Feasibility of Adobe as a Construction Material A Case Study

by

Abu Naser Md. Enamul Hoque

A Thesis Presented to the

FACULTY OF THE COLLEGE OF GRADUATE STUDIES

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Feasibility of adobe as a construction material: A case study

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This thesis, written by ABU NASER MD. ENAMUL HOQUE under the direction of his Thesis Advisor and approved by his Thesis Committee, has been presented to and accepted by the Dean of College of Graduate Studies, in partial fulfilment of the requirements for the degree of MASTER OF SCIENCE in CONSTRUCTION ENGINEERING AND MANAGEMENT.

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This thesis is dedicated to my deceased mother.

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THESIS ABSTRACT

Full Name of Student : ABU NASER MD. ENAMUL HOQUE

Title of Study : FEASIBILITY of ADOBE as a CONSTRUCTION MATERIAL : a case study

Major Field : CONSTRUCTION ENGINEERING and MANAGEMENT

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Adobe has been in use as a viable building material in the Southwest of United states on a commercial basis. It has also been successfully used in France and Egypt. Saudi Arabia has a traditional background of buildings with mud all over the country. This research investigates feasibility of adobe buildings in the Eastern Province of Saudi Arabia. Two different soils from two sites were explored. The effects of bitumen emulsion and palm tree fibre as additives were also investigated. For producing the bricks a machine was used that makes compressed bricks. The compressive strengths of the bricks without any additives and with the additives showed lower values than dictated by the adobe codes of the Southwsct of United States. This is partly due to the expansive characteristics of Qatif soil. However, in terms of absorption and shrinkage, the good results were achieved. An economic analysis was done to determine the cost per square meter of adobe and a comparative 20 years analysis with adobe and clay burnt bricks. With 5%

emulsion, the cost per square meter of adobe is the same as that of CMU (Concrete Masonry Units) but cheaper than CMU and Calcium Silicate bricks. Both present worth and annual equivalent worth analysis indicates the economic feasibility of adobe over clay burnt bricks. Given the traditional and architectural background of Saudi Arabia of adobe buildings, further research in this area is required to bring it on par with the other alternative and imported construction materials and methods.

MASTER OF SCIENCE DEGREE

KING FAHD UNVIERSITY OF PETROLEUM & MINERALS
Dhahran, Saudi Arabia

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ملخص

الاسم : ابو ناصر محمد انعام الحق

عنوان الدراسة : دراسة صلاحية الطوب الطيني كمادة بناء

التخصص : هندسة وادارة التشييد .

التاريخ : ١٩٩١/٧

لقد استخدم الطوب الطيني بنجاح كمادة بناء على مستوى تجاري في غرب الولايات المتحدة الامريكية وفرنسا ومصر . ان للمملكة العربية السعودية تاريخ طويل في البناء الطيني وهذه الدراسة تبحث في امكانية استخدام الطوب الطيني كمادة بناء في المنطقة الشرقية . تم اختبار وفحص نوعين من التربة لصناعة الطوب واختبار مدى التحسن على التربة بعد اضافة محلول الاسفلت وشرائح سعف النخيل . وقد تم استخدام مكينة ضغط الطابرق لانتاج الطابوق دلت نتائج الفحوصات ان قوة التحمل لهذه النوع من الطابوق المصنوع من هذه التربة اقل من الارقام الموصي بها في جنوب غرب الولايات المتحدة حتى بعد معالجتها بالمواد المضافة وهذا عائد الى طبيعة التربة ، ولكن من حيث قابلية امتصاص الماء والتقلص فان النتائج كانت جيدة ، وقد تم عمل دراسة اقتصادية لحساب تكلفة المتر المربع من طابوق الطين وقورنت مع تكاليف الطوب المصنوع من الطين المحروق وكانت مدة المقارنة الاقتصادية ٢٠ سنة ، دلت النتائج على ان سعر الطابوق الطيني يعادل الطابوق المصنوع من الاسمنت ولكنه ارخص من الطابوق الطيني ، ، ، او الطابوق الجيري . وقد بنيت نتائج الدراسة الاقتصادية ان الطابوق الطيني اكثر اقتصادياً من الطابوق المحروق . واعتباراً للعادات والتقاليد المعمارية للمملكة العربية السعودية فإن هذا المجال محتاج الى دراسات اخرى لتحسين صفات الطوب الطيني ليرقى الى مستوى مواد البناء الاخرى .

درجة ماجستير العلوم

جامعة الملك فهد للبترول والمعادن

الظهران . المملكة العربية السعودية

CHAPTER 1

INTRODUCTION

1.1 History and Tradition of Earth Construction

The use of earth (mud) as a building material has been known from the earliest of times. Around the world, unbaked earth has been one of the principal building materials. Still today, over a third of the population of the world lives in earth houses. Ancient Mesopotamian and Egyptian civilizations used earth in their times. As also the Romans and the Muslims in the Middle-East, Africa and Europe built in earth. The people of the Indus civilization, Buddist Monks and Chinese Emperors are also known for their use of earth as a building material. During the Middle ages, the practice of construction in earth was found in North America by the Indians, in Mexico by the Toltecs and Aztecs and in Peru by the Inca and Mochica. In Africa, the much diversified cultures of the Barbers, Dogans, Ashanti, Bamlikes and others were found to have mastered the art of earth constructions. The archaeological remains that have survived the passage of time are the proof of the history of construction in earth. (8)

With the Industrial Revolution radical changes have occured in the building industry. New building materials such as concrete, steel and glass found increased use in the field of construction - a shift from the traditional modes of construction in earth and stone. In later times, cheap energy and industrial production plants with good transport infrastructure have popularized the applications of these materials around the world. As a result, in the more developed nations and those on the road to industrialization, the skill and craftsmanship required in the traditional earth construction that were once a commonplace have become a rarity. Third world nations, particularly those with agrarian societies still build with earth. However, the technological and economic developments dictate the fate of earth architecture throughout the world (8).

Economic and technological boom have decorated the built form with a different kind of architecture that is now-a-days called modern and post modern architecture. In the wake of modernization, one is liable to forget the past, the history and the tradition where there used to be houses, monuments and mosques built in earth - the readily available local material. The energy crisis in 1973 along with increased cost of building materials have stimulated interests to go back in history and tradition in the field of construction that can be economic, energy conscious and at the same time preserve the tradition. In recent years, there has been a concentration in research and application in earth construction that is leading towards a renaissance. Apart from the Third-World countries, the countries blessed with technological resources are also showing increasing interest in investigating earth as an alternative building material. Perhaps, France could be cited as the most progressive in this field, where schools exist to carry out research and application in earth construction. Whilst some states in the U.S.A. have industrialized earth construction, making the mud bricks, and also adopted building codes. Continuous research is being carried out in India, Pakistan, Bangladesh, Sudan and other African countries where earth or mud construction is found to be thermally comfortable, economical for the low income groups that also keeps up with their tradition. (8)

In the context of Saudi Arabia, earth construction has a historical and traditional background. Throughout the Kingdom, there are examples of earth buildings which were once a part of the Saudi tradition and culture. But the economic boom in Saudi Arabia seems to have washed away the traditional construction forms with the import of concrete, glass and steel technology. However, it is time to put forward efforts to keep the traditional building forms alive in contrast with the modern architecture. This will be a constant reminder of the tradition of the built form to the generations to come. Research interests needs to be directed towards the revival of earth as a viable alternative building material that can, if not compete with the technologically developed materials and methods of construction, keep the tradition alive.

Recently the Kingdom has escalated its interest in traditional construction materials and contemporary architecture, and as such, mud architecture and construction is gradually taking great precedence. This is evident from the few design projects in mud being carried out and the Riyadh Traditional Exhibition on Mud Architecture held in 1988. However, very little research has been done on mud construction in Saudi Arabia.

The traditional background of earth structures in Saudi Arabia together with the increasing interest in its revival and the added advantage of its good thermal performance are the motivating reasons in undertaking this thesis. The work will attempt to locate possible sources of raw earth, collect samples and subject them to preliminary soil performance tests. Various types and proportions of additives will be investigated to prolong the life of the earth materials. To summarize, this study investigates earth construction in Adobe, it will recommend optimum soil-mix from the available sources for the production of compressed adobe bricks suitable for use in the geological and environmental context of the Eastern Province, and provide a working ground regarding production, costs and feasibility.

1.2 Objective

The objectives of this thesis are :

1. To review literatures of existing practices of Adobe Construction in Saudi Arabia and elsewhere around the world.
2. To study the mix proportions of soil and stabilizing agents and their effects on the quality and durability of the adobe bricks.
3. To study the economic feasibility of adobe construction.

1.3 Scope and Limitations

1. The research is limited to the investigation of soils from two sites in the Eastern Province of Saudi Arabia in Al-Qatif and Dhahran.
2. Variation of the soil mix proportions are based on the range suggested in literature.
3. The bricks are made by compression by a hand operated brick making machine.
4. Performance tests of the bricks are done after seven days of curing in the shade.
5. Additives that are used are added in different proportions as suggested in the literatures.

6. The performance of the bricks are determined by compressive strength and absorption.
7. Economic analysis takes into consideration the unit cost of producing compressed adobe bricks and comparing with other locally available building bricks.
8. And this study is reflective of the soil samples used herein.

1.4 Methodology

In the effort to develop, produce and disseminate the adobe know-how towards the revival of earth architecture, a part of the Saudi tradition and building, this research is categorized into the following phases.

A) Materials: Soil is the foremost ingredient of earth construction. Surveys are made to locate potential soil sites in the Eastern Province of Saudi Arabia, followed by collection of samples for tests. Samples are subjected to the following tests:

a) Sieve analysis (ASTM D421 and D422).

b) Atterberg Limits (ASTM 4318).

c) Specific Gravity (ASTM 4854).

d) Moisture content (ASTM D2216).

In accordance with the test results, soil mix proportions are recommended by compressive strength test on the bricks.

B) Additives: In adobe construction, a variety of additives are used with the soil mix as it tends to improve the quality and durability of the adobe bricks. A number of additives will be used with the soil to explor their effects on the bricks quality.

C) Feasibility: A feasibility study is performed to determine the cost of the adobe bricks and compare its unit cost with the other various types of bricks produced and available locally, such as Concrete Masonry Units, Calcium Silicate Blocks and Burnt Clay Blocks.

D) Conclusion and Recommendations: Based on the work outlined above, conclusion and recommendations are drawn on the use of adobe in the Eartern Province of Saudi Arabia. The summary of the work procedure is given in the flow-chart in Figure 1.1.

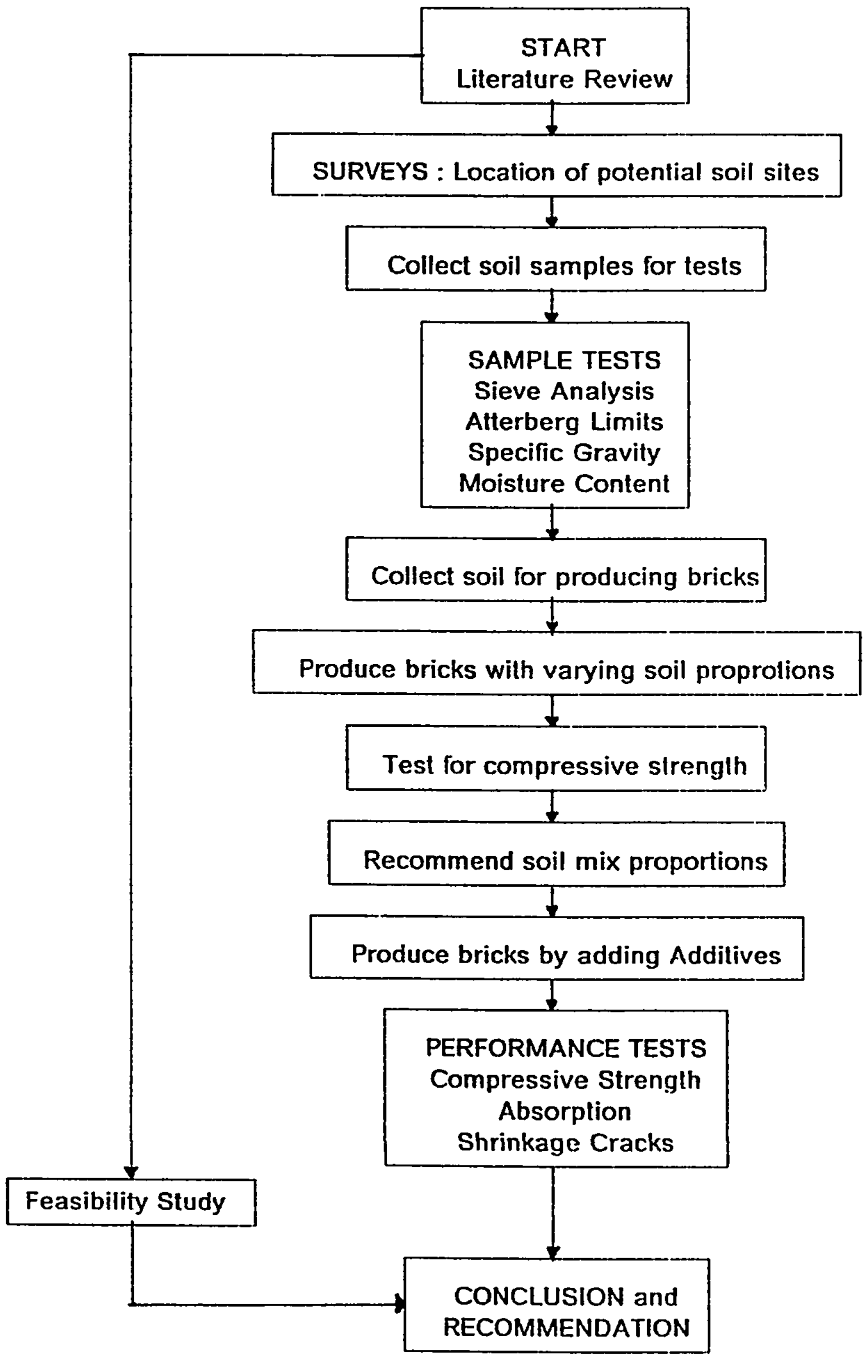


Figure 1.1 Flow-chart of work procedure.

1.5 Significance of this Thesis

This thesis will attempt to identify adobe construction as a viable construction method that can be equally important as other modern construction methods of concrete, glass and steel. Adobe construction should not be thought of as the only solution; it should rather be thought of as an alternative that for many reasons has been abandoned and superseded by modern construction methods. It is anticipated that this work will induce interest and create a greater acceptance of adobe construction in the minds of the public and professionals alike. This study will help those interested in building with adobe, in the selection of the material and the additive to produce quality and durable adobe blocks. Furthermore, it will help professionals extend studies beyond the scope of this research into other areas of the Kingdom and also into other various types of additives and their feasibility.

