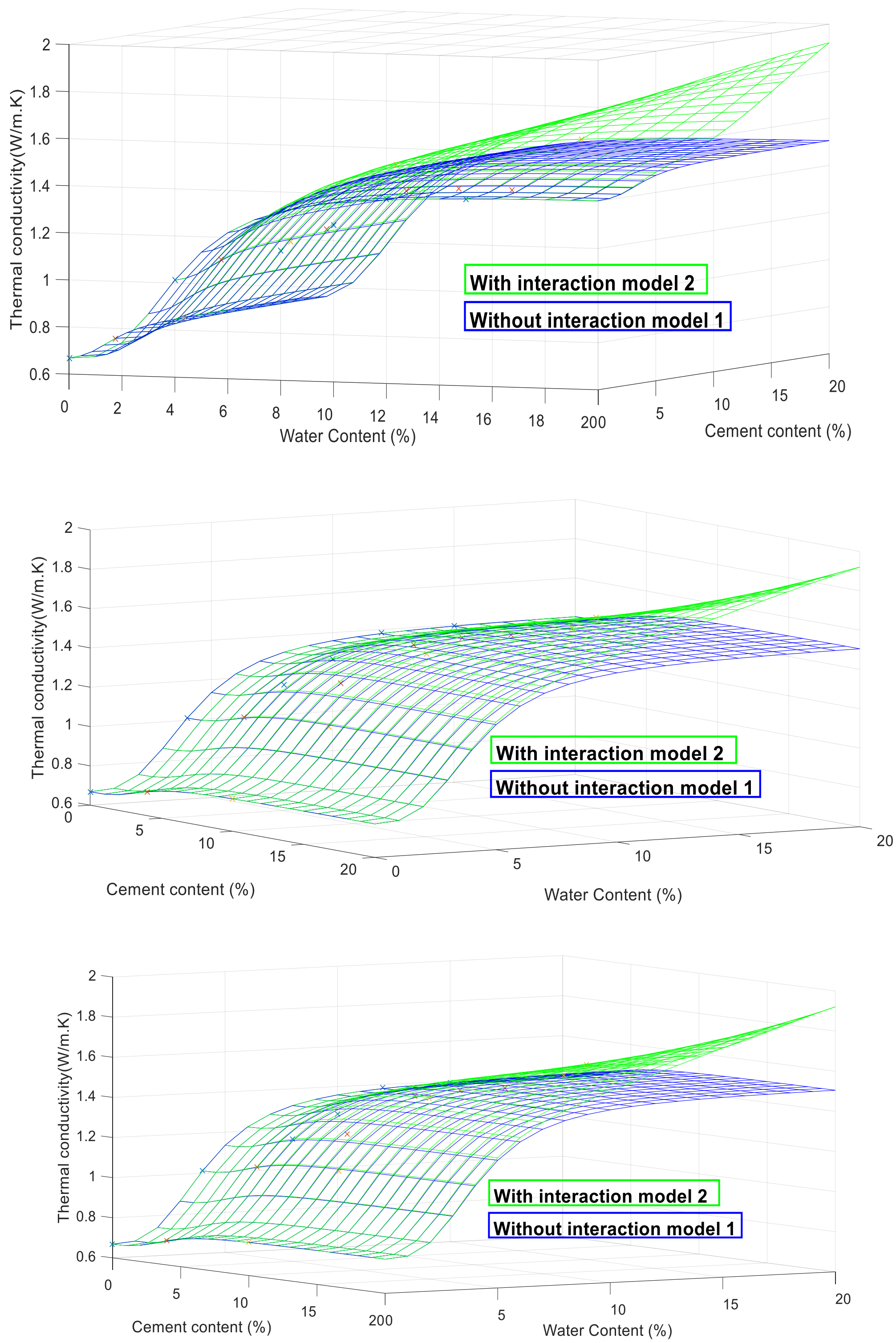


FIGURE 79. 3D CURVES OF THE THERMAL CONDUCTIVITY ACCORDING TO THE CEMENT CONTENT AND WATER CONTENT OF CEBS.

Using equations V. 17 and V. 18, the technico- economic optimum of the cement content and water content are calculated. This optimum is determined for the three samples of CEBs with three different ratios of cement (0%, 4% and 10% of cement content) and optimum is determined for three different ratios of water content for these three samples (0%, 4% and 15% of water content). The optimum of the thermal conductivity (Kc) is determined for these three samples CEBs.

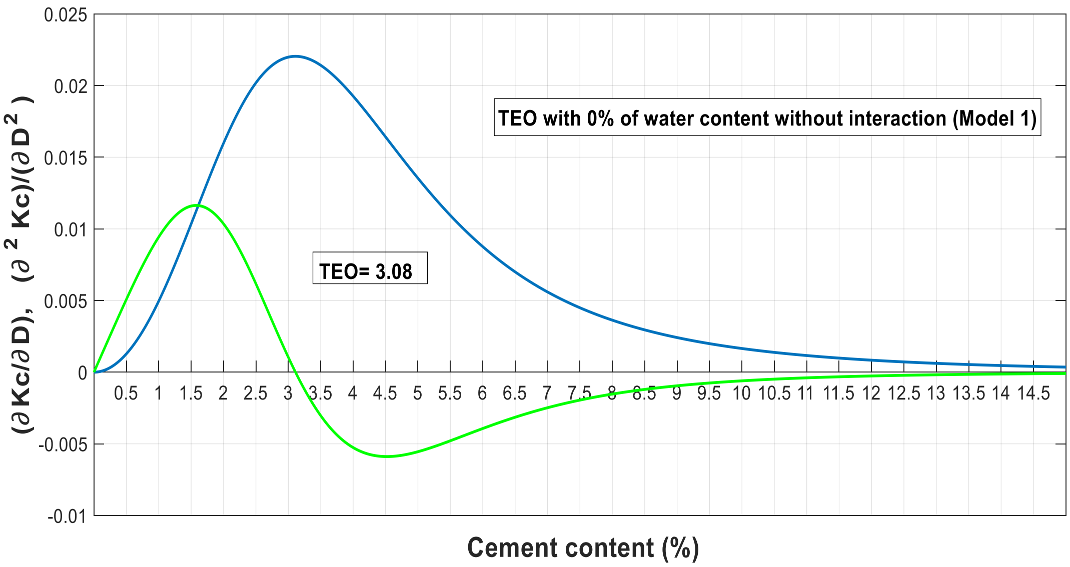


FIGURE 80. EVOLUTION OF THE GRADIENT OF KC AS A FUNCTION OF D (MODEL 1).

