DURABILITY PROPERTIES OF STABILIZED EARTH BLOCKS

YASER KHALED ABDULRAHMAN

AL-SAKKAF

UNIVERSITI SAINS MALAYSIA

2009

DURABILITY PROPERTIES OF STABILIZED EARTH BLOCKS

by

YASER KHALED ABDULRAHMAN AL-SAKKAF

**Thesis submitted in fulfillment of the requirements
for the degree of
Doctor of Philosophy**

January 2009

DEDICATION

This thesis is especially dedicated to the following

For their love, support and patience:

- My father, and mother,

- My brother and sisters,

- My wife, and my children,

And all my brothers every were including my home country of Yemen and my second home in Malaysia

Acknowledgements

All praise be unto Allah and may his peace and blessings be upon his final prophet and messenger Muhammad peace be upon him.

First and the foremost, I would like to extend my most profound gratitude and deepest thanks to my principle supervisor Professor Ir. Dr. Mahyuddin Ramli, Universiti Sains Malaysia, for his guidance, commitment and encouragement throughout the entire period of the research project . His dedication and continuous guidance enabled me to remain focused on the research investigation from the beginning of the project to the very end for all the time spent on coordinating and supervising the whole thesis. Without his constant support and timely interventions, without Allah and then him, none of this would have been possible. I would also like to convey my sincere thanks to Dr. Mohd Rodzi Bin Ismail as the co-supervisor for the project.

My deepest thanks are also due to my parents (father and mother), who have been an inspiration and I ask Allah to grant them His paradise. Thanks also goes to my family and my brother and sisters for all the hours of transcribing, proof reading, and patience given to me in my quest and their great support in highly appreciated.

My sincere thanks are also to the academic and technical staffs at the Universiti Sains Malaysia and to my University in Yemen (Hadhramout University/ Mukalla) and their staffs for the assistance rendered.

I would certainly like to thank to the laboratory assistants namely; Mr. Khalid Ahmad, Mr. Ooi Cheow Lam and Mr. Idris Shaari for their continuous assistance in conducting laboratory tests for the main experimental investigations. I remain deeply indebted to all and to those who assisted me during the course of my study and I am asking Allah to guide them to the right way for the great religion of Islam.

TABLES OF CONTENTS

CHAPTER 5- ANALYSIS AND DISCUSSIONS

LIST OF TABLES

LIST OF FIGURES

SIFAT-SIFAT KETAHANAN BLOK TANAH YANG STABIL

ABSTRAK

Tanah sebagai bahan binaan bangunan yang mudah diperolehi. Di negara-negara membangun, pembinaan menggunakan tanah adalah lebih ekonomik dan berkesan. Permintaan yang tinggi dengan sumber yang tidak terhad. Teknik pembinaan berasaskan tanah secara tradisional seperti bata tanah liat tanpa bakar adalah lemah kepada air dan retakan. Penyelenggaraan berterusan diperlukan bagi memastikan ianya sentiasa dalam keadaan baik. Tesis ini menerangkan hubungan antara sifat-sifat tanah, beberapa penstabil, kekuatan mampatan dan ketumpatan dari tanah yang diambil sekitar Pulau Pinang.

Menggunakan 'CINVA-Ram Hydraulic Machine', blok tanah termampat yang distabilkan dengan 5 % setiap penstabil dibentuk. Blok-blok ini diuji pada 1, 7 dan 28 hari. Keputusan ujian mampatan menunjukkan keputusan terbaik dan peratusan penstabil terbaik dipilih. Peratusan-peratusan yang dimaksudkan adalah 10 % simen, 5 % kapur, 6 % (pra-campur simen) bitumen dan 0.75 % (pra-campur simen) calcium silicate. Campuran 10 % simen dan 5 % kapur juga adalah dicadangkan. Ujian makmal dijalankan untuk menyiasat sifat-sifat dan kebolehan blok-blok dalam cuaca tropika. Menggunakan perincian seperti dinyatakan diatas, blok termampat distabilkan dihasilkan dalam lima kategori dengan lima tempoh jangkamasa ujian (7, 28, 56, 90 dan 180 hari). Blok tanah yang dibuat secara manual juga dihasilkan untuk dibandingkan prestasi dan kekuatan mampatannya antara blok termampat dan tidak termampat distabilkan.