CHAPTER 2

LITERATURE REVIEW

2.1 Earth Construction : the various forms

Ever since mankind started building and living in mud houses, earth construction has further evolved throughout the passage of time. The innovative nature of mankind, his curiosity and need for better shelter enabled early man to cover brush and wood houses with mud plaster. It is this curiosity and need to investigate linked with varying cultural and traditional backgrounds that produced a variety of earth construction forms on different parts of the globe. The following are a few examples :

A. Jacal :

The earliest form of earth shelter constructions were called Jacal. This form of shelter ,in history, goes back as far as the archaeological investigations can take. Figure 2.1(a) shows a sketch of this type of shelters. These were mere outgrowths of shelter made from brush and sticks and covered with mud for water-proofing. Jacal was meant only for protection from adverse weather for otherwise outdoor oriented people. (18)

B. *Pit Houses* :

As the need for sophistication developed with growing human intellect Pit Houses were created. Used by the Hohokam farmers of the south-western United States (100-900 AD), Figure 2.1(b), these are dwellings that were partly underground, in a way similar to a cave. (18)

C. *Rammed Earth* :

A monolithic method of earthen construction formed by placing a soil mix between wooden or metal forms in layers to gradually build up the walls - as shown in Figure 2.2(a). It has been widely used in Australia, North Africa, France, Eastern Seaboard of United States and other humid climateregions. Rammed Earth construction is faster and usually does not require any additional plaster finish. (18)

D. *Adobe* :

The term of Spaniard and Arabic origin denotes sun-dried brick of a clay and sand mixture. These bricks are used to build walls, vauits and domes. The bricks can be made in moulds (wooden or metal) on the bare ground or with brick making machine that usually produces compressed bricks. Although making the adobe bricks in moulds on the ground is a faster process, the compressed brick is gaining more popularity because of its additional strength and reduced porosity. Shown in Figure 2.2(b) is an

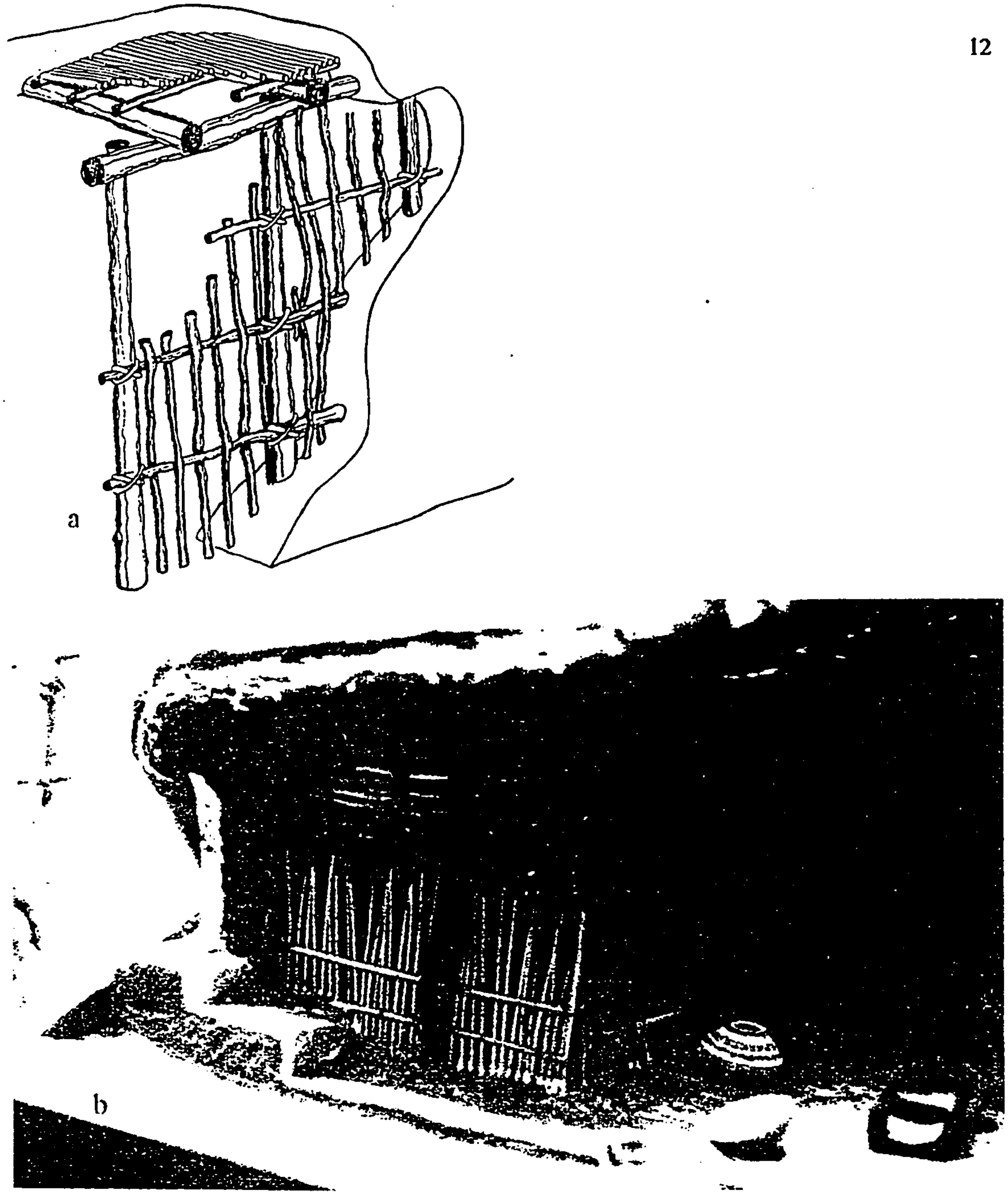
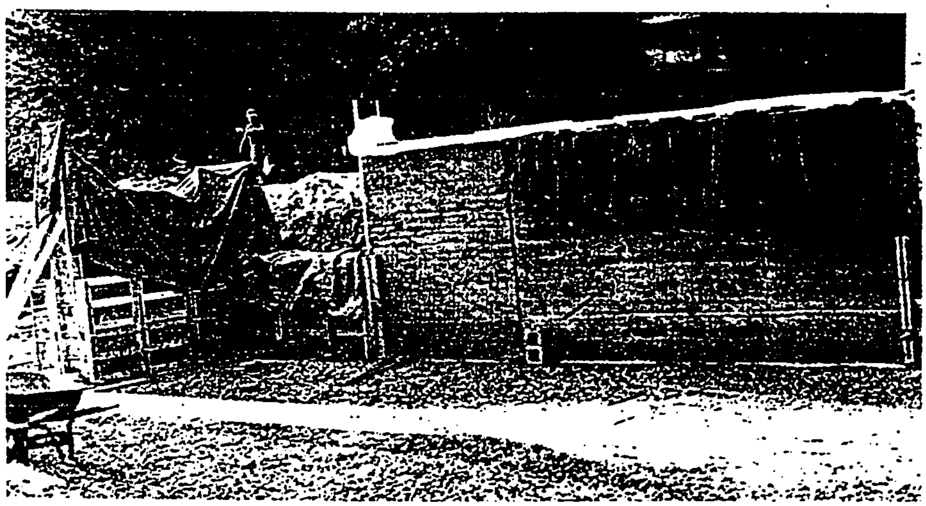
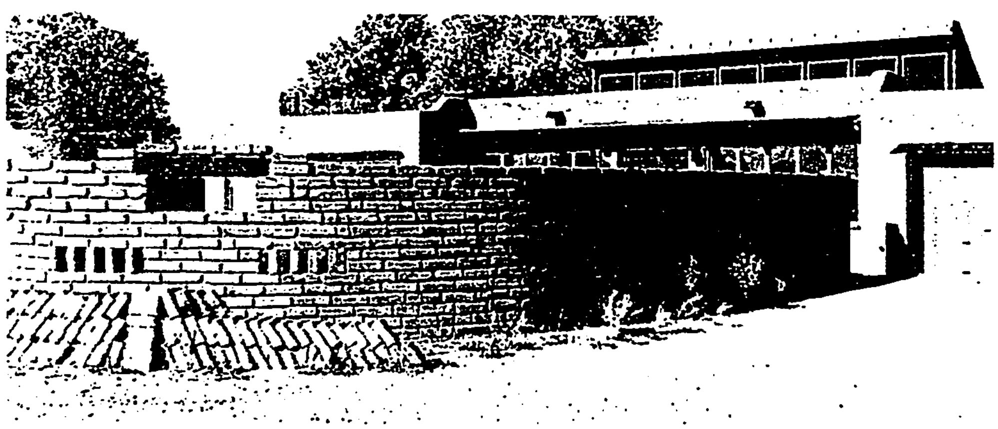


Figure 2.1 (a) Jacal, the earliest form of shelters, **(b)** Typical Pit House - cut away secttion. (18)



a



b

Figure 2.2 (a) Rammed Earth wall in construction. **(b)** A house built with adobe. (18)

example of a house bulit in adobe. Adobe has been very successful in the United States, France, Egypt and many other Third-World countries. (7)

Of all of the above forms of earth construction, Rammed Earth and Adobe are the most common. Rammed Earth construction has been used very successfully where the climate is humid and high precipitation prevents sun-drying of clay blocks of Adobe. Where the climate is arid Adobe has proven to be a more logical choice of construction method. The reasons for selecting adobe from the various earth construction methods for study are its popularity and the arid climatic condition of the Eastern Province.

2.2 Interests and Studies

Throughout the world continuous researches are being carried out on the various forms of earth constructions. Studies are done to improve the quality of earth forms. This section discusses the studies on the adobe bricks.

2.2.1. Constituent Materials Studies

The reviving interests in earth construction has triggered appreciable research and application in several countries, the pioneers being Egypt, France and U.S.A. It was architect Hassan Fathy whose endeavour revived interests in earth construction in Egypt. His studies were dedicated towards the technology and craftsmanship of earth roofing systems - the vault and the dome. An entire village, housing seven thousand peasants in Gourna, Egypt, with examples of earth vault and dome roofs is a success outcome of Fathy's studies (9). The School of Architecture of Grenoble, France has set up an 'Earth Laboratory' for basic researches on earth construction. At Grenoble, earth is studied as a prime construction material and research is carried out to draw up standards and rules for production and quality control of earth construction materials in France. Figures 2.3 and 2.4 shows photographs of works at Grenoble. (6)

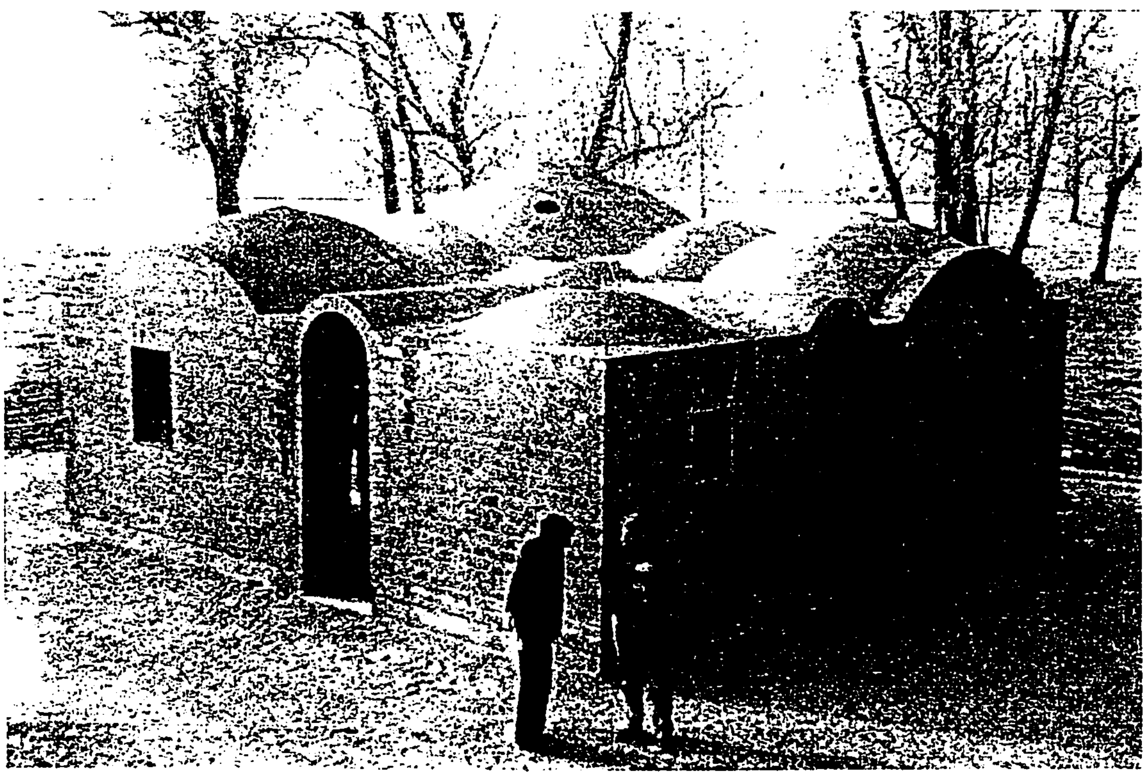


Figure 2.3 Example of an adobe house at Grenoble, France. (6)

Figure 2.4 Testing an adobe arch at Grenoble, France. (6)

The Gourna housing in Egypt - designed by Hassan Fathy is certainly one of the pioneer projects in earth construction of the modern times. The project was meant to be low cost housing but retaining qualities with the revival of the use of traditional architecture and construction methods. The soil used for the production of the bricks was a Nile silt deposit collected from the bank of Fadleya canal which was close to the site of construction. Since there can be a wide variability of the composition and properties of soil, Fathy suggested chemical and physical analysis of the soil prior to use in brick production and also carry out laboratory tests on sample bricks to determine the quality of the bricks in terms of compressive strength, shrinkage, behavior under wetting and drying and other physical properties. The soil used for the Gourna project showed a 37% shrinkage shortly after drying of the bricks made of the soil alone without any additives. Therefore, Fathy mixed sand and straw, as a binder, with the soil. After experimenting with different proportions of soil, sand and straw, Fathy came up with the following mix proportions :

Soil (Nile Silt) ...	1 meter cube ;
Sand ...	1/3 meter cube ; and
Straw ...	20 Kg

The bricks measuring 23X11X7 cms. were produced with the above mix proportions in molds without any mechanical device. Approximately 900 bricks can be produced from the above amount. Regarding stabilization of the soil, he warns that expensive stabilization methods can be totally unneccessary. Fathy gives an item by item cost data of the Gourna project that proves his point of cost effectiveness and architectural beauty and traditional revival as well. Shown in Figures 2.5 and 2.6 are two examples Gourna Housing. The housing is still in use. (9)

In constructing the Exhibit-Centre at Janadria, Riyadh with adobe the local soil from the same site was used. The project was undertaken by the Royal Commission of Jubail and Yanbu and was designed and constructed by the joint efforts of CRATerre, France and AlBenaa, architectural magazine group. Students from the College of Environmental Design of KFUPM also participated in the construction process. It is a 15.5 m by 15.5 m exhibit house in adobe which has four domes on the four corners. In making the bricks, the manually operative Platbrood F. brick making machine was used. Bricks were made by adding 6% of cement to the soil for increased strength and durability. Figures 2.7 and 2.8 shows construction at Janadria.

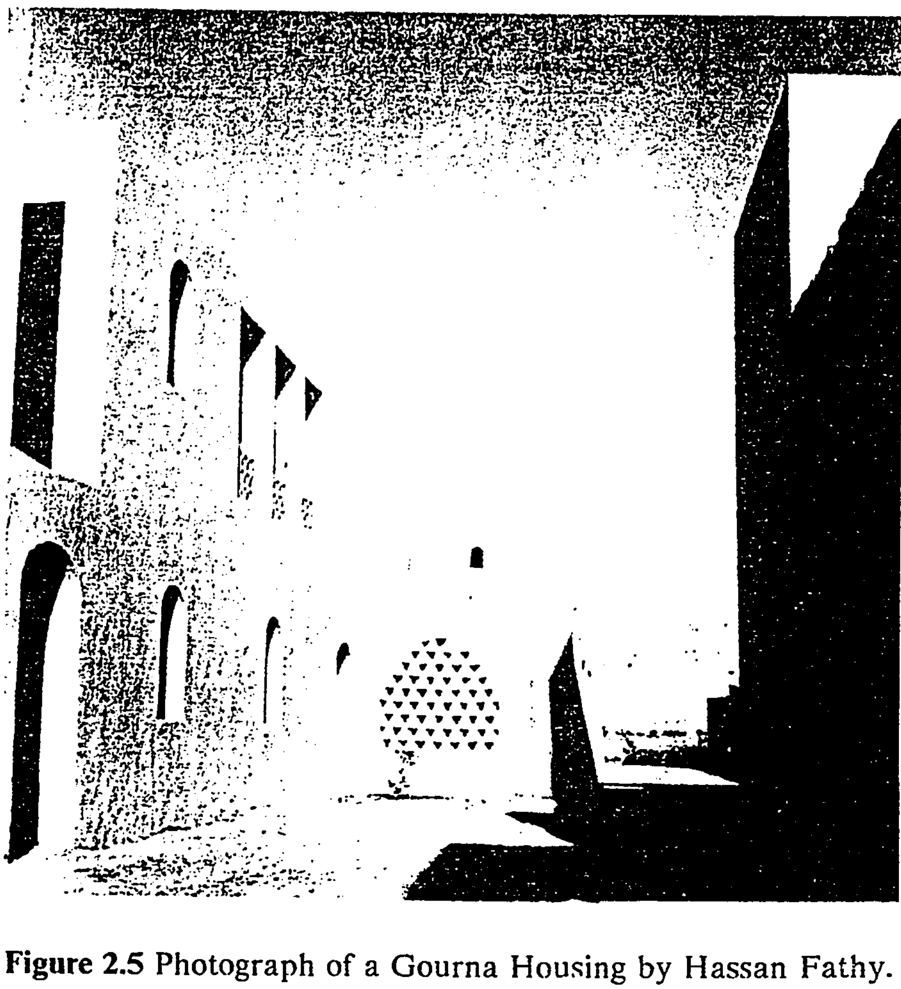


Figure 2.5 Photograph of a Gourna Housing by Hassan Fathy. (9)

Figure 2.6 Photograph of a street in Gourna Housing by Hassan Fathy. (9)

Figure 2.7 Example construction of Exhibit-Centre at Janadria, Riyadh - work above the arch.