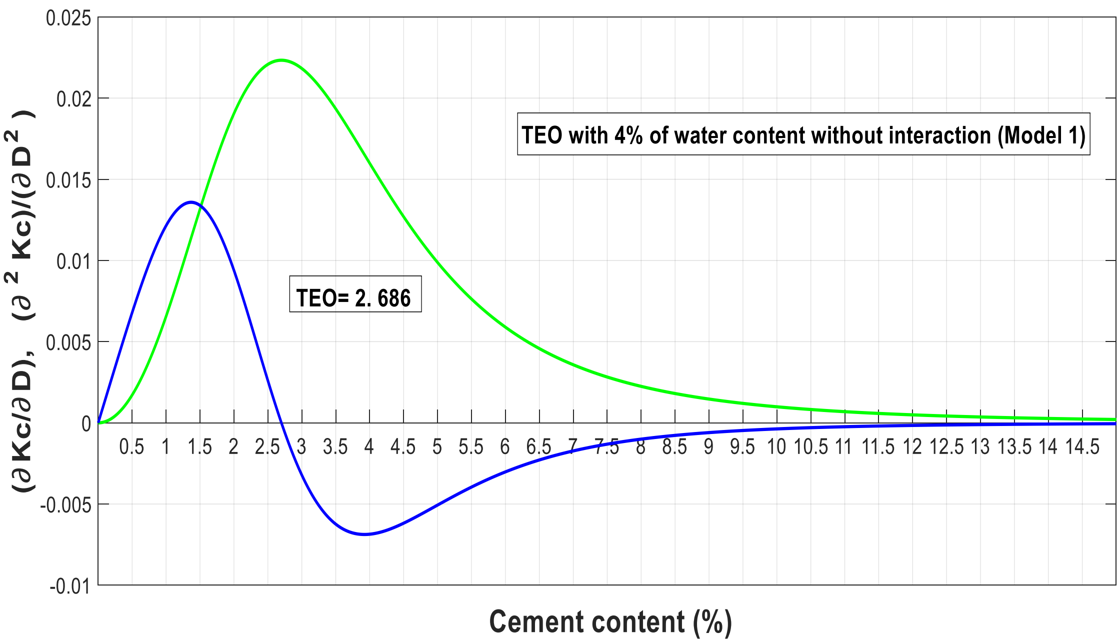


FIGURE 81. EVOLUTION OF THE GRADIENT OF KC AS A FUNCTION OF D (MODEL 1).

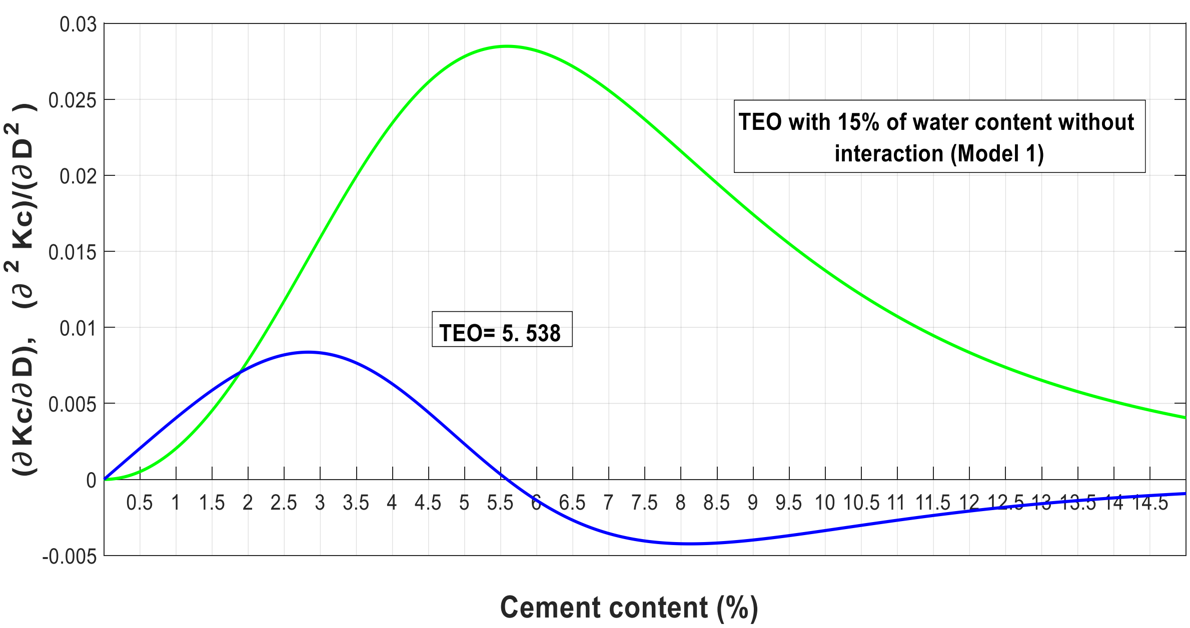


FIGURE 82. EVOLUTION OF THE GRADIENT OF KC AS A FUNCTION OF D (MODEL 1).

TABLE 37. TEO OF THE THERMAL CONDUCTIVITY OF THE SAMPLES CEBS FOR THE WATER CONTENT CONSTANT (MODEL 1) WITHOUT INTERACTION.

Model 1	Water content	TEO
$\frac{\partial Kc}{\partial D}$	0	3.08
	4	2.686
	15	5.538
$\frac{\partial^2 Kc}{\partial D^2}$	0	3.08
	4	2.686
	15	5.538

From the figures 80, 81 and 82 shown the evolution of the gradient of Kc as a function of D with three ratios of water content (0%, 4% and 15% water content) model 1 without interaction, from these figures we got on the TEO (Table 38). Table 38 is presented the TEO for $\frac{\partial Kc}{\partial D}$ and $\frac{\partial^2 Kc}{\partial D^2}$ for each ratios of water content. We noted that there is a difference in values, but in general these values are not great and these values are very close together.

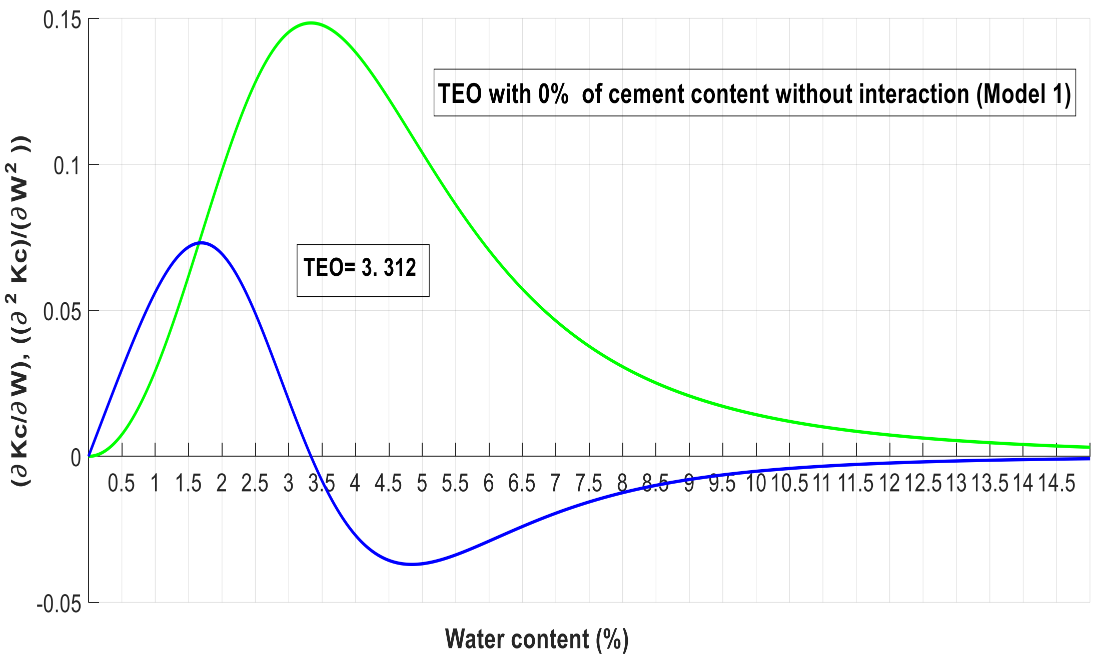


FIGURE 83. EVOLUTION OF THE GRADIENT OF KC AS A FUNCTION OF W (MODEL 1).