Keputusan menunjukkan peningkatan dalam prestasi, kekuatan mampatan dan ketahanan blok. Kekuatan mampatan bagi blok tanah termampat pada 180 hari dengan komposisi simen, campuran kapur-simen, calcium silicate dan bitumen adalah 13.2 N/mm^2, 6.4 N/mm^2, 16.3 N/mm^2, 11.7 N/mm^2, dan 12.6 N/mm^2 manakala bagi cara manual 3.8 N/mm^2, 1.5 N/mm2, 3.5 N/mm^2, 2.8 N/mm^2, dan 3.4 N/mm^2. Kekuatan mampatan terbaik adalah dari campuran simen-kapur dan ini adalah campuran baru dan rekabentuk bancuhan yang dipertingkatkan. Bagi ujian penyerapan air dan ujian kapilari, campuran simen-kapur menghasilkan keputusan terbaik pada hanya 5.9 % dan 5.7 %, ketelapan manakala 8.6 % bagi blok simen-bitumen didalam air mendidih dimana ia agak baik bagi blok tanah. Penstabilan dan pemampatan mengurangkan kadar pengecutan. Bacaan tertinggi adalah 0.43 % pada 180 hari untuk blok kapur dan yang lainnya adalah lebih rendah. Ujian kebolehtelapan gas juga dijalankan menggunakan saiz spesimen piawai. Ujian halaju denyutan juga dijalankan pada umur 180 hari dan keputusan menunjukkan perhubungan yang baik antara kekuatan mampatan dan halaju denyut daripada blok-blok yang diuji.

DURABILITY PROPERTIES OF STABILIZED EARTH BLOCKS

ABSTRACT

Earth as a building material is available everywhere. In developing countries, earth construction is economically the most efficient means to house the greatest number of people with the least demand of resources. Traditional earth construction techniques such as adobe bricks suffering from water attack and cracks, thus they need continuously maintain it in order to keep them in good condition. This thesis studies the relationships between soil properties, several stabilizers and their compressive strength and density using local soil taken from site at city of Penang in Malaysia.

Using CINVA-Ram hydraulic machine, stabilized compressed earth blocks were cast with the five percentages of each stabilizer, and these blocks were tested at (1, 7 and 28 days). Compressive strength results showed the best result and the appropriate percent of each stabilizer were chosen. These percentages are 10 % cement, 5 % lime, 6 % (of the used cement) bitumen and 0.75 % (of the used cement) calcium silicate. A mix of 10 % of cement and 5 % of lime is recommended. Laboratory tests were conducted to investigate the properties and performance of the blocks in its normal conditions. Using the previous details the required stabilized compressed earth block were cast for the five block categories and for five periods of testing (7, 28, 56, 90 and 180 days). Manually cast blocks were also done to compare the performance and the compressive strength between compressed and un-compressed stabilized earth blocks.

Results revealed improvements in the blocks compressive strength and durability. The compressive strength of the compressed earth blocks at 180 days prospectively for cement, lime with cement, calcium silicate, and bitumen, were 13.2 N/mm^2, 6.4 N/mm^2, 16.3 N/mm^2, 11.7 N/mm^2 and 12.6 N/mm^2 while it were 3.8 N/mm^2, 1.5 N/mm^2, 3.5 N/mm^2, 2.8 N/mm^2 and 3.4 N/mm^2 for the manually cast blocks. The highest compressive strength results were derived from the mixture of cement and lime blocks and this was a new mixture and improvement mix design, while the cement blocks gave optimum compressive strength by manual casting. For water absorption test and capillary test the cement and lime mix blocks gained the best results of only 5.9 % and 5.7 % respectively, while it was 8.6 % for cement and bitumen blocks in the boiling test, which are quite good for earth blocks. Stabilizing and compressing decrease the blocks shrinkage. The highest was 0.43 % at 180 days for the lime blocks and other categories were lower. Gas permeability was also tested using standard size of specimens. Portable ultrasonic test (Pundit) was also carried out for the 180 days of age and the results showed good relationship between compressive strength and pulse velocity of these stabilized blocks.

CHAPTER ONE

INTRODUCTION

1.1 Introduction

This chapter briefly outlines the motivation for this work and explains why research in this area is of interest to human beings. It focuses on aspects of the traditional adobe, characteristics of the raw material and why they are important for human needs. It also focuses on the need for development to face new requirements and the need to understand the properties of building materials to increase the strength and durability of earth blocks against destructive effects. This is very important towards a more sustainable construction of walling and buildings.