Figure 2.8 Example construction of Exhibit-Centre at Janadria, Riyadh - making the dome.

Ahmed, et al (3) presented adobe blocks in providing low income housing in Pakistan. The bricks were made by adding certain percentage of cement with the soil to give additional strength of adobe. Ahmed, et al called it Soil-Cement Blocks. Soil-cement blocks have been used successfully in the developing countries of Africa, Asia, Latin America and other parts of the world. A Cinva-Ram block making machine was used for the production of the blocks. As a result the 12"X6"X4" blocks were dense and smooth-surfaced with square edges and corners and uniform in color. Almost any soil that is free from salt, rubbish and vegetable matter has been suggested for the block production. However, the soil most suitable for the soil-cement blocks is a well-graded soil consisting of fine clay, silt and sand in equal proportions. The soil should pass through No.4 (square) sieve and be free from stones, bricks etc. that are hard particles. The sand content can be increased if the soil contains inadequate sand. The physical properties of the soil used by Ahmed, et al were as follows:

Soil Type...	Sandy Silt
Specific Gravity...	2.65 - 2.63
Liquid Limit...	29 - 32
Plasticity Index...	6.7 - 11.0
Organic Content...	.11 - .14

Ahmed, et al suggested a cement content of 5% to 10% by volume depending on the use of the soil-cement. Cement is to be mixed by hand with the dry soil in small batches enough to make about 100 blocks. Water content was determined by the simple ball test on site. If a ball of the soil-cement squeezed between the hands can be broken in half with no crumbling and no moisture on hand, then the water content would be right. Curing time for the Cinva-Ram soil-cement blocks was 2 weeks and during the curing period water may be sprinkled 3-8 times daily depending on winter and summer conditions. Results of performance characteristics of the soil-cement blocks showed maximum increase in 28 day compressive strength with 6% cement content. A 10-15% sand content was found to be optimum. Sand content of more than 15% resulted in brittle and crumbling blocks. (3)

Mohan, De and Rai (19) in their research for new building materials experimented the possibility of sand-lime bricks and also stabilization of mud bricks with a mixture of rice-husk and lime-slug. However, no data has been presented as regards the performance of the bricks. For water-proofing of mud walls they devised a new technique of asphalt and kerosene mixture spray finish on the exterior which increased the life of mud walls against rain erosion by three to four years. The research also included laterite soil bricks stabilized with lime and lime-fly ash stabilized soil. The soil composition, the percentages of the additives and the curing conditions are not discussed in detail. But compressive strength results showed a high strength of 710 to 850 psi for laterite soil stabilized with lime after 28 days of curing. Whereas laterite lime-fly ash soil showed a low strength of 280 - 350 psi. Other low cost building materials in their research included bamboo reinforcements in cement concrete, wood-cement based board products etc. (19)

Hassan and Fatani (13) studied the feasibility of in-situ soils, copper mill tailings (suspended impurities from the copper ore treatment plant) and fly ash to produce low-cost and durable building bricks. The engineering properties of the materials are shown in Table 2.1.

As stabilizers Hassan and Fatani used 0%, 4%, & 6% of cement and Dow Corning-772, a chemical water-proofing agent composed of Sodium Methyl Siliconate, with the in-situ soil and a 50/50 copper mill tailings & fly ash. For test purposes, specimens of 7.62X15.24X5.08 cm were made, curing in the shade for seven days at about 70 degree F and 50 % relative humidity. Capillary absorption test was conducted by placing the specimens on a filter papers with water level upto 3 mm. above the base. After 24 hours, the bricks were weighed and oven-dried to determine the percentage of water absorption. Also surface absorption test was performed by recording the time it took to infiltrate 25 ml. of distilled water through the specimens on a diameter of 1.9 cm. For testing the effect Dow Corning solution, the specimens were surface treated with two coats of a 30:1 solution in water. After three days of curing the solution absorption tests were performed. Table 2.2 shows the results of compressive strength, surface and capillary absorption tests.

Table 2.1 Properties of materials used by Hassan and Fatani (13).

Properties	Soil	Tailings	Fly Ash	50% Tailings +50% Fly Ash
Sand, %	69	70	20	53
Silt, %	20	20	78	35
Clay, %	11	10	12	12
Plasticity Index	7.0	---	---	---
Specific Gravity	2.71	2.72	2.35	2.54
Max. Dry Density, g/cc	2.02	1.88	1.50	1.76
Optimum Moisture Content, %	8.5	12.5	15.7	13.5

Table 2.2 Performance of specimens done by Hassan and Fatani (13).

Material	Cement Content	psi	Surface Absorption Untreated	Surface Absorption Treated*	Capillary Absorption Untreated	Capillary Absorption Treated
Yaqui	0%	464	40 min.	0	11.5%	1.2%
Soil	4%	490	40 min.	0	11.8%	1.0%
	6%	810	55 min.	0	12.1%	0.8%
Tailing-	0%	276	35 min.	0	14.0%	0.9%
Fly Ash	4%	817	47 min.	0	15.5%	1.1%
Soil	6%	833	105 min.	0	12.1%	0.8%

* absorption in four hours.

Test results indicated far greater compressive strengths than the Uniform Building Code (UBC) requirements of 300 psi in both the in-situ soil and tailings-fly ash mix. The durability tests showed no surface absorption, no rain erosion and minimal capillary absorption when both the soil and tailings-fly ash mix were surface-treated with the Dow Corning-772 solution. (13)

Osman (20) studied the behaviour of a clayey soil treated with cement, hydrated lime and raw lime stabilizers. The soil used in this research had the following properties :

Sand...	65 %
Silt...	17 %
Clay...	18 %
Plasticity Index...	14
Max. Dry Density...	1.95 mg/cu. m.
Optimum Moisture Content...	11 %

The stabilizers were used in the proportions of 2%, 4%, 6%, 8%, and 10% by weight of dry soil. The stabilizers were mixed with the soil manually and tested in the laboratory for different properties. For the test purposes 15X15X15 cms cubes were made and cured in wet sand for 7 days. The performance tests indicated the tendency of increasing liquid and plastic limits with the additions of the stabilizers and a decrease in the plasticity index of the soil. The decrease in the plasticity index increases the workability of the soil. Also it was observed in th compressive strength tests that cement produced a noticeable increase in the crushing strength, while both hydrated lime and raw lime had very little effect on the crushing strength of the soil.

Figure 2.9 shows the effects of the stabilizers on the compressive strength of the bricks. The dry densities of the soil showed a reduction by about 10% with the addition of stabilizer contents increased from 0% to 10%. In addition, a 10% increase of the stabilizers increased the optimum moisture content by about 50% as compared to raw soil. (20)

Kafescioglu, et al (14) experimented with varying proportions of gypsum to produce adobe bricks. According to the writer, adobe blocks stabilized with gypsum plaster, which in short is called ABGS, is advantageous over other stabilizers such as cement, lime etc. Gypsum plaster requires less energy and mechanical equipment for production - gypsum being abundantly available on the earth. With gypsum stabilizer construction is possible shortly after the production of the bricks with no delays for drying and curing. The soil used for the production of the bricks had the following properties :

Clay	4 %
Silt	26 %
Sand	70 %
Liquid Limit ...	33 %
Plastic Limit ...	24 %
Shrinkage ...	15 %
Plasticity Index ...	9

Mixes made with gypsum/soil ratios of 0%, 5%, 10%, 15% and 20% and lime/soil ratios of 5% and 10% and effect of addition of 2.5% and 5% lime with 10% gypsum were investigated. The method of mixing found most

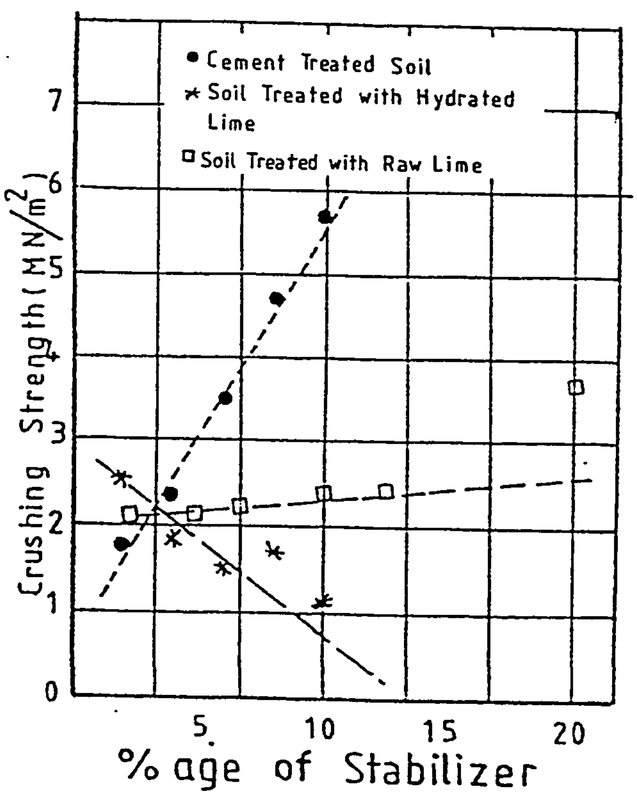


Figure 2.9 Compressive strength versus percentage of stabilizers. (20)

convenient in this case was wetting the soil into mud - water added was about the plastic limit of the soil. Then a one to one gypsum water slurry was added to mud. Mixing and molding was to be done quickly as the mixture of gypsum and mud sets within 5-10 minutes. From the test results it was concluded that improving effects of gypsum were observed with gypsum/soil ratios of 10% and above. 28 days compressive strengths on 70 mm cubes with 10 % gypsum noted 4.45 N/square mm - which is nearly double than that of adobe. Gypsum-lime mix caused a slight decrease in the strengths. Although adobe stabilized with gypsum/lime did not have any effect on the water resistance capability, the compressive and flextural strengths recorded a two to three folds increase, while shrinkage decreased by three to four folds as compared to untreated adobe. (14)

Kahtany (15) in his search for Indigenous building Materials and Construction Methods in Saudi Arabia discussed the mud brick technology as it prevailed in the South-West of Saudi Arabia, the traditional construction process and suggested ways for preservation and improvements by inducing public awareness, preservation programs, government awareness and introduction of modern technology to make room for improvements. (15)

In an effort to come up with cheaper adobe bricks Uzomaka (25) used three types of soils. The soil properties are shown in Table 2.3. Three types of additives : akwara fibre, coir fibre and straw were tested with the soil.

Table 2.3 Properties of soil in Uzomaka's research (25).

Properties	Silty Clay	Sandy Silt	Silty Sand
Sand, %	20	60	84
Silt, %	35	40	16
Clay, %	45	0	0
Liquid Limit, %	79	67	33
plastic Limit, %	34	28	20
Specific Gravity	2.60	2.72	2.60
Max. Dry Density, Kg/cubic m	1633	1501	1878
Optimum Moisture Content, %	23	26	16

Akwara fibre was obtained from raffia palm in lengths of 1.5 m. found in circular, rectangular of elliptical cross-sectional shapes. These were then made into rings found to give better results. Coir fibre was obtained from coconut husk - the outer-coating of the nut and straw commonly found as packing straw. The fibres were mixed with the moist soil just before the moulding of the bricks. Mixing of the fibres were not very effective as the fibres tended to adhere together. (25)

Bricks were made with a hand operated compaction machine. Preliminary tests of 28 days compressive strength of bricks made from the silty clay, sandy silt and silty sand soils showed 3.8, 2.8 and 1.7 N/square mm respectively. Since clay bricks appeared promising in terms of compressive strength further studies with additives were carried out with clay soil only. Although the intention of the research was to study the effects of the fibres, cement upto 5% with silty clay and silty sand soil bricks, tests indicated a decrease in strengths of clay bricks with increasing cement percentage and increase of strengths of the silty sand bricks. With 5% cement, both the soils showed the same strength of 3.4 N/square mm. (25)

Effects of drying conditions were also studied by Ozumaka. Figure 2.10 shows the compressive strength as the drying conditions were varied. It is evident that better strength development occurs when drying is done under shade. Shown in Figure 2.11 are the compressive strength test results of the

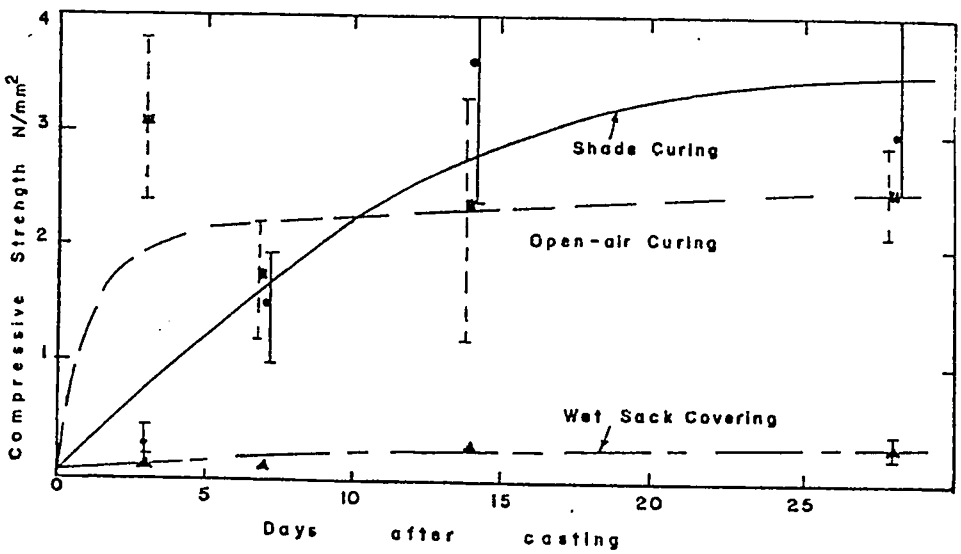


Figure 2.10 Effect of drying condition on compressive strength. (25)

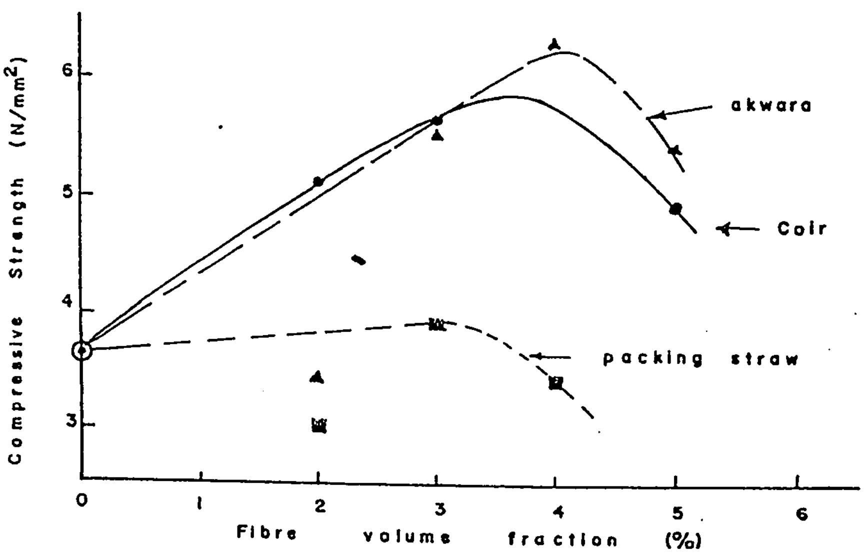


Figure 2.11 Compressive strength of fibre stabilized clay bricks. (25)

bricks with the fibres - cured under shade. Shrinkage cracks were found to have considerably reduced in the stabilized bricks than those of plain clay bricks. Although bricks with akwara fibre showed higher strengths, it was suggested that coir fibre should be used instead. The suggestion was made based on lower cost and easier handling of coir fibres. (25)