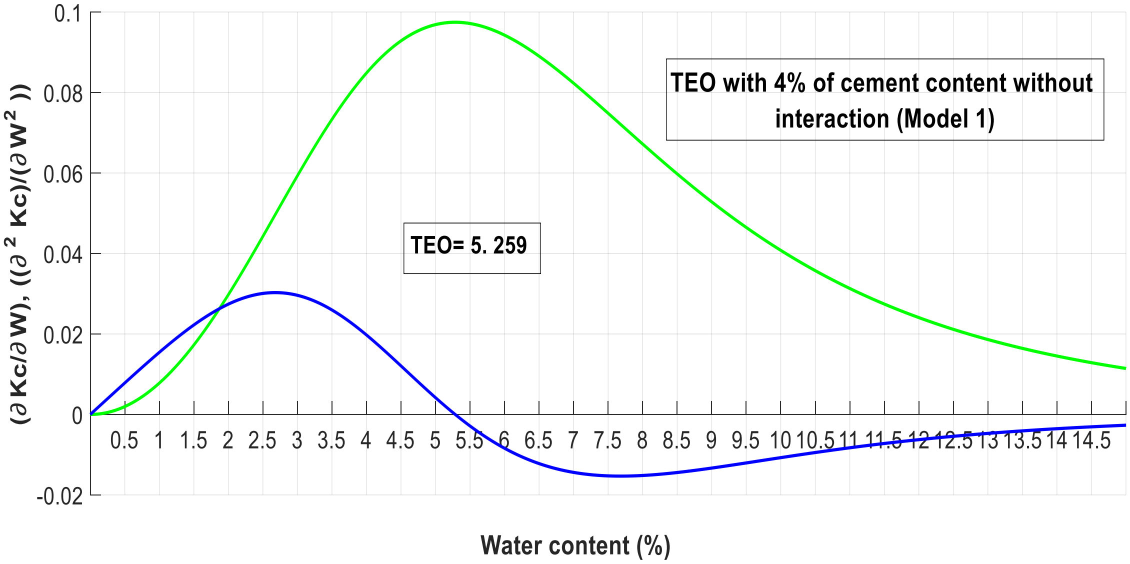


FIGURE 84. EVOLUTION OF THE GRADIENT OF KC AS A FUNCTION OF W (MODEL 1).

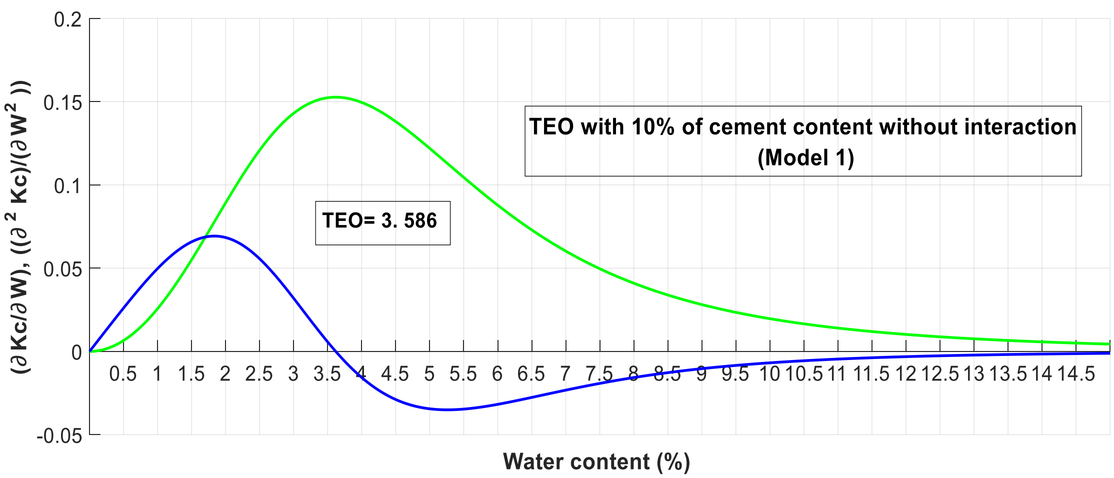


FIGURE 85. EVOLUTION OF THE GRADIENT OF KC AS A FUNCTION OF W (MODEL 1).

TABLE 38. TEO OF THE THERMAL CONDUCTIVITY OF THE SAMPLES CEBS FOR THE CEMENT CONTENT CONSTANT (MODEL 1) WITHOUT INTERACTION.

Model 1	Cement content	TEO
$\frac{\partial Kc}{\partial W}$	0	3.312
	4	5.259
	10	3.586

$\frac{\partial^2 Kc}{\partial W^2}$	0	3.312
	4	5.259
	10	3.586

The figures 83, 84 and 85 shown the evolution of the gradient of Kc as a function of W with three ratios of cement content (0%, 4% and 10% cement content) model 1 without interaction, and table 39 is presented the TEO for $\frac{\partial Kc}{\partial W}$ and $\frac{\partial^2 Kc}{\partial W^2}$ for each ratios of cement content, also there are a difference in values, but not great and very close.

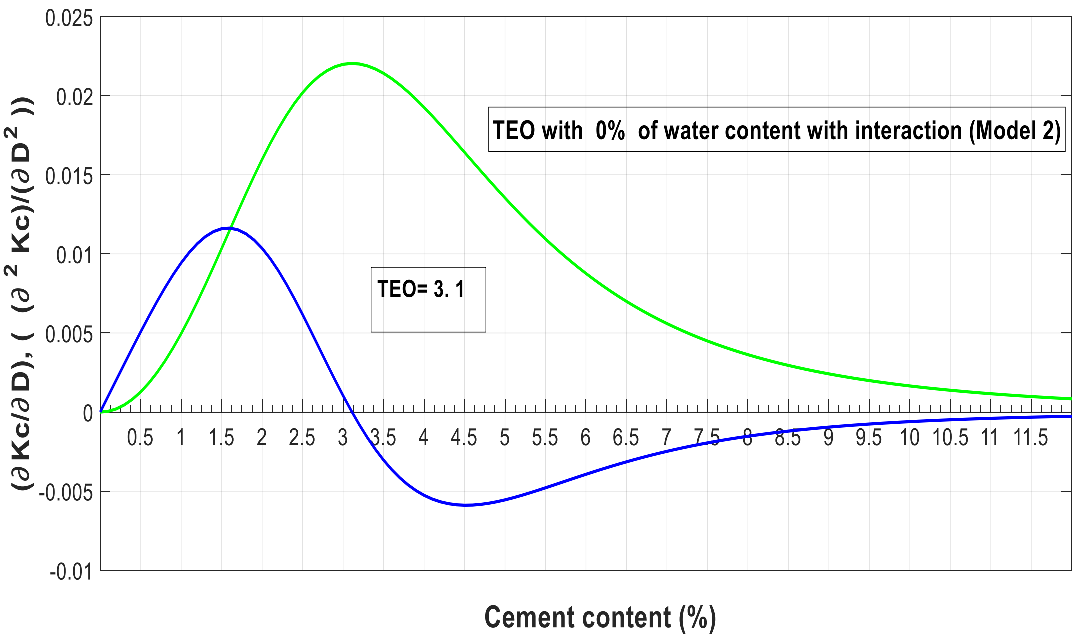


FIGURE 86. EVOLUTION OF THE GRADIENT OF KC AS A FUNCTION OF D (MODEL 2).