1.2 Background

1.2.1 Why use earth for building?

Many benefits that are offered by earth construction are often underutilized in the developed world where the use of earth as a low-embodied material is often the case (Middendorf, 2001).

Historically, earth has been the most widely known and used building material in construction and probably has been the most important of all building materials (Legget, 1960). According to Middendorf (2001) recorded cases of the use of earth bricks dates back to Mesopotamia "around 8000 BC". Recent reports indicated that, about half of the world's populations are still living in earth buildings (McHenry, 1984; EBAA. Australia). Of all urban housing units worldwide there are about 25 % that does not conform to building regulations while 18 % are considered non-permanent structures (Habitat, 2001).

Earth as a building material is available everywhere and exists in many different compositions. It is most efficiently used in developing countries to house the greatest number of people with the least demand. The world map below shows the distribution of buildings units using earth material and construction around the world (Fig. 1.1). However, it must be noted that earth buildings are not a phenomenon only of the Third World countries, but also in developed countries (EBA New Zealand, 1998).

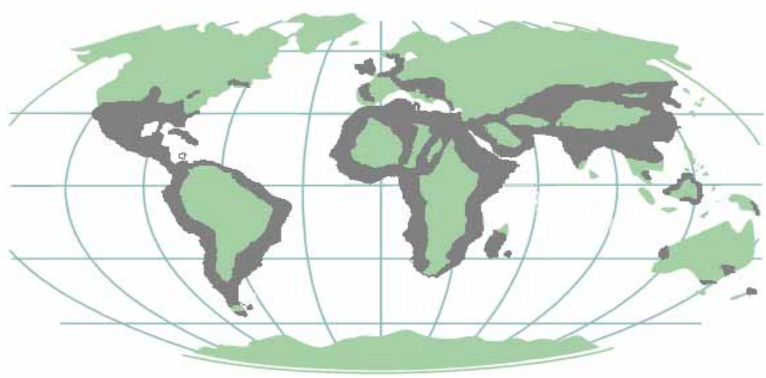

Fig.1.1: Earth material and construction around the world
Source: (Houben & Guillaud, 1994)

It is important to ensure that the materials used in construction meet all the specification in every respect. This means that all relevant properties must be checked properly before construction (Tuffin, 2007).

There are many benefits of earth buildings. For example, earth structures are completely recyclable, so sun-dried bricks return to the earth without polluting the soil (Rigassi, 1995). Using earth for such environmental-friendly buildings will be a strong component in the future of humankind (Bossel, 1998; Hochella, 2002). In addition, energy requirement to produce adobe block is only 5 (kWh)/cubic meter, while it is about 1000 (kWh)/ cubic meter for fired brick and 400-500 (kWh)/ cubic meter for concrete (Table 1.1).

Table1.1: Energy requirement to produce different building materials (Kleespies, 1991)

Building materials	Unit	Energy (kWh)
Cement	Sack	50
Concrete	Cubic meter	400 - 500
Fired brick	Cubic meter	1000
Adobe	Cubic meter	5

Generally, people are re-discovering the benefits of having earth walls in developing countries (Middendorf, 2001). This is because better properties can be obtained by using additives to the earth material. In addition, earth construction is possible with a wide variety of building methods. Egyptian architect, Hassan Fathy (1973) argues that housing design should not be based solely on imported forms, but rather on traditional forms of architecture as well.

In 1998, 88% of Yemeni families were living in villages and in their own made houses. There are many economical, demographic and social problems associated with housing issues as the need for housing in Yemen which is increasing rapidly (Al-Jahdari et al., 1998). For example, there is a clear shortage of houses compared to the number of families. A study about the housing situation in the Republic of Yemen has indicated that the average yearly demand has been about 149,500 units, from 1992 to 2005 (Al-Jahdari et al., 1998).

In cities of developing countries, there are many problems such as homelessness and unsuitable living conditions (Ballerino, 2002). This can be observed everywhere, especially in developing countries such as Manila, Mexico City and Jakarta as well as the industrialized countries. This has resulted in millions of squatter camps made of plastic sheets, flattened cans or cardboard, spread on strips of land beside canals and railways, sometimes even in the shadows of high-rise "low-cost" housing. In these areas, such as in Calcutta, the cost of manufacturing building materials is high (Reddy, 2004).