In his research for the development and use of cheap building material for low-income population group, Gohar (11) suggests various alternative building materials. The use of mud bricks, clay burnt bricks, clay tiles, lightweight concrete aggregate, wood and bamboo materials have been studied including methods of improvement of quality of these materials. To overcome the susceptibility of erosion, dampness and short life span of mud bricks, cow dung, grain husk, bitumen are suggested to be mixed with the mud. His research also suggests the improvement of compressive strength and water resistance while stabilizers such as cement and lime are used. (11)

In a comparative cost study, Gohar studied three alternative methods of construction shown in Table 2.4. Alternative 1 uses mud-based material with thatched roofing. In Alternative 2 mud-based material, clay burnt bricks, cement and asbestos sheet roofing have been used. While Alternative 3 uses clay burnt bricks, cement-fly ash mortar with concrete roofing. Cost study shows Alternative 1 with US Dollars($) 36.00 per square meter as most economical. Costs of Alternative 2 and 3 are $ 64.00 and $ 96.00 per square meter respectively. (11)

Table 2.4 Alternative Cost Studies by Gohar.(11)

Construction Component	Materials used
(a) Foundation	
Alternative 1	Excavation in ordinary soil, 9 inch (179 mm) mud mortar and brick aggregate in foundation, stabilised mud blocks or mud brick in mud mortar upto plinth.
Alternative 2	Excavation in ordinary soil, 9 inch (179 mm) mud mortar and brick aggregate in foundation, burnt clay brick in mud mortar upto plinth.
Alternative 3	excavation in ordinary soil, 9 inch (179 mm) lime-surkhi-brick aggregate, burnt brick work in cement-fly-ash mortar upto plinth.
(b) Walls	
Alternative 1	Mud blocks, mud brick in stabilised mud mortar, plastered on both sides with bitumen sprayed on external surfaces and two coats of lime wash.
Alternative 2	Brunt clay brick in stabilised mud mortar, cement-flyash mortar on both sides, with 3 coats of lime wash both sides.
Alternative 3	Brunt clay brickwork in cement fly ash mortar, plastered both sides, with 3 coats of lime wash both sides.
(c) Roofing	
Alternative 1	Thatch roof or sloping roof of burnt clay tiles on wooden beams and battens.
Alternative 2	Asbestos sheet roofing (sloping) or stone slab roofing with wooden beam and battens (flat) with stabilised mud plaster finish.
Alternative 3	Reinforced brick roof or reinforced concrete roof with proper terrace finishes.
(d) Flooring	
Alternative 1	Stabilised mud blocks with stabilised mud finish.
Alternative 2	Brunt brick on edge flooring pointed with cement mortar.
Alternative 3	Cement concrete flooring finished with cement mortar.

Table 2.4 Continued. Alternative Cost Studies by Gohar (11).

Construction Component	Materials used
(e) Doors and Windows	
Alternative 1	Secondary wood, doors without frame, painted with side, with ordinary fitting, window of brick or terra-cota jalli.
Alternative 2	secondary wood door and window frames and shutters. painted both side, glass used for window.
Alternative 3	Second class teak wood doors and window frames and shutters painted both side, glass used in windows.
(f) Sanitation	
Alternative 1	One hand flush seat with soak pit arrangement, two water taps with open drainage system.
Alternative 2	One flush seat with leaching pit-system, two water taps with open drainage system.
Alternative 3	One flush seat with proper sewerage system, two water taps and underground draining system.
(g) Electricity	
Alternative 1	Battened wiring system with 3 points.
Alternative 2	Battened wiring system with 3 points.
Alternative 3	Concealed conduit wiring system with complete fittings.
(h) Costs	
Alternative 1	$ 36.00 per square mmeter (approximately).
Alternative 2	$ 64.00 per square meter (approximately).
Alternative 1	$ 96.00 per square meter (approximately).

Recounting the major disadvantages of mud as a building material, namely low tensile strength, easy erosion due to water and wind, susceptibility to damage etc. Agarwal (2) suggested ways of preventing them according to local climate and rainfall condition. These preventive measures are shown in Table 2.5 published by The Building and Road Research Institute at Kumasi, Ghana. The table suggests as a general principle the protection of walls and foundations as the climatic condition changes from dry to wetter. Thus roof overhanging for the protections of walls may not be necessary in the dry areas such as the Middle East. But it becomes necessary in regions with higher annual rainfall.

Research regarding soil stabilization included cement, bitumen and lime. Agarwal (2) suggested various cement percentage depending on the clay content of the soil. Recommendation regarding cement content is as follows :

Composition of soil		Cement required %
sand %	clay %	
70	30	8
60	40	12
50	50	15

In stabilization with asphalt, best mix suggested by Agarwal (2) is 4-6% to high sand content soil, 7-12% to medium sand content and 13-20% with high clay content soil. One advantage of adding asphalt is greater brick durability, better water-proofing and insect-proofing as well. Stabilization with lime has been suggested where the clay content is more than 50 percent.

Table 2.5 Preventive Measures in Different Climatic Conditions. (2)

Climatic Conditions	Common Defects	Preventive Measures
A. Desert and semi-arid area with annual rainfall less than 10 inches.	1. Settlement and shrinkage cracks but not extensive. 2. Erosion of walls caused by wind laden with sand. 3. Mechanical damage.	1. Good soil selection — sandy clays or clayey loams or gravely clays. 2. Provision of non-erodable rendering such as lean concrete plasters. 3. Planned layout. 4. Improved workmanship. 5. Loans scheme in cash or in kind for preventive measures.
B. Dry areas with annual rainfall of 10-30 inches.	1. Settlement and shrinkage cracks. 2. Erosion of walls by wind or rain. 3. Mechanical damage.	1. Good soil selection — sandy clays or clayey loams or graveley clays. 2. Provision of non-erodable and waterproof rendering such as lean concrete or soil cement plaster. 3. Planned layout with good drainage facilities. 4. Good roofing and long overhanding eaves. 5. Improved workmanship. 6. Loans scheme in cash or in kind for preventive measures.
C. Wet areas with rainfall of 30-50 inches.	1. Settlement and shrinkage cracks — very extensive. 2. Erosion of walls and foundations. 3. Underscouring. 4. Mechanical damage.	1. Good soil selection — sandy clays or clayey loams or graveley clays. 2. Planned layout with good drainage facilities. 3. Concrete aprons and platforms around building. 4. Vertical down pipes and rain gutters. 5. Good roofing, long overhanding eaves or verandahs. 6. Provision of waterproof and non-erodable rendering. 7. Improved workmanship. 8. Loan scheme in cash or kind for preventive measures.
D. Extremely wet areas with rainfall above 50 inches.	1. Severe settlement and shrinkage cracks. 2. Erosion of walls and foundations. 3. Underscouring. 4. Mechanical damage.	1. Good soil selection — sand clays or clayey loams or graveley clays. 2. Planned layout with good drainage facilities. 3. Concrete footings, concrete blocks, soil-cement and stones for foundation. Where the annual rainfall is 80 inches and above, it is desirable to have foundation height extending to at least two feet above ground level. 4. Damp-roof course. 5. Concrete platforms and aprons around building. 6. Vertical pipes and rain gutters. 7. Verandahs with floors designed in such a way as to throw outwards the water from driving rains; desirable for areas with frequent driving rains. 8. Good roofing and long overhanding eaves. 9. Provision of waterproof and non-erodable rendering. 10. Loan scheme in cash or in kind for preventive measure.

Lime reacts chemically with clay thus strengthening the soil. Lime is available in most countries in calcium carbonate (Chalk, Limestone, Coral, etc.) which can be used economically on a small scale. (2)

2.2.2. Thermal Studies

Several studies have been done on the thermal performance of adobe. Robertson (22) discusses the thermal performance of walls with emphasis on adobe. The research was done by the Southwest Thermal Mass Study (SWTMS) on the thermal performance of adobe. Robertson defines thermal mass as that which "consists of massive (usually high density) materials, within a building or as part of a building envelope". A thermal mass is capable moderating heat flow through the walls - a significant reduction and delay of daily heat pulse will be achieved from one side of a wall to the other side. This phenomenon also occurs in light-weight walls but in a much lesser degree. (22)

The SWTMS research project involved eight simple and well-instrumented buildings of 20′ by 20′ and 8′ high of four construction materials; such as adobe, insulated wood frames, milled log and concrete that included five adobe buildings of both "traditional" and stabilized bricks with wall thicknesses of 10", 14" and 24". To study the behavior of the walls explicitly, the building initially had no openings (windows, doors, etc.), highly insulated floors and ceilings and uninsulated adobe walls. Afterwards, openings were added to four buildings and one adobe building was insulated. The study answered some of the questions as to the steady state R value of adobe and thermal mass performances. (22)

The steady state R, unit resistance, value of adobe walls with 1/2″ mud plaster on each side of the walls were calculated using long term averages of wall heat flow and surface to surface delta T. The walls were well cured with moisture content of less than 2.0 % by weight for 10″ and 14′ walls and 3.0 % for the 24″ walls. The results obtained were as follows :

for 10″ Wall...	2.0 hr.X ft square X degree F / Btu
for 14″ Wall...	2.7
for 24″ Wall...	4.4

These R values represent the particular type of adobe used for the SWTMS Project. The R value will vary with the density of adobe - higher R value for lower density adobe bricks. The density of adobe, apparently, varies between 90 and 120 lb/ft cube. The adobe bricks for the SWTMS study had a density of 117 lb/ft cube. The low R values of 2.0 to 4.4 means high conductivity which is desireable for passive solar applications - more heat can be absorbed, stored and released in the daily solar cycle. Of course, the exterior walls should be well insulated. (22)

The performance of thermal mass and heat transfer characteristics has been summarized in Figure 2.12 - three plots of heat loss versus time that demonstrate the effects of mass and insulation on heat flow through a wall. The plots were obtained with the assumption that the wall is losing heat continuously (in midwinter), the interior temperature is set constant and the outside wall surface has an exposure to a sinusoidally varying temperature. The first curve of Figure 2.12 shows the heat loss pattern that is similar to an uninsulated wood frame wall. The second curve represents the heat loss pattern of 10" uninsulated adobe mass wall. The third curve presents the behavioral heat loss pattern of idealistic insulated mass wall. A 10" well insulated adobe wall has the heat loss pattern that is similar to the third curve. The thermal mass study by SWTMS has focussed , primarily, on residential construction. However, it may also be applicable to small scale commercial buildings. (22)

Hassan and Fatani (13) performed a thermal conductivity test of the adobe bricks made with Yaqui soil and tailing-fly ash. Bricks were also tested with 4 and 6% of cement added as stabilizer. Table 2.6 shows the test results. As it is observed, the thermal conductivity of the bricks in both the cases are lower than that of burnt clay bricks. This indicates that, from heat conservation point of view, compressed adobe bricks are a better material.

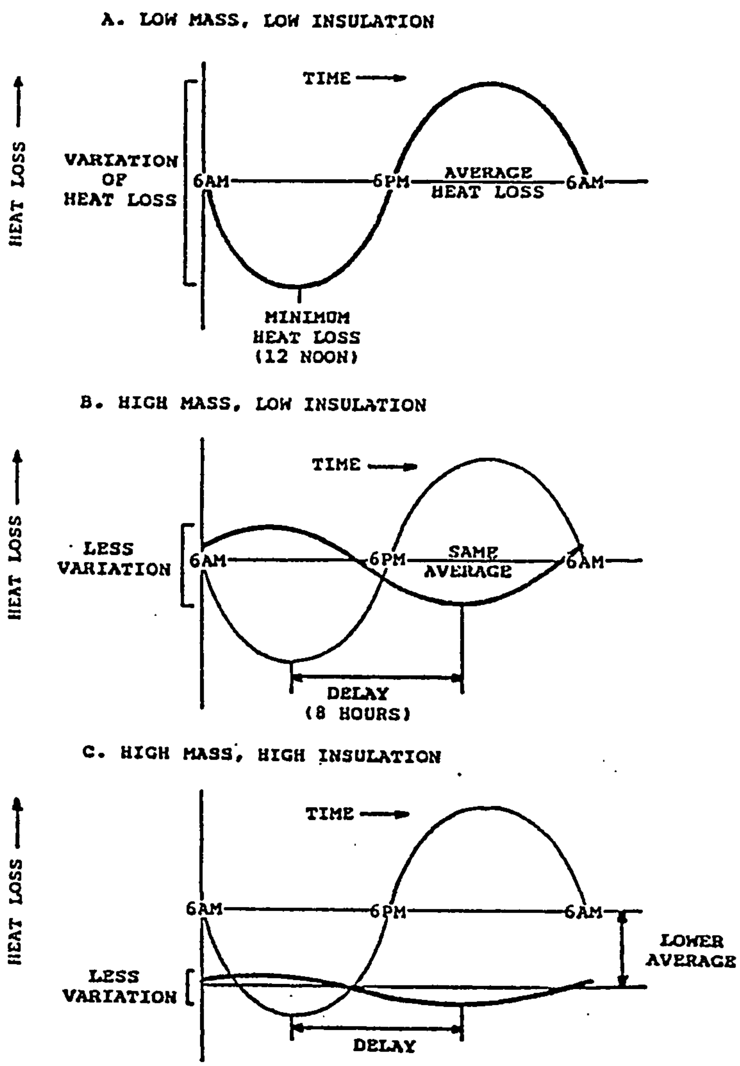


Figure 2.12 Effects of mass and insulation on wall heat loss.(22)

Table 2.6 Thermal conductivity test results by Hassan and Fatani. (13)

Material	**Cement** %	**Thermal Conductivity, k** BTU-in/hr. ft square degree F
Yaqui soil	0	3.35
	4	2.70
	6	3.07
Tailing-Fly Ash	0	3.15
	4	3.93
	6	5.43
Burnt Clay bricks	--	*6.70*

Agarwal (2) collected a whole array of thermal performance values of adobe, rammed earth, common clay brick, concrete, etc. which are presented in table format in Table 2.7 and 2.8. Increasing interest has been placed on thermal studies of mud based building materials specially adobe due to the rising energy costs as adobe has an ability to store energy and stabilize temperature giving the thermal mass effect.

Table 2.7 Thermal Conductivity of Walling Materials. (2)

Material	"k" BTU-in/hr. ft square degree F	Source
Rammed Earth	4.70	Univ. of Saskatchewan
Pressed bricks or blocks	4.70	Assumed
Adobe blocks	3.50	Univ. of California
Adobe-sundried bricks	3.58	Univ. of California
Stabilized adobe bricks	4.00	Univ. of California
Common clay brick	8.00	Building Research Station, U.K.
Limestone	10.60	National Physical Laboratory, U.K.
Dense concrete	7.00	National Physical Laboratory, U.K.

Table 2.8 Overall Heat Transmittance Coefficients (air to air), U. (2)

Type of Walls	Over-all Transmittance Coefficients, U BTU,hr.,ft square, degree F Temp. Diff. for wall thickness					
	6″	9″	10″	12″	14″	18
Pressed brick or block	0.41	0.32	0.31	0.28	0.26	0.22
Rammed in situ	0.41	0.32	0.31	0.28	0.26	0.22
Adobe brick or block	0.34	0.27	0.26	0.22	0.20	0.16
Stabilized Adobe	0.38	0.30	0.27	0.24	0.22	0.18
Common brick		0.44			0.35	
Concrete	0.50	0.42	0.39			

2.2.3. Effects of Additives

Various types of additives have been used in research and studies in order to produce better adobe bricks. The performance criteria is basically based on the compressive strength, absorption and shrinkage cracks of the bricks. In some cases results on absorption and shrinkage were not given. Although the idea behind using additives is to improve the quality of the bricks, some additives showed very little improvements. This section summarizes the effects of additives on various soils, which are shown in Table 2.9.

Table 2.9 Summary of various additives' performances.