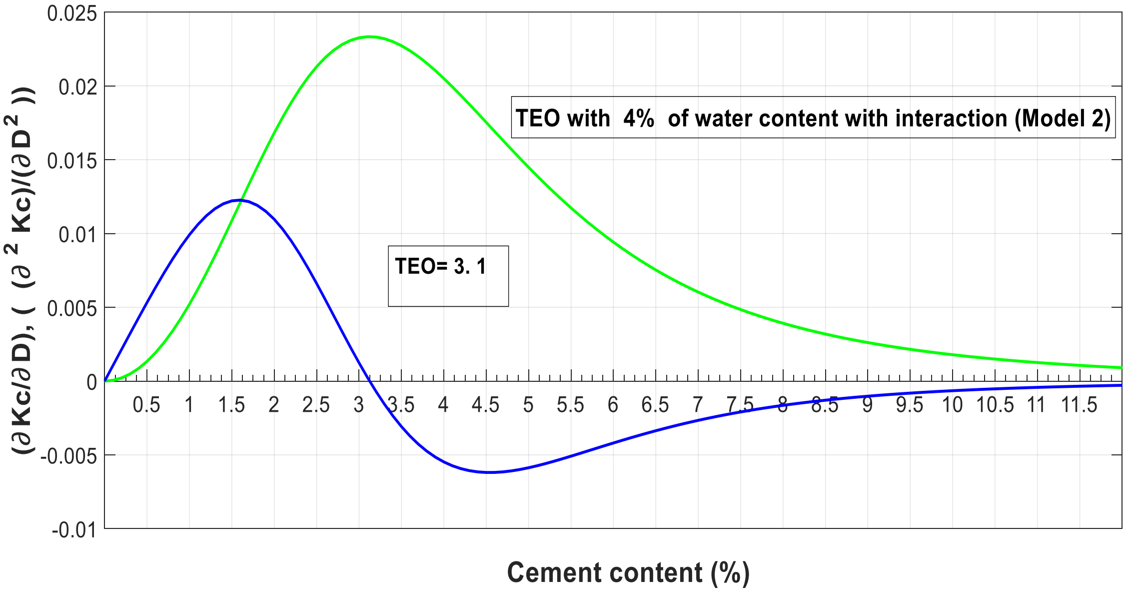


Figure 87. Evolution of the gradient of Kc as a function of D (model 2).

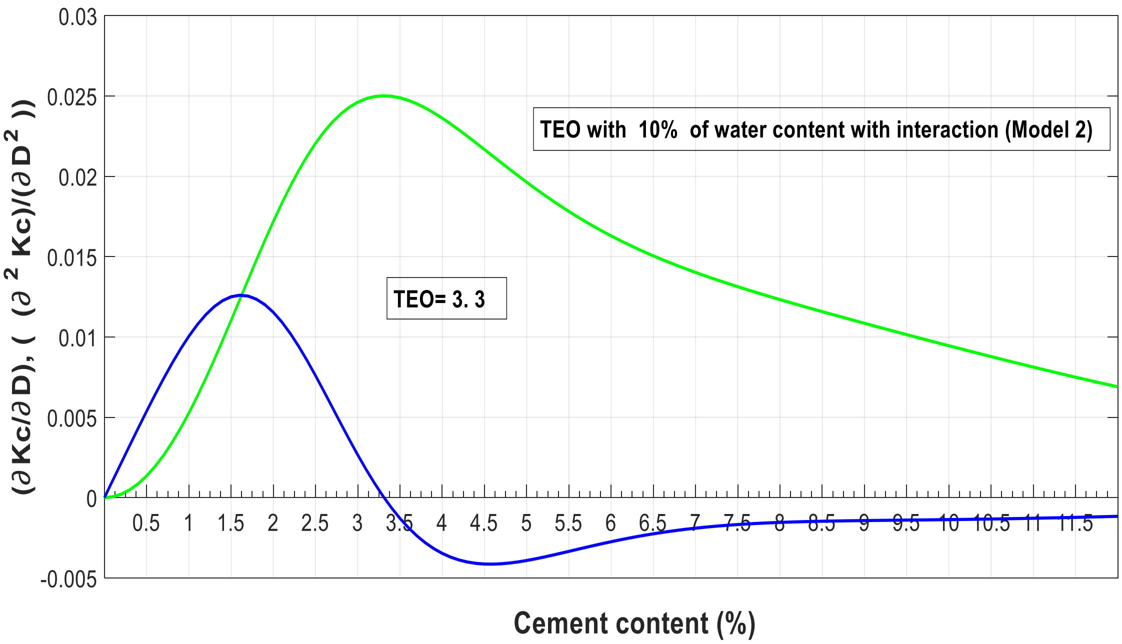


FIGURE 88. EVOLUTION OF THE GRADIENT OF KC AS A FUNCTION OF D (MODEL 2).

TABLEAU 39. TEO OF THE THERMAL CONDUCTIVITY OF THE SAMPLES CEBS FOR THE WATER CONTENT CONSTANT (MODEL 2) WITH INTERACTION.

Model 2	Water content	TEO
$\frac{\partial Kc}{\partial D}$	0	3.1
	4	3.1
	15	3.3
$\frac{\partial^2 Kc}{\partial D^2}$	0	3.1
	4	3.1
	15	3.3

From the figures 86, 87 and 88 shown the evolution of the gradient of Kc as a function of D with three ratios of water content (0%, 4% and 15% water content) model 2 with interaction, from these figures we got on the TEO (Table 40). Table 40 is presented the TEO for $\frac{\partial Kc}{\partial D}$ and $\frac{\partial^2 Kc}{\partial D^2}$ for each ratios of water content. We Noted that the values are not great and all are similar are 3.3%.