Actually, most developing countries are facing a real housing deficiency (Harison & Sinha, 1995). Therefore, there is an urgent need to construct and build houses that are more durable at a low cost. In this regard, clay masonry has a long and illustrious record of providing durable and attractive buildings (Fig.1.2). Recently, the technology of traditional earth construction has undergone considerable developments that have enhanced earth's durability and quality as a construction material for low-cost buildings (Adam & Agib, 2001).

Fig. 1.2: Example from Yemen. Mud clay ancient palace, Tarim city (Bradley, 1997) Source: Aga Khan Trust for Culture

Buildings made from earth materials can be a way towards sustainable management of the earth's resources. They can be put in place using simple machinery and human energy. Earth buildings avoid high-energy costs in the initial manufacturing and construction period, in their use as homes, and eventually in their recycling process (Temeemi & Harris, 2004). Thus, it is not surprising that many people value earth construction for the above reasons for their durability (Reddy, 2004) and for the following qualities:

1. The principal reason for using earth is its excellent sustainability characteristics. These include, the efficient use of finite resources, minimizing pollution and waste and low carbon emissions especially in industrial countries (Little & Morton, 2001). In comparison with other materials, adobe and rammed earth, buildings reflect the embodied energy required for the production and use of various materials. In comparison to brick ad concrete, adobe bricks have the less embodied energy (McHenry, 1984) (Table 1.2).

2. Adobe blocks do not use organic resources for firing and it does not consume any non-renewable energy. Thus, it has environmental advantages and does not contribute to deforestation. In addition, adobe blocks use very little water, which are essential for people (Little & Morton, 2001).

3. Adobe blocks have good economical advantages. It requires no major financial transport costs. It is often comparable in cost with or more economical than other competing technologies. Adobe blocks require only simple production and application tools (moulds, presses, light shuttering and masonry tools, etc.).

Table1.2: Embodied energy in BTU's required for the production and use of various materials (Christensen)

Common brick	13,570 BTU
Concrete block	29,018 BTU
Earth (Adobe) block (mechanized production)	2,500 BTU

Source: Book earth guidelines
http://greenbuilder.com/sourcebook/EarthGuidlines.html

By understanding the characteristics of soil we can promote the use of earth as an ecological on-site building material (Adam & Agib, 2001). Many types of soil are suitable for use as building materials. To improve their quality, one needs to identify the characteristics of the soil and its appropriateness for using in building construction. Besides the addition and removal of certain constituents, several tests need to be carried out (Stulz & Mukerji, 1988; Kerali, 2001).

There are also problems that need to be solved to increase durability, for example, the problem of rain penetration in buildings. According to Jefferson, rain penetration results in condensation of water vapour on cool surfaces leading to damp walls (Ritchie, 1960). Damp walls have become more common since the 1920s. This is because of changes in materials use and construction methods (Crawford, 1978).

The most significant part of the physical structure is the walling constituents, which is about 60 % (Agevi, 1999). Thus, it makes greater sense to concentrate work on low-cost walling. Dwelling cost can be split into a number of separate areas.

Block pressing machines have been designed and are used for "self-built initiatives" such as the CINV-Ram machine (manual block press) and the Brepak (hydraulically assisted block press) (Montgomery, 2002). These presses are not too expensive as they do not require high quantities of cement for adequate performance and their maintenance is not complex.

1.2.2 Low cost

Soil is widely available and in some parts of the world, especially remote areas, it is the only material available (Adam & Agib, 2001). Soil is suitable for construction in many building components as it uses only about 1% of the energy required to manufacture and process the same volume of cement concrete. Furthermore, using soil requires less specialized equipment compared to other forms such as brick walls and cement block, which cost more than soil cement walls (Bush, 1984; Adam & Agib, 2001).

However, production cost should not be the only basis of comparison with other building materials. The expensive additives that are used to manufacture the walls and the transportation cost of materials also greatly affect the cost of low-cost walling. Moreover, good quality compressed stabilized earth blocks do not require external renderings. The large block size results in less labor and a lower amount of mortar is needed for block, which will result in additional savings being made. Another important factor is the equipment and tools needed for the manufacture of compressed and stabilized blocks. Earth block can be made locally and a variety of equipment can be used to construct low-cost residential houses. Pressed block making machines such as the CINVA-Ram and similar portable hand-operated machines are used in many places around the world. They are good examples of tools for making pressed block (Bush, 1984; Houben & Guillaud, 1994). In addition, study in Italy showed the difference quality and feasibility in wall types and the cost of the stabilized earth blocks was the lowest (see Table 1.3).