Additives	Soil Type	Performance
Cement (13)	Clay 11% Silt 20% Sand 80%	6% cement increases compressive strength from 464 psi with no cement to 810 psi. No marked improvements in absorption. Absorption is negligible when treated with Dow Corning 772 solution.
Cement (13)	Clay 12% Silt 35% Sand 53%	Compressive strength increases three fold with both 4% and 6% cement. No absorption when treated with Dow Corning solution.
Cement (25)	Clay 45% Silt 35% Sand 20%	Reduction in strength occurs as cement is increased from 0% to 5%.
Cement (25)	Clay 0% Silt 35% Sand 65%	Strength increases with maximum at 5% cement content.
Cement (20)	Clay 18% Silt 17% Sand 65%	Strength increases as cement is added by 2,4,6,8 and 10%. Maximum strength gain occurs with 10% cement.
Cement (3)	Sandy Silt	Maximum strength at 6% cement. 24 hours absorption varied between 20.5 and 31.5%.
Raw Lime (20)	same as above	Very little increase of strength.
Hydrated Lime (20)	same as above	Decrease in strength as more hydrated lime added.
Gypsum (14)	Clay 4% Silt 26% Sand 70%	Strength increases by two times with 10% gypsum. No marked effect on absorption.

Table 2.9 Continued - Summary of various additives' performances.

Additives	Soil Type	Performance
Lime (14)	same as above	Strength increases by two times with 10% lime. No marked effect on absorption.
Gypsum-Lime mix (14)	same as above	Slight decrease in strength occurs than that with 10% gypsum alone.
Lime (19)	Laterite soil	Higher Compressive strength of 710-850 psi is observed.
Lime-Fly ash (19)	same as above	Low strength of 280-350 psi.
Straw (9)	Silty Clay	Optimum strength obtained with 20 kg straw when added to 1 cubic meter soil and 1/3 cubic meter sand.
Straw (25)	Clay 45% Silt 35% Sand 20%	Decrease in strength with 2% and 4% 3% gave same strength as that without additives.
Akwara fibre (25)	same as above	Increase of strength. 4% fibre gave maximum strength, 6.3 N/sq.mm.
Coir fibre (25)	same as above	Increase of strength. 4% fibre gave maximum strength, 5.8 N/sq.mm.

Chapter 3

SOIL SELECTION CRITERIA

3.1 Soil Sites

For adobe construction, the soil is required to have some amount of clay contents as it is evident from the various publications on soil as a construction material. Despite being the land of deserts Saudi Arabia has considerable soil deposits spread throughout the Kingdom that can be utilized for adobe construction. Extensive studies has been carried out by Al-Tayyib, et al (24) to designate the locations of soil throughout the Kingdom. Figure 3.1 shows the map of promising soil deposits. There are several locations of Clay and Marl deposits in the Eastern Province spread over the Qatif, Al-Hasa, Dammam, Dhahran and Jubail areas.

The soil most suitable for adobe construction should constitute of coarse sand or aggregate, fine sand, silt and clay. The total absence of one of these constituents may still make the soil satisfactory for adobe bricks. These constituents can be seen to be analogous with aggregate, sand and cement of concrete construction.

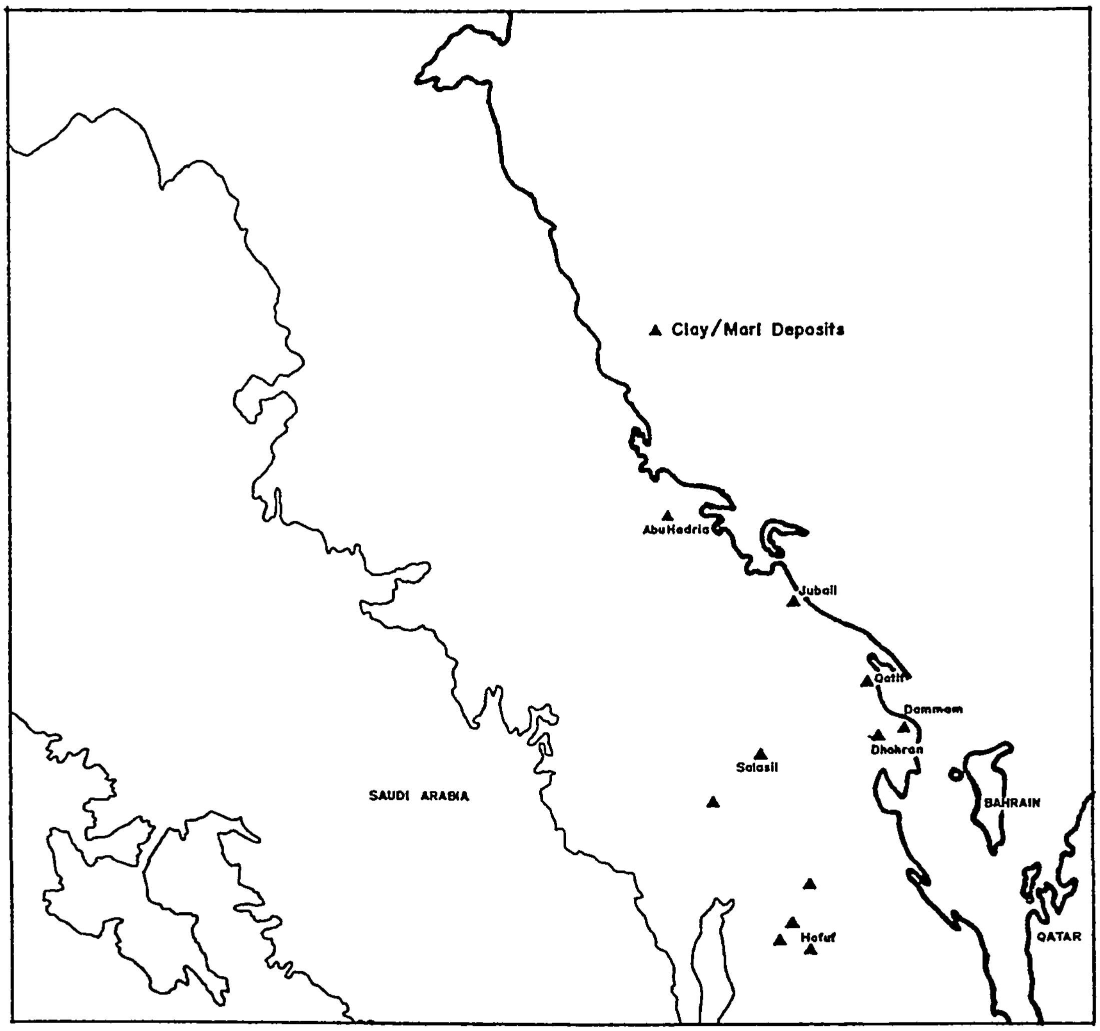


Figure 3.1 Map of potential soil locations.(24)

In concrete construction aggregate gives the strength, sand is the filler and cement is the binder. In the case of adobe, coarse sand or aggregate provides the strength, fine sand fills and locks the grains of coarse sand and silt and clay acts as the gluey binder. As in concrete construction appropriate proportions of the constituent materials are required for proper strength, so is the case in adobe construction. A high sand content may make strong bricks but they may be vulnerable to erosion due to rain and wind. On the other hand, a high clay content may make erosion resistant bricks but they may have less structural strength. (17)

Soil deposits occurring naturally may widely vary in their sand, silt and clay contents. Therefore, before selecting and using the soil for adobe construction, it must be subjected to tests for particle size, clay content and type. The US Department of Interior and National Park Service performed such tests on successful adobe structures that had used a wide range of the constituent materials. This leads to the conclusion that modifications of the soil acquired from their deposits may be needed to produce adobe bricks. (17)

3.2 Soil Constituents

As the constituents of various soil deposits may vary McHenry (17) suggested the following brackets of soil constituents suitable for adobe construction :

Sand	55 - 75	%
Silt	10 - 28	%
Clay	15 - 18	%
Organic Materials	< 3	%

Various studies done on adobe construction discussed in the Literature Review used a similar constituent proportions of soil for their researches.

For this thesis, two locations were selected for the collection of soil samples from the sites identified by Al-Tayyib (24). One sample was collected from Qatif. The other sample was collected from Dhahran. Qatif soil has been collected from near the Qatif Hospital on the Dammam-Jubail highway and Dhahran soil has been collected from Doha. These soil samples were then subjected to the preliminary tests for identifying their suitability. The tests performed for preliminary identification were Sieve Analysis, Atterberg Limits and Specific Gravity. The test methods and results are discussed below.

3.3 Test Methods

3.3.1 Laboratory Tests

To determine the soil type and quality, there are numerous tests specified by ASTM Standards. For this research, sieve analysis, Atterberg limits and specific gravity tests were performed. These tests are a good indicator of the soil quality.

A) Sieve Analysis - It is a routine test to determine the grain sizes of the soil. Basically there are two sieve analysis methods - the dry method and the wet method. While the dry method is used for coarser materials; such as sand, aggregates etc., the wet method is more accurate for finer materials; such as clay, silt. There are ASTM Standards D421 and D422 for sieve analysis for both dry and wet methods. (5)

B) Atterberg Limits - For the soil to be used in making the adobe bricks, it is necessary to test the plasticity of the soil and the liquid and plastic limits as well. These tests enable to determine the amount of water to be added for the soil mix. ASTM 4318 Standard is the specified test method for liquid and plastic limits. (5)

C) Specific Gravity - It is the measure of average value of the soil grains. Specific gravity of any substance is defined as the unit weight of the material divided by the unit weight of distilled water at 4 degrees Celsius.

Method of determination of specific gravity is specified by ASTM Standards D854.(5)

D) Moisture Content - Determination of moisture content is a routine test to find out the amount of water present in the source soil that is to be used for making adobe bricks. The water content is expressed in percentage of the dry weight of the soil samples collected from the potential sites. This test helps in determining the amount of water to be added during the production process of adobe bricks. If the moisture content of the source soil is high, a low amount of water would be required for the soil-mix. The reverse would be true for a low moisture content. In Saudi Arabia, there are locations which are high above the sea level and exposed to the dry atmosphere. However, if the soil source is along the sea level, then a moisture content test should be performed. ASTM D2216 Standard is the specified moisture content test method. (5)

3.3.2 Other Local Site Tests

Besides the above tests to determine the quality of the soil, in terms of gradation, clay content, Atterberg limits etc. in laboratory set-ups, there are simple tests that can be performed on the field site. These tests become handy and quicker where laboratory tests are not available. The following are the two field tests suggested by McHenry (17).

A) Jar Test - A glass jar is approximately half-filled with the soil to be tested and then water is added to fill three-forth of the jar. The jar is then shaken to disturb the soil and then allowed to set until the top water layer becomes clear. After settling, that may take about 24 hours or more, the various soil ingredients will form layers of sand, silt and clay with sand at the bottom, silt and clay in successive top layers. The height of these layers will indicate the approximate relative proportions of the soil ingredients. (17)

Rope Test : This is another simple field test that can be used to determine the clay content and plasticity of the soil. It is similar to that of Atterberg Limits Test but done on field. A stiff lump of mud is made with mixing small amount of water to a sample of the soil. The lump is then rolled in hand to a rope like shape about 2 cm. in diameter. The clay content of the soil is indicated by the plasticity of the soil-rope and its after dry cracking. If the rope remains intact after drying and no cracking occurs, then the soil is considered to be good for adobe bricks. (17)

3.4 Additives

The inherent drawbacks of Adobe are durability, need for frequent repair, erosion caused by wind, rain and permeated salt. Also adobe bricks (bricks in general) have low tensile strength which means the roofs are difficult with adobe except for the geometric shapes of vault and dome.

Therefore, it is essential to improve the quality of Adobe by devising ways to deal with these shortcomings. Using additives in the soil-mix that acts as 'Stabilizers' is common practice to improve the quality and durability to a greater degree. The possibility of various additives are enormous - the following list is indicative of the possibilities:

a) Lime,

b) Cement,

c) Gypsum,

d) Straw,

e) Bitumen Emulsion,

f) Polyvynile Chloride,

g) Natural & Epoxy Resins,

h) Silicone Solution,

i) Palm Tree Fibre, etc.

In the various studies done on adobe with additives, it is seen that the same additive has different effects on different soils. As the soil changes the performance of additives also changes. But cement is found to have a better effect on the adobe bricks. From the above mentioned additives Polyvynile Chloride, Natural & Epoxy Resins and Silicone Solution can be quiet expensive, this research includes only the locally available Bitumen Emulsion, Palm Tree Fibre and Cement as the additives to produce the adobe bricks and exploit the advantages of these additives in producing quality adobe bricks. The additives are discussed below :

3.4.1 Bitumen Emulsion :

Asphalt base emulsion is an excellent material for water-proofing and damp-proofing in various stages of construction and maintenance. Very little is known about the use of bitumen emulsion as an additive for adobe bricks. Mohan, De and Rai (19) used asphalt with kerosene as a mixture spray on finished mud walls, Prakash and Singh (21) and Agarwal (2) suggested the use of emulsion as an economic additive. The intention of this research is to examine the effect of emulsion if mixed with the soil during the production of the bricks. Bitumen emulsion is produced in Saudi Arabia as a product of the petroleum industry.

There are several asphalt and emulsion manufacturing industries in Saudi Arabia. One of the firms was contacted for their emulsion product. There are a number of bitumen emulsion produced by this firm that can be used. The brand names of these products are as follows :

i) Everlast-H, Multipurpose Asphalt Emulsion;
ii) Everlast-LTX;
iii) Super Everlast LX; and
iv) Everlast-LX.

The variation in these products are due to the difference in binder content and latex content. Of these products only Everlast-H is used in this research which was supplied by the firm.

3.4.2 Cement :

As it is observed, in the various studies, cement acts as very good stabilizer. In one case, where the native soil had a very high clay content (25), cement had a negative effect on the compressive strength if the soil is used in its native state. However, in soils with clay content between 11% and 18%, cement acts as a very good additive that increases the compressive strength considerably. Therefore, cement has been used as the second additive in this research to see its effect on the local soil.

3.4.3 Palm Tree Fibre :

Palm tree is the abundantly grown tree in Saudi Arabia. The tree has been used in constructing the roofs of traditional houses. However, very little has been done about the use of this abundantly available tree in the building industry as a processed material. Uzomaka (25) used raffia palm fibre to produce adobe bricks. But he suggested the use of coir fibre based on economic viability as coir fibre is cheaper and produces bricks of a little lower compressive strength than those with palm fibre. In a Civil Engineering project sponsored by KACST (unpublished), the local palm leaf fibre was used as an alternative for sound insulating boards. In this research, the stem of the leaves is used as a fibrous material with the soil as a potential ingredient of adobe bricks. To produce the fibrous material, the stem of the green leaves are, first, collected from the trees. The leaves are then left for drying in the shade for a minimum of one month. Drying the leaves in the shade makes the water loss from the stems slower and hence the fibre, produced, will be of better quality. The stems are then crushed into fibrous state. This was done, first, by hammering to soften the stem, then cutting into small pieces and finally crushing with the kitchen grinding machine. This produces pulp-like fibre, which was added to the soil-mix. However, the amount of fibre required by volume is great due to its light-weightiness. To add 5% of fibre to make a batch of test bricks, the required fibre to be crushed is considerable amount by volume. And the process of hand-crushing becomes a very laborious and tedious job.

Chapter 4

SOIL AND BRICKS TESTS

4.1 Soil Tests

Soil as it occurs naturally varies in its constituents. Therefore, any soil being considered for adobe construction should be subjected to the tests described in Chapter 3. The soil collected from the two sites, for this research, have been tested in the laboratory for their gradation and clay content. The amounts of soil collected for this research was about 40 kg from each site. The results of the soil tests are discussed below.