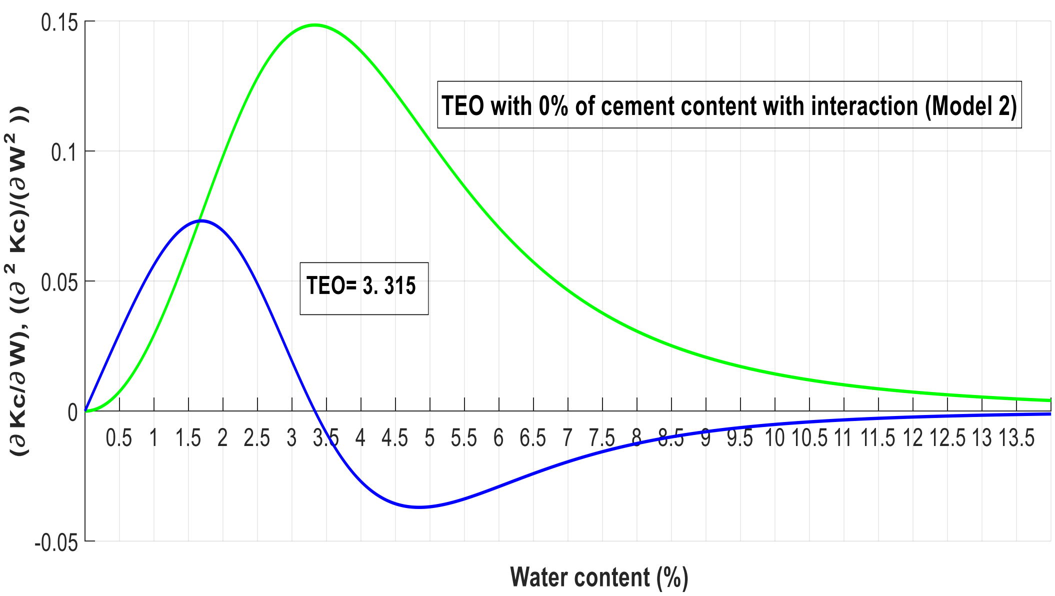


FIGURE 89. EVOLUTION OF THE GRADIENT OF KC AS A FUNCTION OF W (MODEL 2)

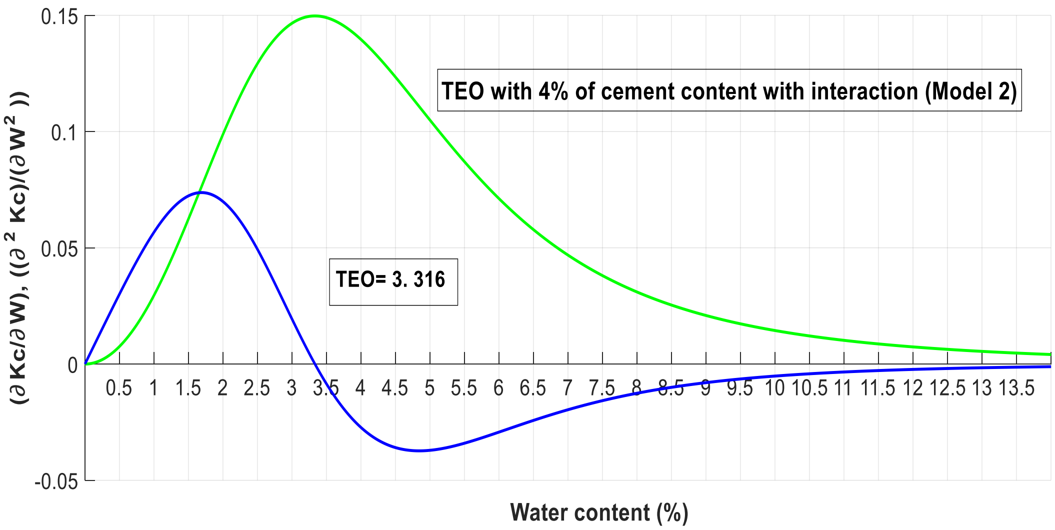


FIGURE 90. EVOLUTION OF THE GRADIENT OF KC AS A FUNCTION OF W (MODEL 2)

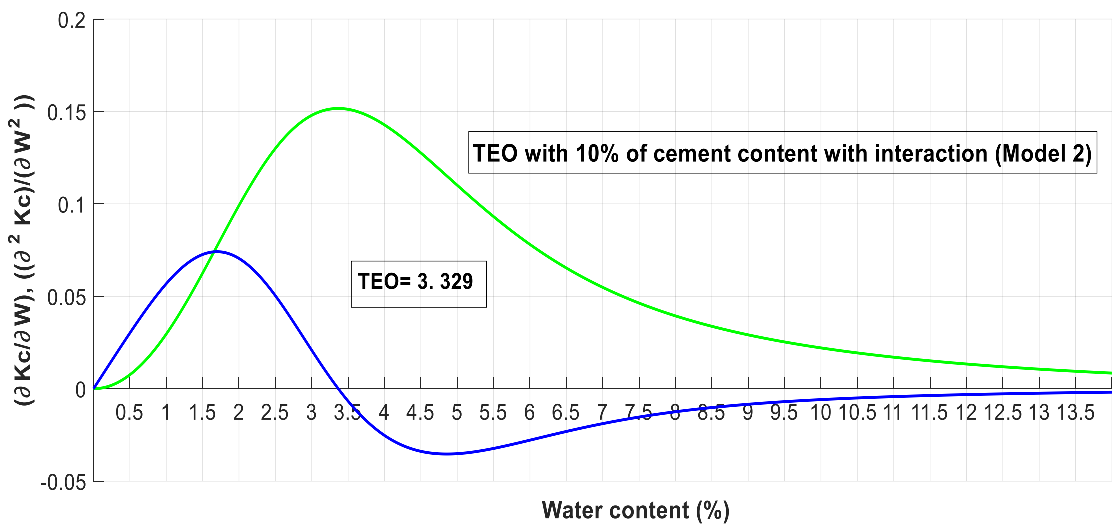


FIGURE 91. EVOLUTION OF THE GRADIENT OF KC AS A FUNCTION OF W (MODEL 2).

TABLE 40. TEO OF THE THERMAL CONDUCTIVITY OF THE SAMPLES CEBS FOR THE CEMENT CONTENT CONSTANT (MODEL 2) WITH INTERACTION.

Model 2	Cement content	TEO
$\frac{\partial Kc}{\partial W}$	0	3.315
	4	3.316
	10	3.329
$\frac{\partial^2 Kc}{\partial W}$	0	3.315
	4	3.316
	10	3.329

For the figures 89, 90 and 91 shown the evolution of the gradient of Kc as a function of W with three ratios of cement content (0%, 4% and 10% cement content) model 2 with interaction, and from these figures we got on the TEO (Table 41). We noted the from the table 41 the same results in figures 86, 87 and 88 that the values are not great and all are similar are 3.3% for each ratios of cement, which is the same as the values we obtained in table 41.