Table 1.3: Comparison between five different wall types

	Concrete blocks	Hollow bricks	Solid bricks	Machimbre (not insulated	Stabilized earth blocks
Dimension (cm)	40*20*20	33*18*18	30*6*15		28*9.5*14
Cost analysis Cost ($/m2	12.94	14.97	17.42	19.32	8.72
Thermo physical analysis Transmittance (W/m2^{o}C	2.116	1.792	2.421	1.687	1.674
Front thermal capacity (KJ/ m2^{o}C	131.9	207.6	253.0	53.0	197.1
Delayed heat transmission (h)	2.88	5.39	4.88	1.66	5.46
Attenuation factor (-)	0.85	0.63	0.56	0.93	063

Source: (Mattone et al., 2005)

The sight to the characteristics of building with the earth material can assume many important advantages like the great spreading and very low cost or free material in some places around the world, the environment, saving the energy. According to Al-Jadid (2004), some of those characteristics are important for the developing countries more than others, other characters are important to the advanced and western countries and some of these characteristics are important to all countries (see Table 1.4).

Table 1.4: Characteristics of earth blocks (Al-Jadid, 2004)

The most advantages of built with earth	Degree of importance to the counties					
	Developing countries			Western and Industrial		
	High	Mid.	Less	High	Mid	Less
The low cost and availability.	*			*		
Limited pollution and depletion of environmental resources.			*	*		
Ease of construction with earth material.	*					*
Reduced unemployment of unskilled labor.		*				*
Variation in constructions techniques and methods.		*			*	
Savings in transportation cost.	*				*	
Saving in energy consumption	*			*		
Engineering characteristics of earth material.		*			*	
Easing recycled of earth products.			*		*	

In spite of all the advantages this material is still unsuitable for use in many countries around the world, mainly attribute to the disadvantages of this material and lack of information on the material properties. Compressed stabilized earth blocks can be used as a construction material for housing. The purpose of the stabilizer is to prevent softening of the soil on absorption of moisture (Harison & Sinha, 1995). The earth-compressed blocks are widely used around the world in the last 30 years not only in the third world countries but also in the developed countries like USA, French, Canada and Australia.

1.2.3 Adobe blocks

Adobe has a great heritage of sustainable clay buildings around the world and has special experts in this area. The adobe block follows the heritage of the traditional architecture of numerous countries using local materials (Little & Morton, 2001) (Fig. 1.3). In some wet and humid areas where unburned bricks are used, roofs are designed to shade the mud wall. This means that the building is only one or two stories high. These places have cheap wood for the roofs. Wood is usually very expensive in many countries, and is not suitable for low-cost houses (Middendorf, 2001). In Yemen (for example), the biggest problem in the unburned clay buildings is the water effect and the brick strength (Lewcock, 1986).

Fig. 1.3: Egyptian mud-brick storage rooms (3200 years old) (CRATerre-EAG) and cob buildings in Sa'dah, Yemen (Marechaux, 1998)

1.2.3.1 Traditional adobe

Traditional adobe is made out of soil and straw and found mostly in older homes. The straw prevents cracking and adds strength. Adobe buildings can last easily for about 100 years or more if the walls are dry and are kept away from wicking up water from the earth. Thus, maintenance is important since moisture can get in through cracks (Fransworth, 1999; Middendorf, 2001).

1.2.3.2 Traditional Yemeni clay buildings

The tradition of mud-brick architecture in the Hadhramout region in Yemen offers a unique source of cultural and technical knowledge. It is rich in its variety; for example, the traditional houses in Shibam city are built of mud-brick on stone foundations (Fig. 1.4). Walls are tapered on the outside from about 1 m thick at the bottom to less than 30 cm at the top (Lewcock, 1986). The top one or two levels of all the buildings are protected from rain by white lime plaster. Photo 1.3 also shows historic buildings in Yemen, which have been recognized by UNESCO (Hughes, 1991). The recognition is based on the following reasons:

i) Unusual soil properties

ii) Unique construction techniques in an arid climate

iii) The preservation of the building

Fig. 1.4: Shibam, city in Wadi Hadhramout/Yemen (Doan, 2007)

1.2.4 New techniques

In Yemen, over an enormous geographical area, there are many modern earth buildings which have been constructed through new techniques. Worldwide, the new earth buildings added new methods to develop new technologies. Most of these methods were derived from traditional methods (Middendorf, 2001). These methods will be discussed in Chapter Two of the Literature Review.