4.1.1. Laboratory Test Results

A) Sieve Analysis **:** The wet method was used for the sieve analysis of the soil samples collected from the soil sites. In this method, about 700 grams of the soil sample was first soaked in distilled water for a day. The sample was then diluted in small amounts with distilled water in a mechanical mixer and then sieved with running distilled water. The sieve analysis was performed in accordance with ASTM Standards D421 and D422. Figure 4.1 shows the set-up for sieve analysis, the top water tank (a jerry can) is used for running water and it is collected at the bottom in a bowl. The soil passing No. 200

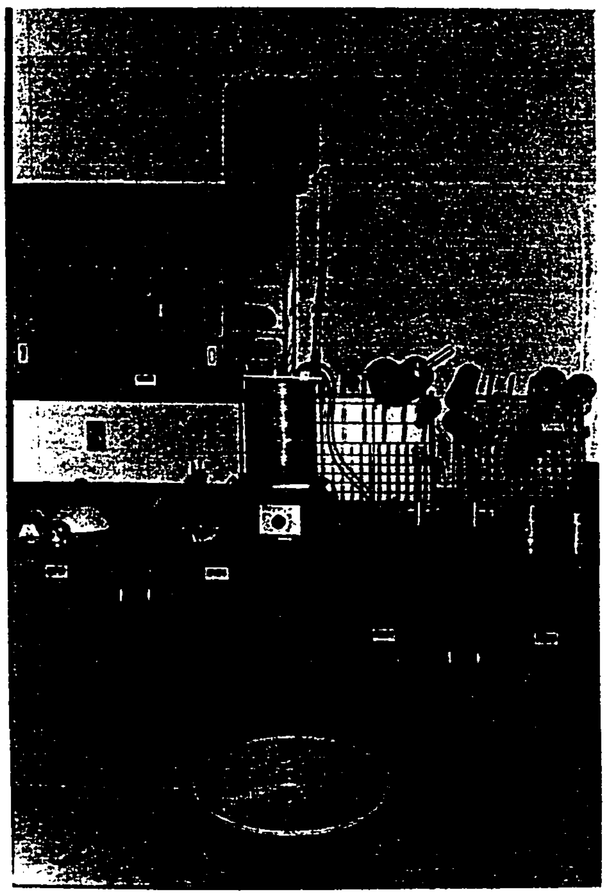


Figure 4.1 Set-up for sieve analysis.

sieve was oven dried to take its weight. The results of the sieve analysis, shown in Table 4.1 and 4.2 and Figure 4.2, indicated that the Qatif soil a very fine clay material, while the Dhahran soil is a sandy silt material.

B) Atterberg Limits : The tests of plastic and liquid limits showed that soil sample no. 1 (Qatif soil).has a very high plastic limit of 51% and a liquid limit of 106%. This indicates that Qatif soil is highly clayey. On the other hand, soil sample no. 2 (Dhahran soil) failed the Atterberg limits test which means that this soil has no clay content thus lacking the binding capacity. Figure 4.3 shows the set-up for Atterberg limits test. The result of this test for the Qatif soil is given in Table 4.3 and Figure 4.4.

C) Specific Gravity : Determination of specific gravity of the two soils are performed according to ASTM Standard D854. For both the soils, three preparations were made. The specific gravity value is the average of the two preparations that are within two percent of each other. Specific gravity of Qatif and Dhahran soils are found to be 2.76 and 2.92 respectively. The determination of the values are given in Tables 4.4 and 4.5.

D) Moisture Content : Although this test is a routine test while collecting soil samples by boring holes into the ground as samples collected will have water retained. Both the soil samples collected for this case study were available from on top of the ground surface and thus exposed to the atmosphere. Hence, moisture content tests were not performed as the soils were dry.

Table 4.1 Sieve analysis of Qatif soil.

Sieve no.	Diam.(mm)	Wt. Retained	% Retained	% Passing
16	1.18	17.0 g	2.4	97.6
40	0.425	5.0	0.7	96.9
60	0.250	3.0	0.4	96.5
100	0.150	2.0	0.3	96.2
140	0.106	5.0	0.7	95.5
200	0.075	8.0	1.1	94.4
washed		668.0		
Total		708.0		

Table 4.2 Sieve analysis of Dhahran soil.

Sieve no.	Diam.(mm)	Wt. Retained	% Retained	% Passing
16	1.18	59.46 g	8.5	91.5
40	0.425	30.36	4.4	87.1
60	0.250	16.46	2.4	84.9
100	0.150	19.49	2.8	81.9
140	0.106	27.95	4.0	77.9
200	0.075	76.80	11.0	66.9
washed		464.57		
Total		695.09		

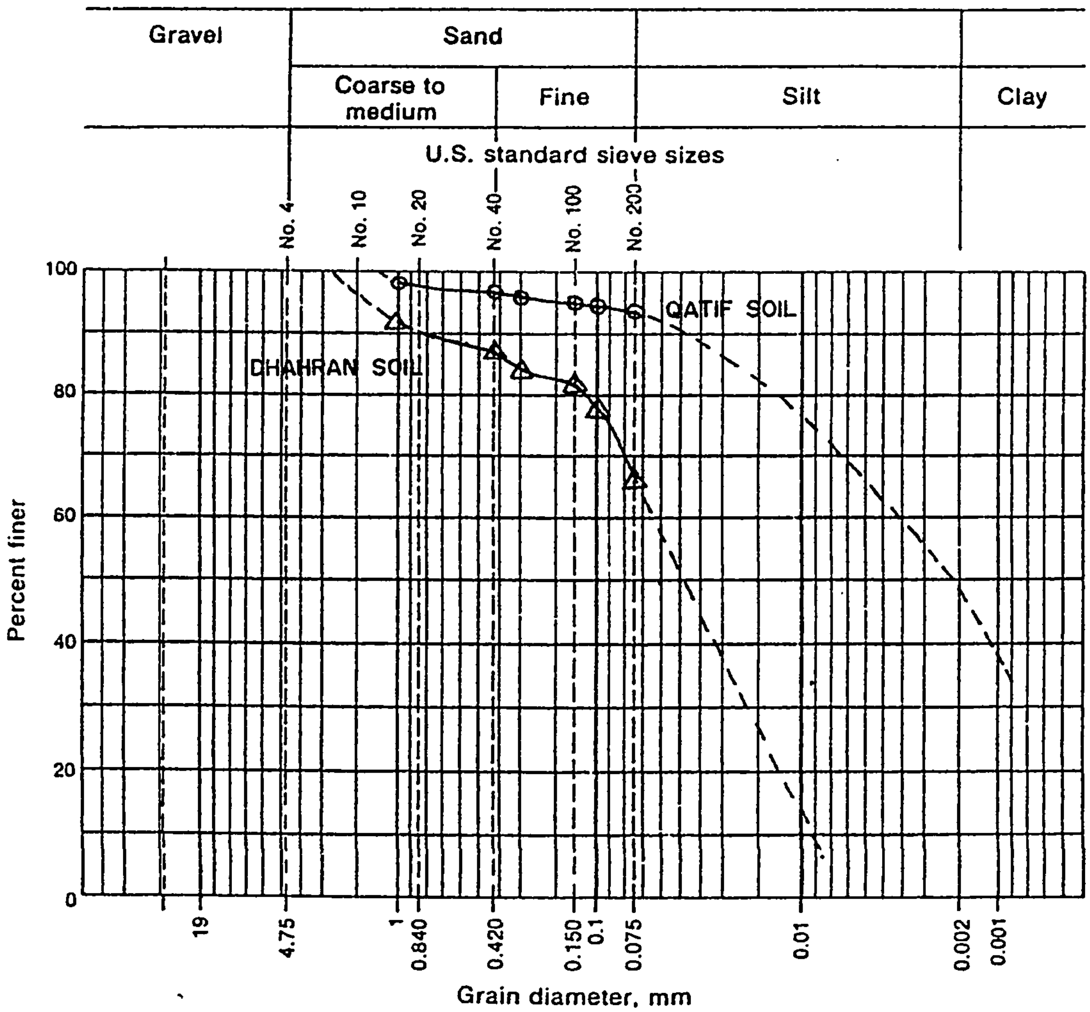


Figure 4.2 Plot of grains distribution of Qatif and Dhahran soils.

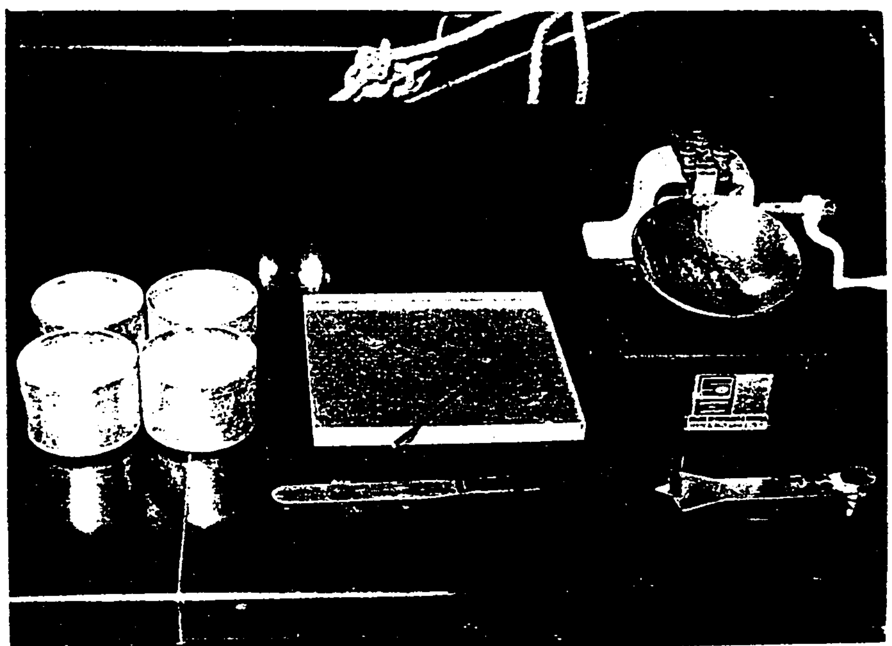


Figure 4.3 Set-up for Atterberg limits.

Table 4.3 Atterberg limits determination of Qatif soil.

Liquid Limit Determination :

Can no.	26	92	32	6	81
Wt. of wet soil + can	41.971	36.101	44.990	45.030	47.020
Wt. of dry soil + can	36.855	30.180	38.113	38.042	38.682
Wt. of can	31.525	24.455	31.960	31.830	31.740
Wt. of dry soil	5.330	5.725	6.153	6.212	6.942
Wt. of moisture	5.116	5.921	6.677	6.988	8.338
Water content, w%	96.0	103.4	108.5	112.5	120.1
No. of blows, N	31	28	25	22	15

Plastic Limit Determination :

Can no.	80
Wt. of wet soil + can	38.645
Wt. of dry soil + can	33.852
Wt. of can	24.382
Wt. of dry soil	9.470
Wt. of moisture	4.802
Water content, w%	51.0

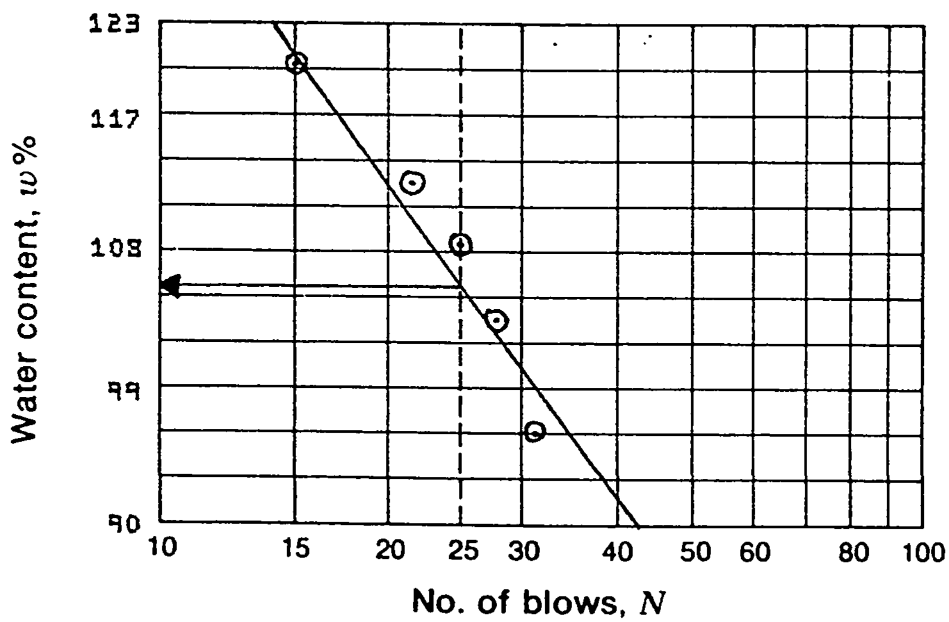


Figure 4.4 Atterberg limits determination of Qatif soil by plot.

Table 4.4 Specific gravity determination of Qatif soil.

Test no.	1	2	3
Vol. of flask at 20 °C	500 ml	500 ml	500 ml
Method of air removal	vacuum	vacuum	vacuum
Wt. flask + water + soil = W_{bws}	687.86	687.50	689.93
Temperature, °C	23	23	23
Wt.flask + water = W_{bw}	677.20	677.55	679.55
Evaporating dish no.	#2	#3	#4
Wt. evap. dish + dry soil	491.68	469.85	486.77
Wt. evap. dish	475.16	454.23	470.51
Wt. dry soil = W_s	16.52	15.62	16.26
$W_w = W_s + W_{bw} - W_{bws}$	5.86	5.67	5.88
$G_s = \alpha W_s / W_w$	2.82	2.75	2.76
$\alpha = 0.99935$			

Test nos. 2 and 3 resulted in closer value.

Average specific gravity of the soil, G_s = (2.75 + 2.76) / 2 = 2.755 ~ 2.76

Table 4.5 Specific gravity determination of Dhahran soil.

Test no.	1	2	3
Vol. of flask at 20 °C	500 ml	500 ml	500 ml
Method of air removal	vacuum	vacuum	vacuum
Wt.flask + water + soil = W_{bws}	708.40	711.10	719.30
Temperature, °C	25.3	25.3	25.3
Wt.flask + water = W_{bw}	667.35	676.39	677.64
Evaporating dish no.	#2	#31	#40
Wt. evap. dish + dry soil	493.82	537.17	547.76
Wt. evap. dish	431.05	484.60	484.06
Wt. dry soil = $Wsubs$	66.77	52.57	63.70
$W_w = W_s + W_{bw} - W_{bws}$	21.72	17.86	22.40
$G_s = \alpha W_s / W_w$	2.89	2.94	2.84
$\alpha = 0.99998$			

Test nos. 1 and 2 resulted in closer value.

Average specific gravity of the soil G_s = (2.94 + 2.89) / 2 = 2.92

4.2 Soil-Mix for Adobe

From the test results, it is seen that Qatif soil is a high clay soil and Dhahran soil is non-clayey. Literatures suggest that soil with high clay content is not suitable for adobe and soil with no clay content does not have any binding effect. Therefore, it is evident that the two soils are not at all good for making the bricks if they are used individually. However, mixing the two soils along with sand, within proportions suggested by McHenry (18), can produce good results. Initially, several soil mixes were prepared by varying the mix contents of clay, marl and sand in order to find out a mix proprtion which produces bricks with obtainable maximum strength. This mix proportion will then be used for making the bricks with the additives. In doing so, four mix proportions were used for making the bricks and testing them. The mix proportions shown in Table 4.6.

The mix proportions were kept within the limits given by McHenry (18). Although the proportional range suggested by McHenry may not be applicable in other locations, non-the-less it is a good reference point of start. In two mixes, Qatif clay was kept constant and sand was kept constant in three mixes. Before making the mixes, Qatif soil had to be pulverized as it was collected in hard chunks. The pulverization was done first manually with hammer into small gravel sizes and then by the L. A. Abrasion Machine. It was then sieved through No. 4 and the passing soil was used for the mix.

Table 4.6 Mix proportions of Qatif soil, Dhahran soil and sand.

	Mix # 1	Mix # 2	Mix # 3	Mix # 4
Qatif soil	15 %	12 %	15 %	18 %
Dhahran soil	45 %	28 %	25 %	22 %
Sand	40 %	60 %	60 %	60 %

all proportions are by weight.

Dhahran soil was also used after passing through No. 10 sieve. Figure 4.5 shows a sample of a brick with mix proportions from mix #1 described in Table 4.6.

4.3 Making the Bricks

4.3.1 Production Options

There are two options for the production of adobe bricks. One option is production at the site of the basic materials and the other is at the construction site. The selection of either of these options will depend upon several factors.

A) Production at the Site of the Materials : This is a very convenient method of producing the bricks provided preliminary soil tests affirm that the soil has the right composition for adobe bricks and the required water supply is available. If the soil is good for adobe, then a temporary setup can be established for making the bricks and drying them. The advantage of this setup is that the construction site receives dried bricks ready for use.