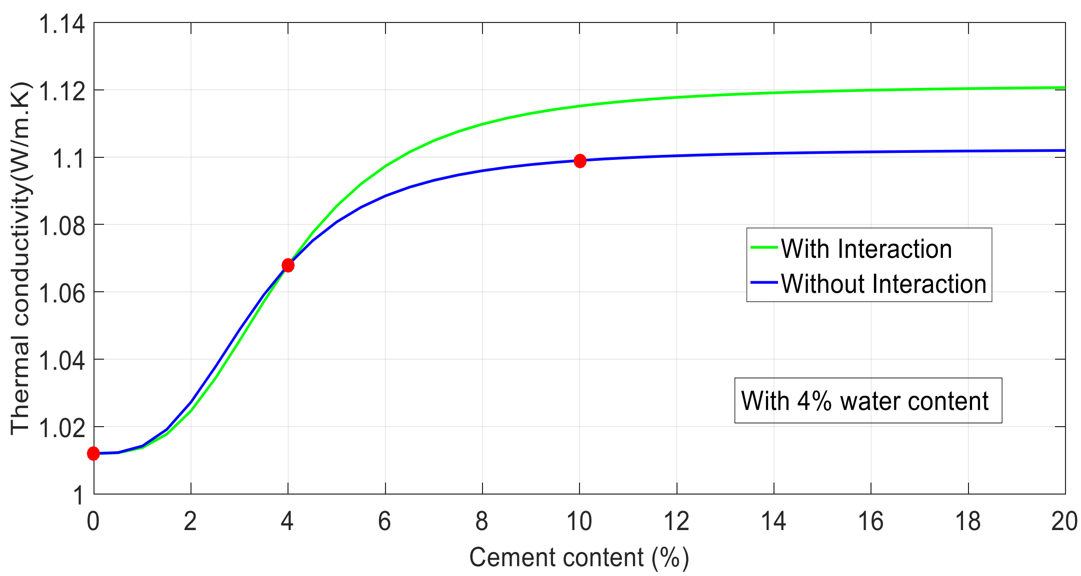


FIGURE 92. EFFECT OF THE INTERACTION ON THE EVOLUTION OF THE THERMAL CONDUCTIVITY AS FUNCTION OF CEMENT CONTENT.

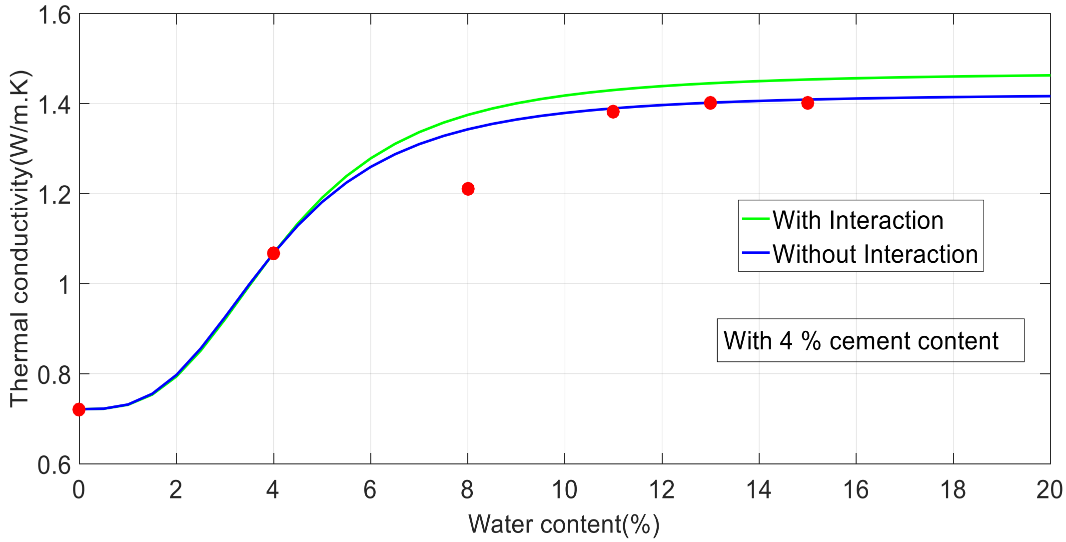


FIGURE 93. EFFECT OF THE INTERACTION ON THE EVOLUTION OF THE THERMAL CONDUCTIVITY AS FUNCTION OF WATER CONTENT.

In figures 92 and 93 shown the evolution of the thermal conductivity as a function of the cement content and water content, with and without the interaction. The interaction leads to improving the gain of the Kc magnitude with regard to the cement content and water content, the cement content or water content being fixed equal to D_0 or W_0 respectively. Also, we observed the interaction not only leads to increasing the thermal conductivity (maximum contribution equal to a_{DW_0}or a_{WD_0}), but it also allows displacement the optimum towards the low values of the cement or water variable, which is economically good.

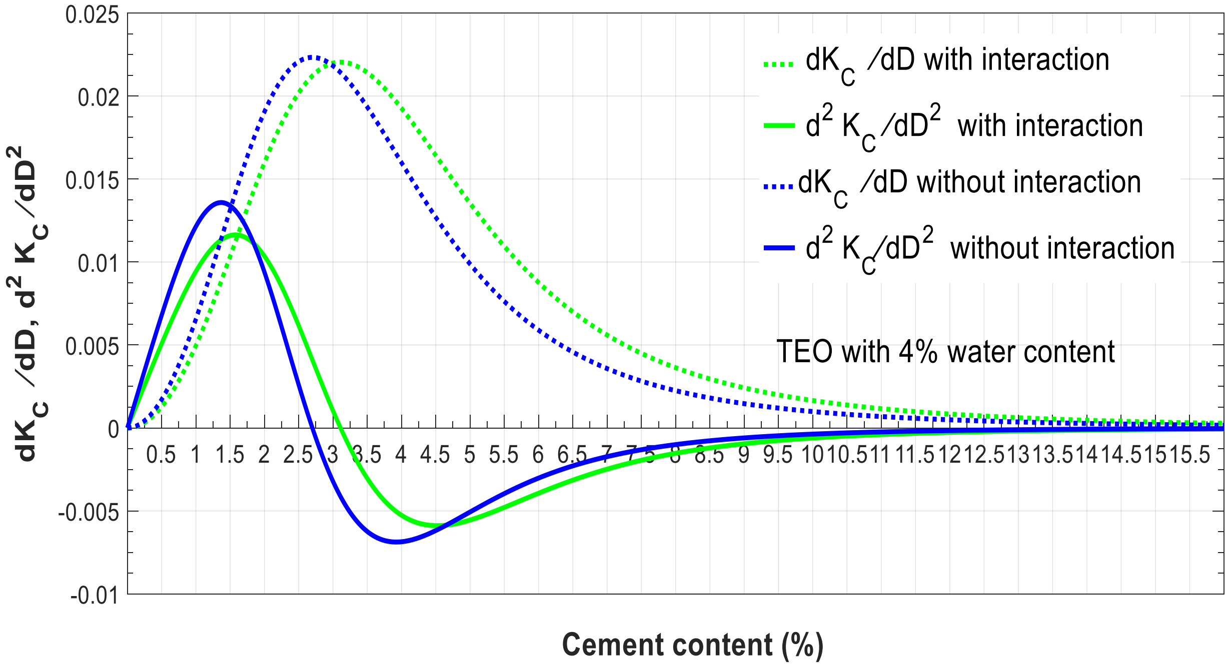


FIGURE 94. EFFECT OF THE INTERACTION ON THE EVOLUTION OF THE THERMAL CONDUCTIVITY GRADIENT (∂KC/∂D, (∂^2 KC)/〖∂D〗^2) AS A FUNCTION OF THE CEMENT CONTENT (WITH 4% WATER CONTENT).