In industrial countries such as in the Southwest U.S.A, the very rich class often uses adobe, while in "developing" countries; its use is mostly confined to those who are too poor to have access to other building materials. Adobe is appropriate in areas, which are labor-rich and capital-poor; because it is labor intensive, using local materials and simple tools (Kennedy, 1997). Fig. 1.5 is an example of its wide appeal.

Fig. 1.5: Clay buildings in New Mexico. Adobe is the most traditional form of earthen construction in the US (Blanc) (Source: Balderma, 2001)

More than two billion people live in buildings constructed of earth (Little & Morton, 2001; Middendorf, 2001). To improve the quality, the selection of building materials should meet the local conditions of life by improving on existing structures or by building new structures. In the past, improving and developing the natural materials using new technology has created substitute materials (Ballerino, 2002).

1.2.4.1 Stabilized soil

Stabilization is necessary to achieve a lasting structure from local soil. The local material properties determine the appropriate stabilization method (Montgomery, 1998). Stabilization techniques can be broken down into three categories, (Houben & Guillaud, 1994).

- Mechanical stabilization: compacting the soil and changing its density, compressibility, permeability and porosity.
- Physical stabilization: changing the texture properties of the soil. It can be done by controlling the mixture of different grain fractions, drying or freezing, heat treatment and electrical treatment.
- Chemical stabilization: changing the properties of the soil by adding other chemicals or additives. This happens either by creating a matrix, which binds or coats the grains or by a physico-chemical reaction between the grains and the additive materials (Gooding & Thomas, 1995). Many additive materials can be used to stabilize the soil (Hoben, 1994; Kerali, 2001).

The compressive strength of the soil can be improved multifold by using the right stabilization method. This will also improve its durability by increasing its resistance to erosion and water damage. The main categories of binders used for earth construction are Portland cement, lime, bitumen, natural fibers and chemical solutions such as silicates (Houben & Guillaud 1994) as also outlined in the Australian Standard and SAZS 724:2001 Zimbabwe Standard.

1.2.4.2 Compressed earth blocks

The compressed earth block is the modern descendent of the molded earth block. The earth-compressed blocks became widely used around the world in the last 30 years or more, not only in third world countries, but also in developed countries like the USA, France, Canada and Australia. Machines were first used to compress earth as early as the 18^{th} century. In France, architectural purposes came into effect only in 1952 by Engineer Raul Ramirez of the CINVA centre in Bogota, Columbia, designed the ClNVA-Ram press machine. This was used throughout the world (Rigassi, 1995) especially in developing countries in Africa, South America and Asia (Guillaud et al., 1995; Heathcote, 2002; Morel et al., 2007).

Compressed earth blocks are made by using a variety of machines. Some, like the CINVA-Ram were invented for compressing earth blocks (Fig. 1.6). Compressed earth block technology offers an alternative kind of building construction which is more accessible and of high quality. The compressed earth block is one of the most important "modern building materials" which has enough production flexibility to let it be integrated into both formal and informal sectors of structural activities (Rigassi, 1995). Some hydraulic machines were developed to get blocks similar to concrete blocks (Bahar et al., 2004).

Fig. 1.6: The CINVA-Ram hydraulic compressed machine

1.2.5 Water

Water is preamble up from the ground, erodes the bases of earthen walls, affecting them to crumble and fall away quickly. Since, water is the main enemy of all earthen construction (McHenry, 1984; Farnsworth, 1999), walls should be sealed to prevent all kind of moisture: either it is from an external source (rainfall, soil humidity, ground water) or internal source (used water and pipes) (Megyesi, 2003).

In view of this, there are several issues that have to be considered like the weakness of these blocks against the water effects and the need for this cheap material in other areas that are not arid but are wet and cold. These areas may also need housing projects, which utilize low cost buildings for its greater population. So, there is a need for a comprehensive study to determine the properties, the right mixture, suitable new stabilizers and modern technology for government buildings and housing projects.

Other problems that ought to be taken into account are:

1. Use of the traditional plaster is not enough to protect the mud bricks especially against water and humidity.
2. The adobe block should be improved to acquire more durability and strength for new requirements and wider openings and to decrease the drying period.
3. In traditional earth bricks, wall thickness relies on brick size for each level. There are no special sizes for joints or corner demands like half or quarter block.
4. Traditional clay construction does not facilitate building of the balconies and its ability to bear heavy loads is low.