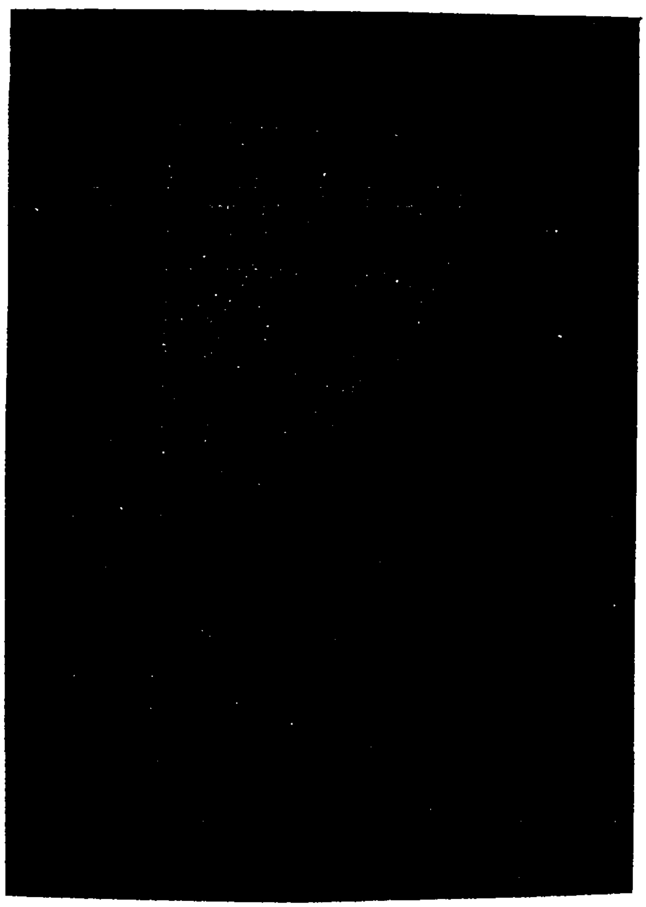


Figure 4.5 Sample of a brick (clay 15%, Marl 45%, sand 40%).

B) Production at the Construction Site: In cases where soils from various locations have to be mixed for optimum composition for adobe, producing the bricks is rather convenient at the construction site or very near to it. This way, transportation cost is reduced by transporting all the different basic materials to the site only once. Of course, a temporary shed has to be made for making and drying of the bricks. This option is popular where adobe bricks are to be made for a particular project and local soil is good for the bricks. The two options merge where the construction site is on or near to good adobe soil.

For the purpose of cost analysis, the second option of production has been considered due to the fact that the materials are from different sources - clay from Qatif, marl from Dhahran (Doha) and sand from the coastal areas and it will be easier to bring all constituent materials to one site to produce the bricks. This site is assumed to be the actual construction site of the project.

4.3.2 The Brick Making machine

The bricks were made using the Belgium made PLATBROOD F. brick making machine, shown in Figure 4.6, that compresses the soil mix into the mould. The machine is manually operative. It has a 29 cm. by 14 cm. opening with 10 cm. depth for receiving the soil. The bottom of the mould flexible and connected with a lever for compressing the brick and removing the brick from

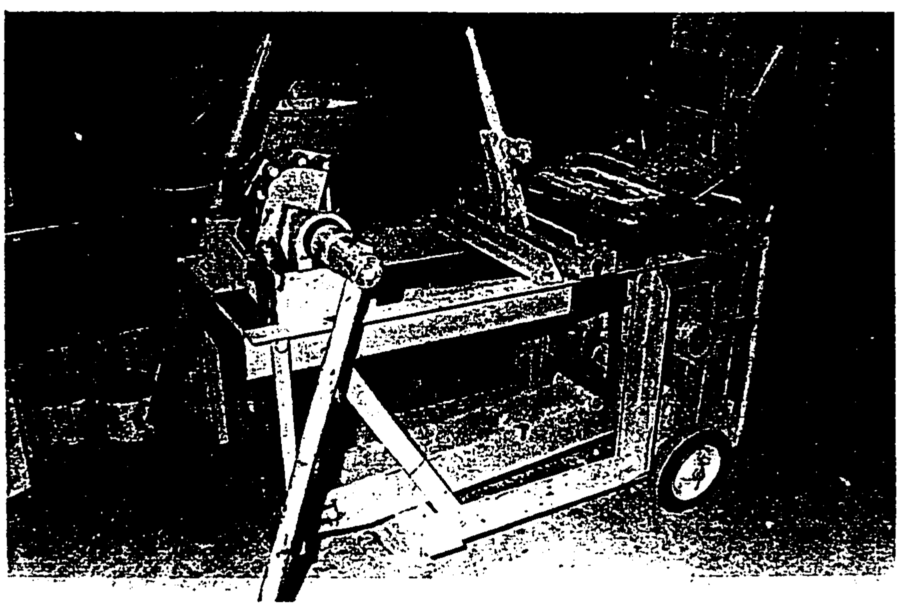


Figure 4.6 The brick making machine.

the mould. There is a steel top with a lever that covers the mould from the top. After putting the soil into the mould the steel top is put in place and fixed with another steel hand operated with a lever. Then the soil is compressed from the bottom with the help of the lever with manual force. After the brick is compressed, the top is moved up and the brick is removed by pushing the bottom up.

4.3.3 Amount of Water Added

Since the bricks are made with compression and by manually operated machine the amount of water to be added for the soil-mix has to be low - just enough to mix the ingredients. The same will be the case while other types of brick making machines are used. Excess water will make loose mix which after compression will make brick stick to the mould. To determine the amount of water to be added several bricks were made with varying the addition of water. It was found that addition of 20 % (by weight of the dry mix) water makes a good soil mix. Water in excess of this amount still produced workable dry mix after compression spillage of water occured in the mould with the result that the soil sticked to the mould of the machine. Of course, if the bricks are made with mould on the ground without compression, the amount of water has to be more for a loose-mix.

4.3.4 Drying of the Bricks

After making the bricks, they were left for drying in shade in the laboratory at about 70 degree F and 50 % relative humidity. The bricks were dried for seven days before performing the tests.

4.3.5 Bricks with Additives

From the four mixes, the mix that produces bricks with higher compressive strength will further be experimented with additives to investigate the effects of the additives on compressive strength and water absorption. The additives added are cement, bitumen emulsion and palm tree fibre. Mixes are made with emulsion and cement added separately by 3, 5 and 7% by weight of dry soil. One mix is made with 5% palm tree fibre, one mix with 5% emulsion and 5% fibre. As discussed earlier, the process of crushing the palm leaves has been a very tedious job. Crushing with kitchen grinder in small amounts is highly time consuming and also laborious. Hence, additional testing with palm fibre in other proportions was not done, as it does not seem economical in practice unless a quicker method of crushing the palm-stalks is available.

4.4 Bricks Tests

Performances of the adobe bricks are generally determined by compressive strength, shrinkage cracks and water absorption. These tests are discussed below :

A) Compressive Strength : This is the foremost test for the performance of the adobe bricks. For the compressive strength of the adobe bricks, three samples were tested from each different mix after seven days of curing in the shade. The tests were performed with INSTRON - a highly sophisticated digital strength testing equipment. The rate of loading was set to 1 mm. per minute - a low rate. This was done due to the fact that a higher loading rate might result in incorrect strengths, since the ultimate strengths of adobe bricks is very low as compared to concrete (300 psi versus 3000 psi).

B) Shrinkage Cracks : Air dried adobe bricks develop cracks due to shrinkage. The cracks effect the strength and durability of the bricks in a negative way. The bricks were observed for shrinkage cracks after seven days before testing for compressive strength.

C) Absorption : This is the determinant of the bricks' durability against rain and susceptibility to water. The higher the absorption, the worse will be the bricks in durability. Bricks will deteriorate when it rains and disintegrate over time in a humid environment. Adobe Codes from Around the

Southwest of United States (1) requires that absorption tests on mud bricks are to be performed on four-inch cube cuts of bricks and put the specimen on water saturated porous surface for seven days. For research purposes, studies have been reported on 24 hours absorption tests. In this experiment, the test was done with the bricks made by the machine cutting them into three equal pieces. The brick pieces were partially covered on the sides with wax for proper handling during the absorption test. In this way, the result will indicate absorption of the same bricks for which compressive strength tests were done.

4.5 Test Results of the Bricks

4.5.1 Bricks without Additives

Compressive Strength tests of the bricks of four different mixes of soil is presented in Table 4.7. Average strength in all the four mixes are found to be low with mix # 3 giving higher value. No cracks due to shrinkage has been seen to have appeared on any of the samples of the four mixes. It is evident in Figure 4.7 - sample of a brick from mix # 3. Absorption test was done the bricks with mix # 3. It was found that with this mix absorption varied between 12.7% and 13.7% with average of 13.3% on three specimens. This is rather very high compared to dictated value of 2.5 % on three inch cube specimens (1). Also the bricks became brittle while doing the absorption test. Figure 4.8 shows the bricks prepared for absorption test.

Table 4.7 Compressive strength of the bricks without additives.

	Clay	Marl	Sand	*Compressive Strength, psi.* #1	#2	#3	Avg.	St.Dev.
Mix # 1	15%	45%	40%	104.6	95.2	95.8	98.5	4.26
Mix # 2	12%	28%	60%	78.4	78.3	77.5	78.1	0.39
Mix # 3	15%	25%	60%	124.3	137.4	124.0	128.6	6.25
Mix # 4	18%	22%	60%	107.6	119.5	111.0	112.7	5.04

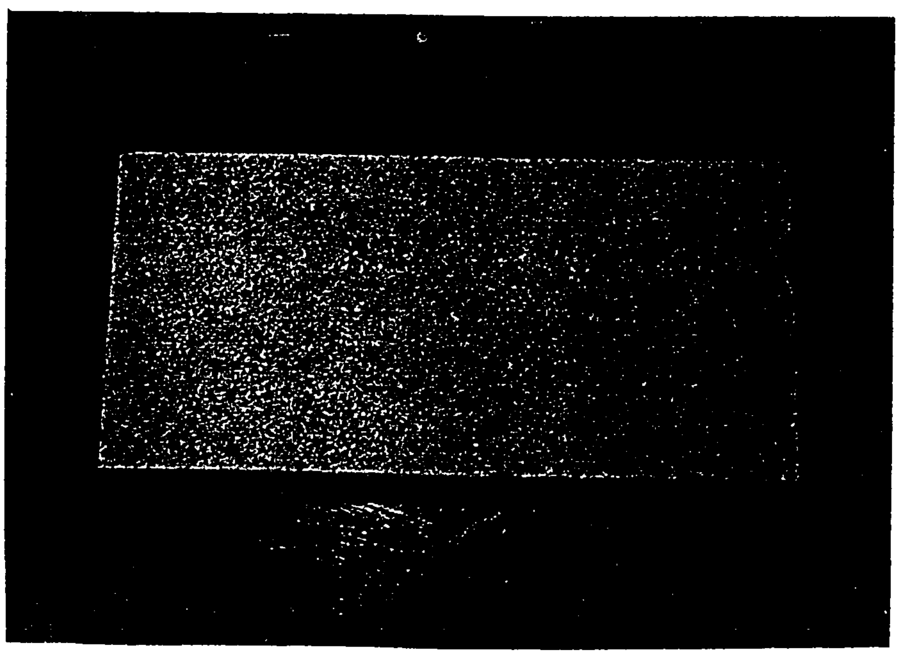


Figure 4.7 Sample of a brick without additives (Mix #3 - Clay 15 %, Marl 25 %, sand 60 %).

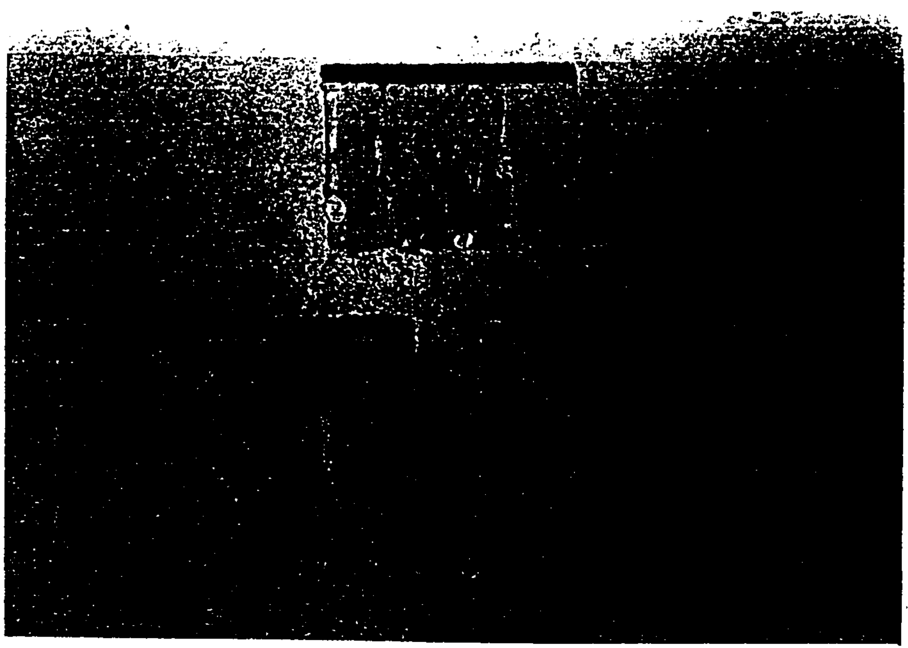


Figure 4.8 Samples for absorption test from mix #3 bricks. *Sample of a brick with 5% bitumen emulsion.*

4.5.2 Bricks with Additives

All the test sample bricks with additives have been produced with mix #3 that contained 15% clay (Qatif soil), 25% marl (Dhahran soil) and 60% sand. As discussed earlier, this was done because with mix #3 proportions bricks had the maximum strength compared to other mix proportions. The test results are discussed below.

When cement was added in percentages of 3, 5 and 7 - an overall reduction in compressive strength was observed. With 3% cement compressive strength was about 37 psi. 5 % cement gave an average strength of 64 psi and with 7 % cement strength was 100 psi. The absorption values were 11.6 %, 1.5 % and 5 % for 3, 5 and 7 % cement content respectively. No cracks due to srinkage was seen to have appeared in any of the samples.

Compressive strength of the bricks with 3 % bitumen emulsion was 80 psi (average) While compressive strengths of the samples with 5% bitumen emulsion are found to be 168 psi average. Average strength of the bricks with 7 % emulsion 65 psi. While bitumen emulsion was added, the absorption was found to be 0.36, 3.5 and 0.76 % for 3, 5 and 7 % emulsion content. No cracks due to shrinkage appeared.

Average compressive strength of the samples with 5% palm tree fibre is found to be 141 psi with individual strengths of 144, 141 and 139 psi. Also no cracks due to shrinkage appeared on any of the samples. No good achievement in terms of absorption, as it averaged to 9.6% on three specimens. Compressive strength of the bricks with 5% bitumen emulsion and 5% palm tree fibre are found to be 202, 203 and 197 which averaged to 201 psi. No shrinkage cracks appeared on any of the bricks. This combination of the additives resulted in low rate of absorption of 3.2 % average.

Tables 4.8 and 4.9 shows the results of compressive strength tests and absorption tests respectively. Figures 4.9 and 4.10 are the plots of the compressive strength. Figures 4.11 through 4.21 shows the sample bricks tested for strength and absorption.

Table 4.8 Compressive strength of the bricks with additives with mix #3.

	Compressive Strength, psi.						
	#1	#2	#3	#4	#5	Avg.	St.Dev.
3% cement	31.6	32.7	34.4	50.2	34.9	36.8	6.83
5% cement	87.8	45.3	54.9	56.6	73.6	63.6	15.12
7% cement	82.9	123.7	95.7	101.6	100.4	100.6	13.29
3% emulsion	51.9	72.6	103.3	69.9	98.4	79.2	19.06
5% emulsion	168.5	169.9	164.3	-----	-----	167.6	2.35
7% emulsion	35.5	42.5	106.4	69.1	71.8	65.1	25.13
5% palm fibre	143.6	140.9	139.5	-----	-----	141.3	1.72
5% palm fibre plus 5% emulsion	201.6	203.0	197.5	-----	-----	200.7	2.34

Table 4.9 Absorption values of the bricks with additives.