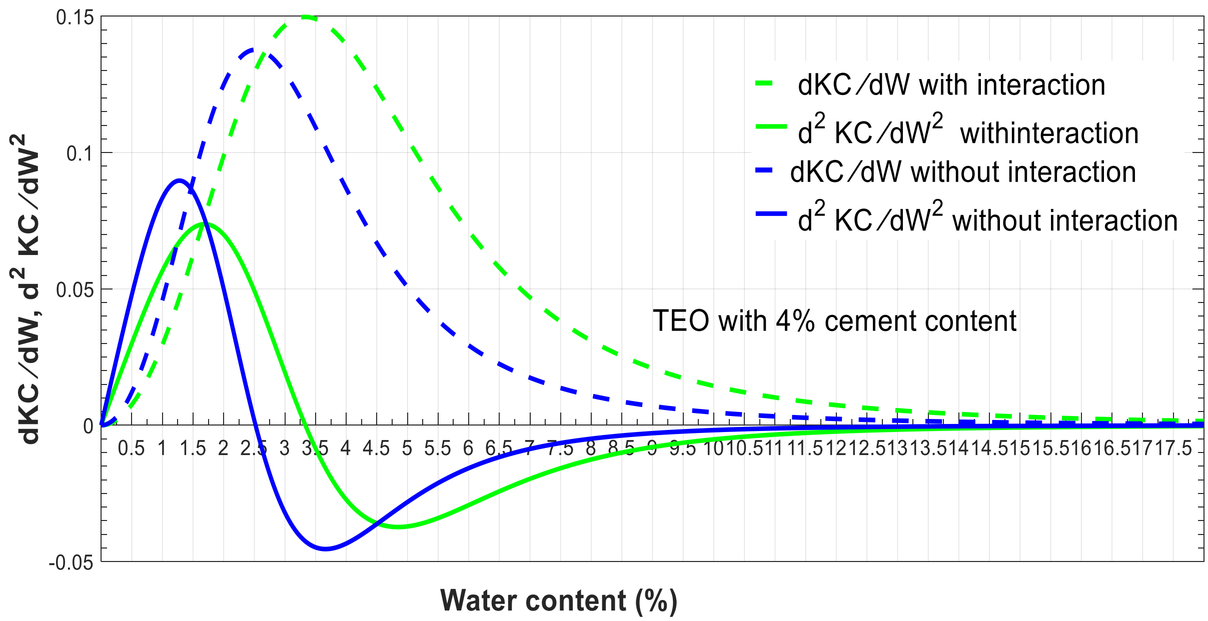


FIGURE 95. EFFECT OF THE INTERACTION ON THE EVOLUTION OF THE THERMAL CONDUCTIVITY GRADIENT (∂KC/∂W, (∂^2 KC)/〖∂W〗^2) AS A FUNCTION OF THE WATER CONTENT (WITH 4% CEMENT CONTENT).

For the figures 94 and 95 are observed that the gain with interaction effect is greater than that without interaction for $\frac{\partial \mathrm{Kc}}{\partial \mathrm{D}}$, $\frac{\partial \mathrm{Kc}}{\partial \mathrm{W}}$. We also note the displacement of the optimum induced by the interaction. And in figures also it is noted that the gain with interaction effect is greater than that without interaction. While, we observed the opposite that the gain without interaction effect is greater than that with interaction for $\frac{\partial^2 \mathrm{Kc}}{\partial \mathrm{D}^2}$, $\frac{\partial^2 \mathrm{Kc}}{\partial \mathrm{W}^2}$. also noted the displacement of the optimum induced by without interaction. And in figures also it is noted that the gain without interaction effect is greater than that with interaction.

Conclusion

The proposed modeling makes it possible with good accuracy to dictate and quantify the evolution of the thermal properties of the compressed earth block as a function of the cement content and water content.

The establishment of these two models requires: 5 experimental tests for model 1 without interaction term with different cement content and water content; and 7 experimental tests for model 2 with interaction term with different cement content and water content.

The addition of cement and water to the compressed earth block induces a gain in thermal properties. The combination of these two effects cement content and water content makes it possible, through their physical interaction, to amplify this gain.

Using the evolution of the thermal properties of the CEB, Mr. Bouabid has been could to propose an optimum of cement content and water content on the technical and economic levels. The technico-economic optimum (OTE) is sought for a given property. It refers to the thermal property for which we want to optimize their stabilization and humidity. The technico-economic optimum depends on the granulometry, the clay fraction, the mineralogical composition, water content and cement content, etc. Because of the characteristics of the material used and the phenomena that take place by incorporating these two effects (cement content and water content), the material tends to favor or disadvantage the block response at that particular property.

General conclusion

Green building is not only related to the management of energy saving and waste management, but also to how well the building materials do not harm the environment, both short term and long term. Energy efficiency and embodied energy, water efficiency and Material Efficiency were the four most important green building. It can be concluded that the most important factors in the construction phase are quality of materials of green building. Building materials for low-cost housing must be produced from locally available raw materials. Furthermore, these raw materials must be abundantly available or they should be renewable in nature. Natural buildings are a subsection of green building that uses actual earth materials for construction: earth, straw, stones, wood and recycled or upcycled materials.

An earth is a material that is widely available in almost everywhere in the world and this green material provides unique thermal qualities. It can be used in many types of earth construction, it is an incredibly versatile product that is renewable, eco-friendly, and easy to obtain due to present in everywhere. It is increasingly being considered as a possible replacement for concret in construction.

And compressed earth block (CEB) construction is the one of earth materials, is an earth-friendly building technology that is superior to concrete and wood construction in terms of its health benefits, affordability, durability, and energy efficiency. CEB technology is a contemporary improvement of ancient earth building methods.

Concerning the issue of scientist searching for sustainable and eco-friendly building material. Compressed Stabilized Earth Block (CSEB) give the opportunity of energy efficient, eco-friendly, agriculture friendly and sustainable development. It does not produce any harmful gasses during production.

The use of compressed earth blocks (CEBs) is widespread in the field of earth construction. They present better mechanical performance than adobe and the equipment for their production is simple.

There are few disadvantages of CEB such as low technical performance compared to concrete hollow blocks, loss of strength when exposed with water, wind or rain. Different studies and researches experimented on how to improve CEBs by stabilization. Stabilization of CEBs consists of improving the soil properties, increasing the compaction pressure and using chemical and fiber stabilizers.

Although, compressed earth blocks stabilized as construction materials are highly unknown to most people, its advantages are seen in terms of rescuing the heritage and also as rediscovered environmentally friendly building materials.

It has low embodied energy because the primary material to create the blocks is soil. CEB construction is cheaper because of the fact that the cost of building materials is increasing.

The detailed previous studies have highlighted that earth based alternative materials and systems researched and developed in will have reduced impact on energy use. This is because they have less thermal conductivity. The thermal comfort research studies on alternative and earthen materials have become necessary. Earth construction encompasses several techniques such as, the most usual being: wattle and daub, cob, rammed earth, earth bricks (adobe) or compressed earth blocks (CEB). With its numerous assets such as its availability, recyclability and the low energy required for the transformation process and transportation, earth is increasingly being studied. In our study we choose compressed earth blocks (CEBs), CEBs this technique is inspired by the Rammed earth technique, but instead of building huge molds in the form of walls, mechanical machines have been created to produce brick cladding or compressed with small size and are used as concrete bricks in construction.