5. The traditional construction systems show a weakness and an inability of conjunction especially in the joints and corners, which need maintenance in many cases.

1.2.6 Critical summary

Good production could be performed by increasing compressive strength and using improved curing (Kerali, 2001). Further improvements in material performance will help to outweigh sloppy production practices. A lot of research work has been done in the development of local low and stabilized soil area (Guettala, 2002; Bahar et al., 2004).

National and international standards have also been developed for these procedures such as New Zealand standard 1998 and Standards Australia handbook 2002 (Walker 1996; Morel et al., 2007). The test methods of earth walls vary from country to country because of the varied weather conditions. They are also not based on the evaluation of field performance (Heathcota, 1995). A number of guidelines and publications that explain various aspects of earth wall construction and testing have been produced as well (Burroughs, 2001). The influences of soil and stabilizers on the qualities of the stabilized material have also been examined (e.g. Bryan 1988; Osula, 1996).

In spite of all these, little work has been done on durability tests such as water permeability, capillary and water absorption. The variety of soils from one region to another is a strong reason for this. The effect of compaction methods on the chemical and mechanical properties needs further studies (Bahar et al., 2004).

Strength testing and quality control of compressed earth blocks has often followed procedures developed for fired clay and concrete block units (Walker, 1996). However, consensus on the test procedure for compressed earth blocks is little (Morel et al., 2007). Previous studies have reported on the compressive strength characteristics of compressed earth blocks (Walker 1997; Reddy, 2003; Morel et al., 2007). Thus, what is needed now is good empirical data to improve the knowledge on soil stabilization for earth wall construction (Burroughs, 2001).

1.3 Scope of the study

This study will focus on wall building materials that can offer better quality structures and faster construction solutions that will be economical. These aspects need to be clarified through literature regarding building materials properties and wall building systems. Thus, it will investigate traditional and innovative techniques that have been used successfully in the Republic of Yemen. It will focus on techniques that have relevance to climatic, technical and cultural reasons.

This study will also examine the stabilized compression of full size compressed earth block samples and determine the relationships between soil properties (gradation, plasticity, and moisture), stabilizer types (asphalt, cement, lime, etc.), stabilizer quantities, and stabilized earth qualities (density and compressive strength) and develop new durable compressed blocks for housing construction.

1.4 Problems statement

The main drawback of soil material is the need for continuous maintenance and the lack of durability and resistance to water (Bahar et al., 2004). Most researches done in this area has always focused on processed durability or strength. All aspects should be considered to produce sustainable, durable, safe and environmental friendly homes and buildings. However, earth construction suffers from shrinkage cracking, low strength and lack of durability (Bahar et al., 2004; Guettala et al., 2006). In addition, most earthen materials are unsuitable for homes of more than two stories, as they are unable to carry the load of the upper walls. The lower walls would need to be thicker than the upper walls in the same building. Thus, labor costs would be very high indeed (Farnsworth, 1999).

The challenge of modern and new requirements, the need for sustainable low cost buildings to house people and the lack of knowledge in this area justify the need for more research to be focused on the strength and durability of earth block.

1.5 Research objectives

This research project is aimed to:

1- gain a better understanding of the characteristics of the material.

2- determine which variables are of greatest influence in the production of compacted samples.

3- define the structural and performance characteristics of laterite that can be expected of additives for stabilizing the blocks.

4- define a laboratory mixture design and testing protocol to ensure the necessary properties and develop new quantitative criteria for soil assessment, selection and stabilization.

5- improve earth blocks durability as well as improve the strength for low cost and sustainable houses.

6- determine the percentages of stabilizer, which depend on the soil quality and the particular requirements and determine the most effective stabilizer for the chosen soil.

7- give an overall view of the qualities and varieties of the use of clay as a building material in combination with some stabilizers.

Most methods are not concerned with durability especially strength and shrinkage aspects. The objective of the second part of this project is to take the findings from the material analysis and develop a systematic method for block production using the beneficial aspects of hydraulic compaction machine.

This study is an attempt to improve building material. It focuses on the properties and the performance of the stabilized compressed block. One purpose of this study is to summarize information on the basic characteristics of soil and on the stabilization and compaction.

1. 6 Hypothesis

Clay is good and strong enough to be used in buildings and housing projects without causing any environmental problems. However, we need to extract its characteristics and apply new technologies.

1. Experimental results should give or show directions for some points of longer spans, wider openings, and thinner walls for multi stories by using compressed earth blocks.
2. Casting and testing stabilized compressed earth blocks in humidity and hot weather will prove that this technology is suitable in tropical areas as well as in arid areas.
3. Is laterite soil in Malaysia suitable for compressed earth blocks for building construction? Should Malaysia start thinking in this area as an option for future housing demands?
4. Durability and strength should improve and shrinkage should reduce with a good stabilizer.

New techniques should be used in developing countries such as Yemen to change the material properties for wide spread use, new requirements needs and low-cost projects.

1.7 Layout of thesis

The body of this thesis consists of seven chapters. The organization of the chapters is as follows:

Chapter one

This chapter presents the history, problems in the area of this study background and the need for this research. This chapter also summarises aims and objectives of the research and presents examples of traditional buildings.

Chapter two

This chapter deals with various issues and research, which are relevant to this study. It starts by tracing the historical background of building with earth materials to explain the importance of this area to mankind. In addition, new work in this area is discussed with some examples from around the world. Soil properties, classification indicators, additive materials, stabilization principles and theoretical concepts of compressed stabilized earth blocks, mix designs and curing methods are also described. Effective factors and compaction methods are also presented. New technology used in stabilization and compression block machines is also explained in this chapter. This chapter also discussed the main concepts of durability in blocks and reviews the wide store of knowledge accumulated in this aspect.

Discussion on a field study in Yemen is also included. It shows the heritage clay cities and some of its mud brick technology. It focuses on traditional clay building technology in Yemen and the properties of the local materials, common stabilizers, and the need of the new techniques and its suitability for Yemen's buildings. This chapter also includes pictures of traditional buildings.

Chapter three

This chapter describes the structure of the thesis, the main experimental design used and the sample preparation. Methods used for laboratory tests, mixing-water content, moulding pressure, curing conditions and presents the laboratory tests that were done for the intended blocks with the varieties of the blocks age.

Chapter four

This chapter presents the results of all the experiments that were carried out and the necessary data to support the conclusions of the experiments. This chapter also presents the comparison of the properties and performance of blocks that represent the core of the experimental work in this research.

Chapter five

This chapter discusses the results, the correlation and the different types of compressed stabilized earth blocks for all periods of this study.

Chapter six

The final chapter of the thesis integrates and summarises the study. It provides conclusions, recommendations and highlights the implications of the research findings and identification of areas for further research are given at the end of this chapter.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Modern earth building is alive and well spread over an enormous geographical area using numerous different methods of construction. The new earth buildings developing worldwide have generally utilized the good aspects of the traditional method while adding aspects and technologies. Today Adobe brick construction has been partially adapted to economical projects. In Mesopotamia, some cases of earth brick construction are as far as 10,000 BC (Heathcote, 1995; Burroughs, 2001; Smith, 2004). Historically some of the building materials are new, while others are very old and started with human shelter as shown in Table 2.1 (Reddy, 2004).

Table 2.1: Chronological sequence of developments in building materials (Reddy, 2004)

Material	Period
Mud, stones, wood/thatch	Prior 8000 BC
Sun dried bricks	6000 BC
Pottery products	4000 - 8000 BC
Burnt bricks	4000 BC
Lime	3000 BC
Glass	1300 BC
Iron products	1350 BC
Lime-pozzolana cement	300 BC - 476 AD
Aluminum	1808 AD
Portland cement	1824 AD
Plastic	1862 AD

From the past to the present day, earth seems to be the material of choice. Mud brick that was made of alluvial soils were mixed with cereal straws. It gave man his first durable construction material and took many forms, such as adobe, rammed earth and straw-clay (Houben & Guillaud, 1994; Smith, 2004). Earth architecture has also deep roots in all old civilizations, the Middle East, Iran and the cradle of the Sumerian civilization in Iraq (Fig. 2.1). At Shibam in South of Yemen, there are more than ten stories high of cob buildings (Houben & Guillaud, 1994). Nowadays, unbaked earth buildings shelter about thirty percent of the world's population (Houben & Guillaud, 1994; Middfort, 2001; Megyesi, 2003).

Fig 2.1: Ruins of earth shelters (Egyptian mud-brick storage rooms, 3200 years) (Middendorf, 2001)