We explored the possibility of using our local soil (earth of Fez) for making compressed earth blocks for the construction of affordable residential buildings, this was done through several tests carried out on selected soil. The CEBs samples were made with a block press that delivers a high compressive effort 2MPa. CEBs samples were also made from soil with (0%, 4%, 7% and 10 %) of Ordinary Portland cement.

The results of test laboratory of the soil that used for making the compressed earth block stabilized samples gave an average dry density of 1,82 (g/cm3), an average water content 12,5 (%), an average Plasticity index 10,26 (%), an average the activity coefficient 1,28, an average surface area 48,93 (m2/g) and an average organic matter 1,8 (%). These values are comparable to recommended values by CRATerre. And from these values have demonstrated that this soil may be suitable to make compressed earth blocks samples. If the native soil is unsuitable or inadequate for building, it can be blended with or replaced by soil from another source.

The thermal analysis of the CEBs is important for thermal insulation purposes, is one of the fundamental materials to establish the design of earth building materials. The heat transfer through the samples CEBs depends on many different variables, including the particle size of soil, it is considered the main component of samples, mineral composition of soil, the temperature of the samples, density, compression, water content and cement content. In this chapter is an experimental study were carried out on the thermal properties of compressed earth blocks with two variables which effect on their thermal behaviour are water content and cement content. The investigated samples include samples of CEBs with four different ratios of cement (0%, 4%, 7% and 10%). The purpose of the thermal conductivity test is to determine the thermal behavior of the samples CEBs at low temperatures. The main objective of this work was to study the influence of water content and cement content on the thermal properties of compressed earth block stabilized (CEBs). Fundamental thermal properties of various high-water content and cement content CEBs samples were determined. Thermal conductivity, heat capacity, and thermal diffusivity were determined. A transient hot ring method technique is used in the experiments, in order to measure the thermal conductivity of CEBs. The results show the thermal conductivity, specific heat and thermal diffusivity of CEBs were strongly influenced by water content, an increased water content is as a substantial negative factor affecting both thermal properties of samples. Also, the effect of cement content is the increase of their thermal conductivity. The cement has been added to the samples in order to increase their durability and to limit water absorption. Although the addition of cement stabilizer enhances the engineering properties of samples CEBs, it is not the case for their hygrothermal properties. The heat will flow faster through the samples when add the cement content and water content that lead to increase their thermal properties. From the presented results above, that with increasing water content and cement content the thermal insulation properties of the samples of CEBs significantly decreased.

Heat transfer in CEBs flow is investigated numerically and experimentally. In this chapter we have developed a numerical model that calculates the temperature through the CEBs with different ratios of cement content and water content, the numerical computations are carried out using finite volume method approach. Validated by the experimental measurements carried out on the hot ring method, this model made it possible to calculate the profile of the temperatures in the CEBs with different ratios of cement content and water content. Indeed, the cement content in the samples of CEBs do not alone effect on behavior of temperature, but also the water content effect on behavior of temperature. The numerical and experimental results have shown a good agreement for the temperature of the contact area.

The proposed modeling makes it possible with good accuracy to dictate and quantify the evolution of the thermal properties of the compressed earth block as a function of the cement content and water content.

The establishment of these two models requires: 5 experimental tests for model 1 without interaction term with different cement content and water content; and 7 experimental tests for model 2 with interaction term with different cement content and water content.

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Université Mohammed V
Faculté des Sciences
Rabat

CENTRE D'ETUDES DOCTORALES - SCIENCES ET TECHNOLOGIES

Résume

Afin d'assurer un confort thermique de qualité dans les bâtiments en terre, une attention particulière doit être portée au type de matériau à utiliser ainsi qu'à ses performances thermiques et son évolution avec l'ajout de ciment et la présence d'eau dans le matériau.
Les travaux de recherche menés dans le cadre de cette thèse proposent des techniques et des procédés pour une meilleure compréhension du comportement de la conductivité thermique vis-à-vis de la teneur en ciment, de la teneur en eau et de leur interaction, afin de réduire la consommation énergétique des bâtiments en terre.
Pour atteindre ces objectifs, nous avons :
- Étudié la minéralogie et la granulométrie (distribution granulométrique) de la terre utilisée pour réaliser les échantillons de blocs de terre comprimée (CEB).
- Fourni, sur la base d'une campagne expérimentale prolongée, une analyse de conductivité thermique liée au bloc de terre comprimée stabilisée avec différentes teneurs en ciments et en eau.
- Développé et testé avec succès un modèle mathématique basé sur la méthode des volumes finis pour modéliser le transfert de chaleur à travers des échantillons de CEB avec différents teneurs en ciment et en eau.
- Proposé une validation d'un modèle Technico-Economique Optimum (TEO) pour le bâtiment en CEB en respectant les effets combinés des deux teneurs. Cet optimum est déterminé en utilisant l'évolution des propriétés thermiques du bloc de terre comprimée en fonction de la stabilisation (teneur en ciment) et de la teneur en eau (présence d'eau).

Les résultats expérimentaux et numériques montrent que la conductivité thermique évolue similairement pour les deux teneurs, en ciment et en eau. L'allure des courbes obtenues sont en S, avec un point d'inflexion qui dépend du matériau utilisé. L'ajout d'une faible teneur en ciment n'affecte pas la conductivité thermique de manière significative. Pour un contenu spécifique, proposé ici comme TEO, la conductivité augmente rapidement avant de stagner. Le TEO correspond au point d'inflexion de la courbe en S.

Mots-clés : Construction en terre, bloc de terre comprimée, Optimum technico-économique (TEO), conductivité thermique, teneur en ciment et en eau, méthode des volumes finis.

Abstract

In order to ensure a high-quality thermal comfort in the earthen buildings, special attention should be given to the type of material to use as well as to its thermal performance and its evolving with cement adding and the presence of water in the material.
The research work carried out as part of this thesis proposes techniques and processes for a better understanding of thermal conductivity with respect to cement content, water content and their interaction improvement in order to reduce energy consumption of earth building.
To reach this aim, this research work:
- Studied both the mineralogy and the granulometry (particle size distribution) of the earth being used to make the samples of compressed earth blocks.
- Provided, based on an extended experimental campaign, thermal conductivity analysis related to the compressed earth block stabilized (CEBs) with different cement and different water, contents ratios.
- Developed and successfully tested a mathematical model based on the finite volume method to model heat transfer through samples of CEBs with different ratios of cement content and water content.
- Proposed a validate a Technico-Economic Optimum (TEO) model for CEB building with respect to the combined effects of these two contents. This optimum is determined by using the evolution of the thermal properties of the compressed earth block according to the stabilization (cement content) and water content (water presence).

The experimental results as well as the numerical results show that the thermal conductivity is found to evolve in the same manner with respect to cement and water content following an S curve, with a specific-material's inflexion point. Adding a small content of cement does not significantly affect the thermal conductivity. For a specific content suggested here as a Technico-Economic Optimum the conductivity rapidly increases before being stagnated. The TEO corresponds to the S-curve inflexion point.

Keywords: Earth construction, compressed earth block, technico- economic optimum (TEO), thermal conductivity, cement and water content, finite volume method, control volumes.