	Absorption, %			
	#1	#2	#3	Avg.
3% cement	10.9	12.8	11.2	11.6
5% cement	1.3	1.8	1.4	1.5
7% cement	4.8	5.1	5.1	5.0
3% emulsion	0.34	0.41	0.33	0.36
5% emulsion	3.7	3.6	3.2	3.5
7% emulsion	0.47	1.10	0.71	0.76
5% palm fibre	9.3	9.7	9.8	9.6
5% palm fibre plus 5% emulsion	2.9	3.3	3.4	3.2

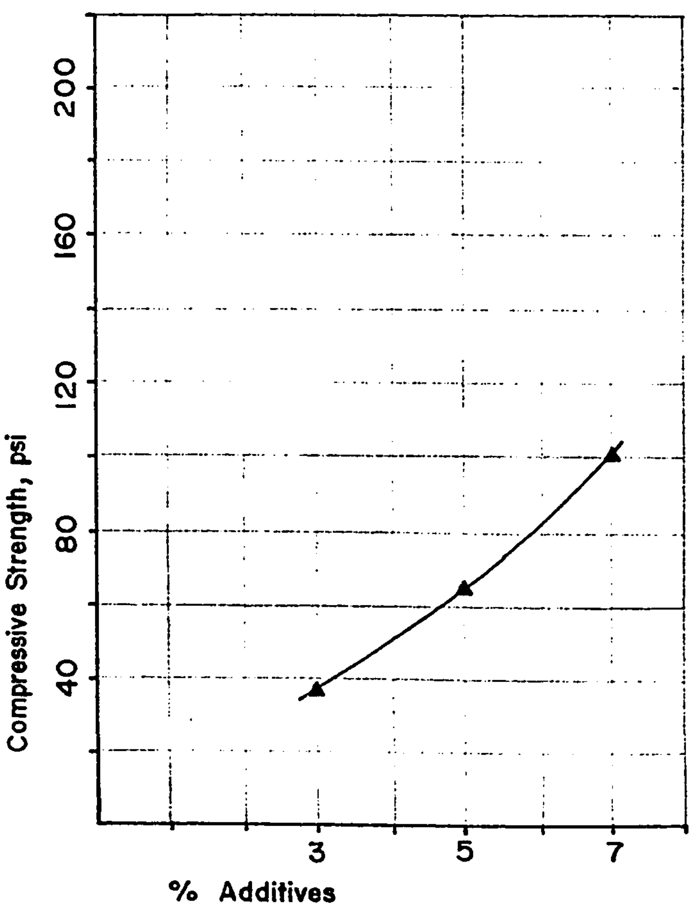


Figure 4.9 Compressive strength versus percentage of cement.

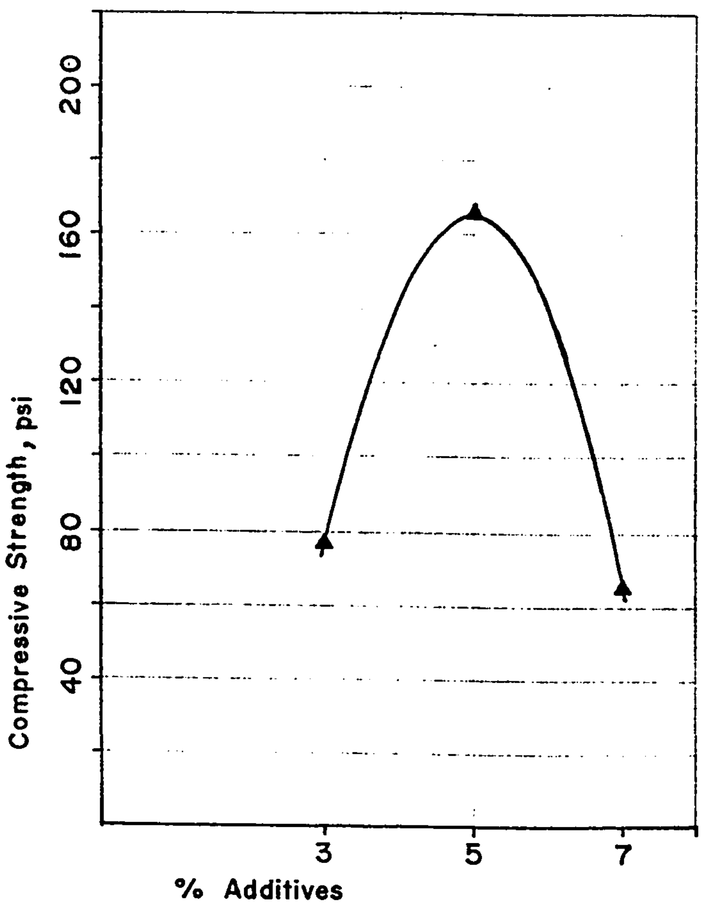


Figure 4.10 Compressive strength versus percentage of emulsion.

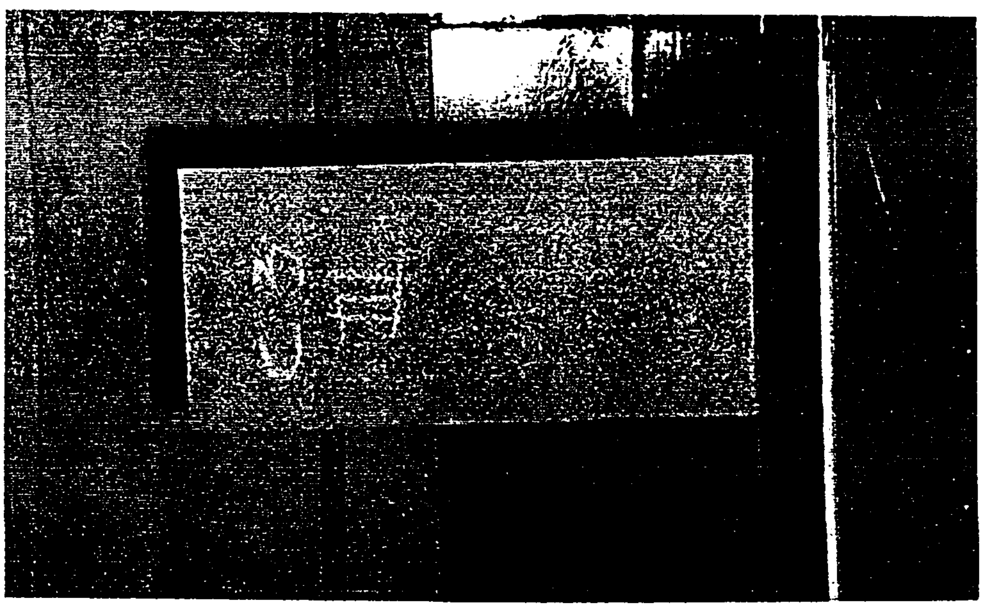


Figure 4.11 Sample of a brick with 3% cement.

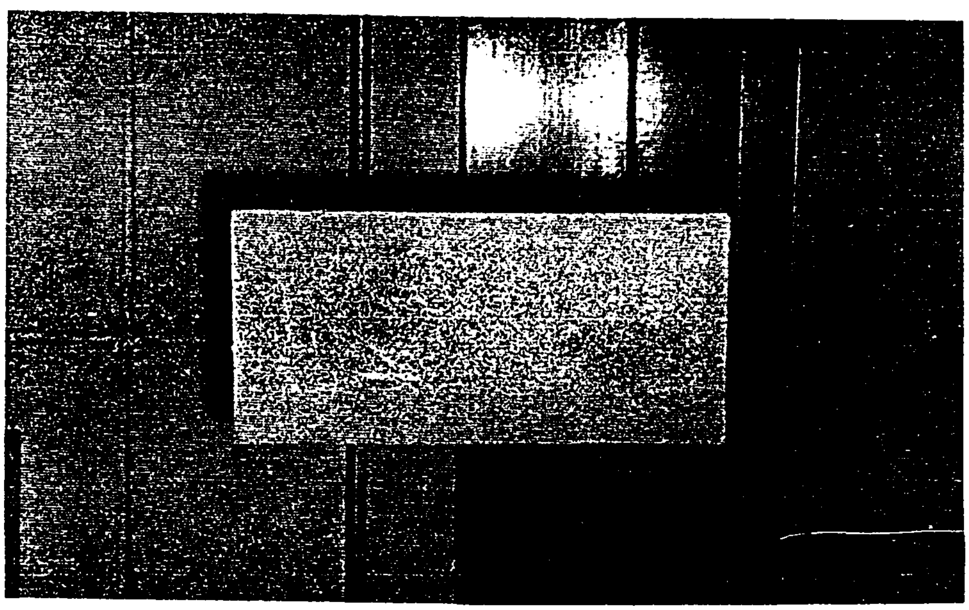


Figure 4.12 Sample of a brick with 5% cement.

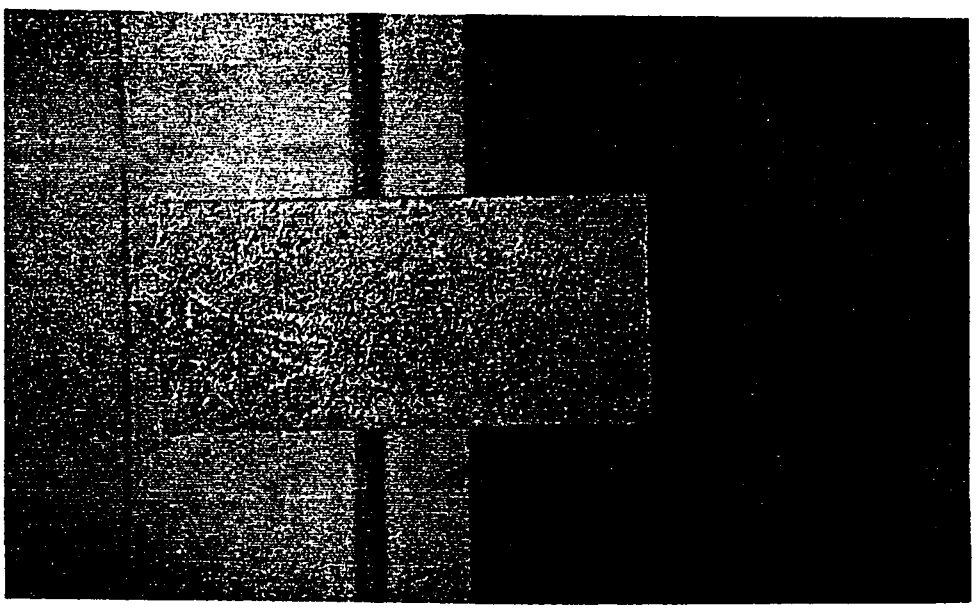


Figure 4.13 Sample of a brick with 7% cement.

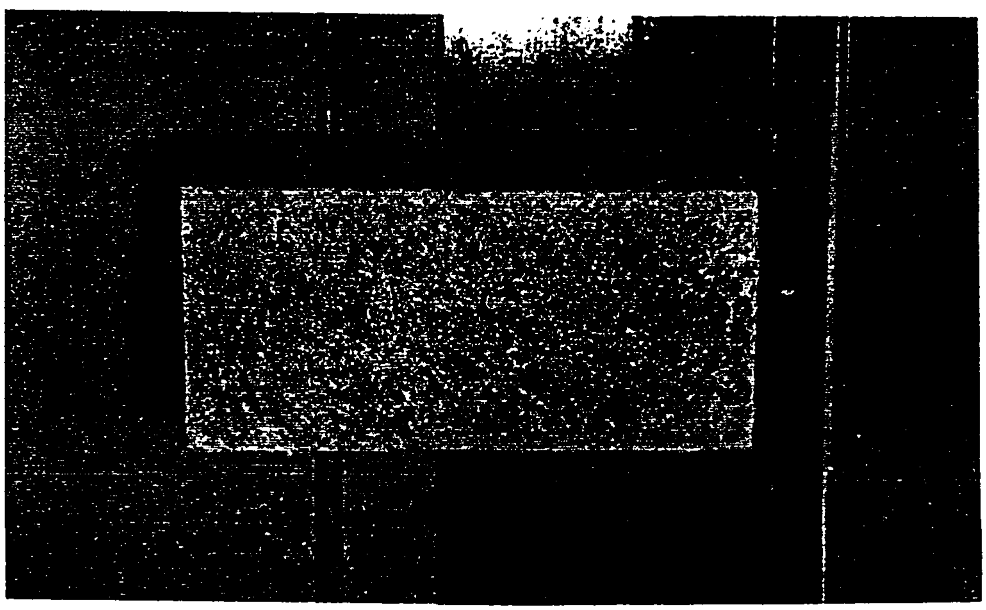


Figure 4.14 Sample of a brick with 3% emulsion.

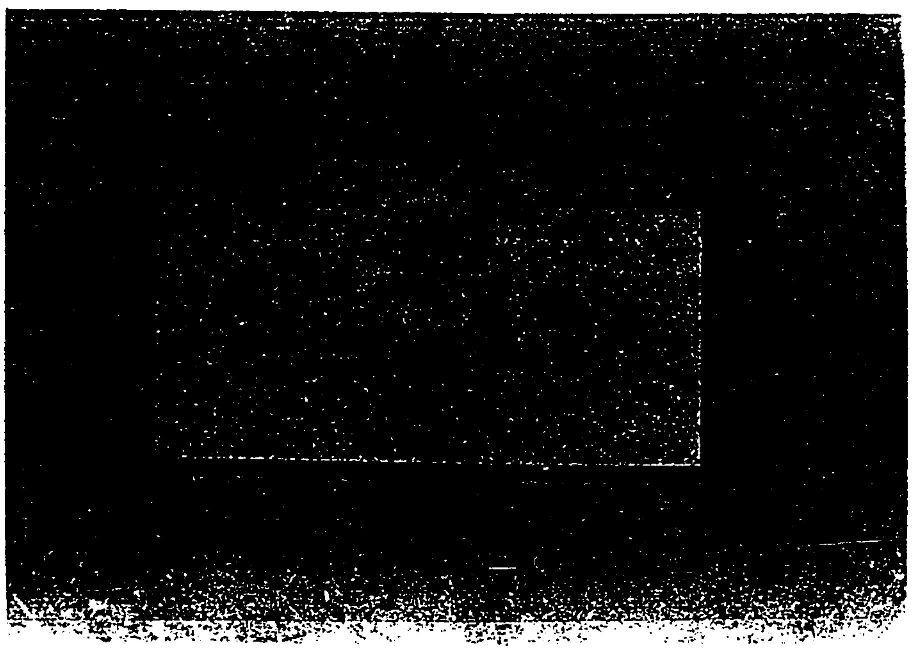


Figure 4.15 Sample of a brick with 5% emulsion.

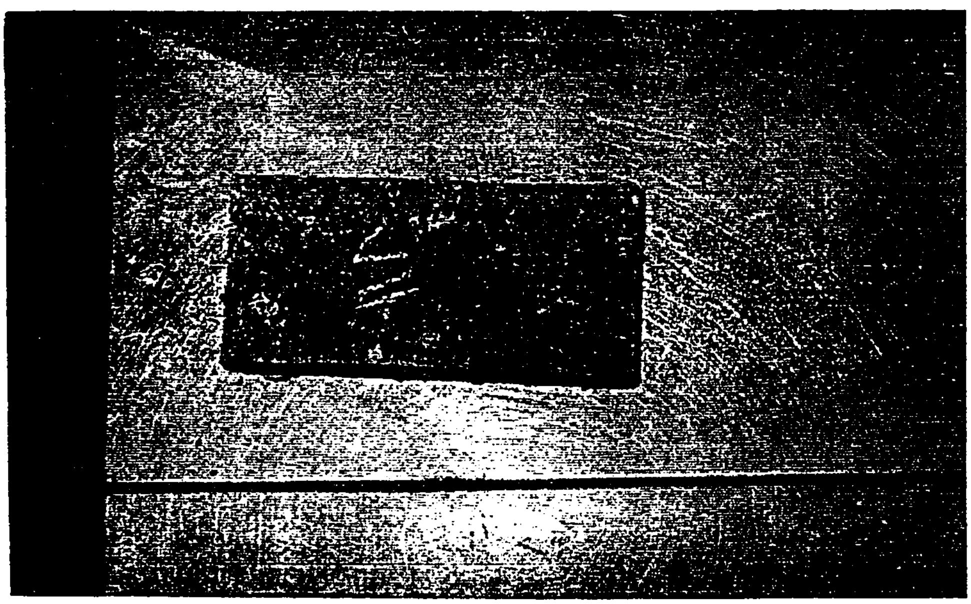


Figure 4.16 Sample of a brick with 7% emulsion.

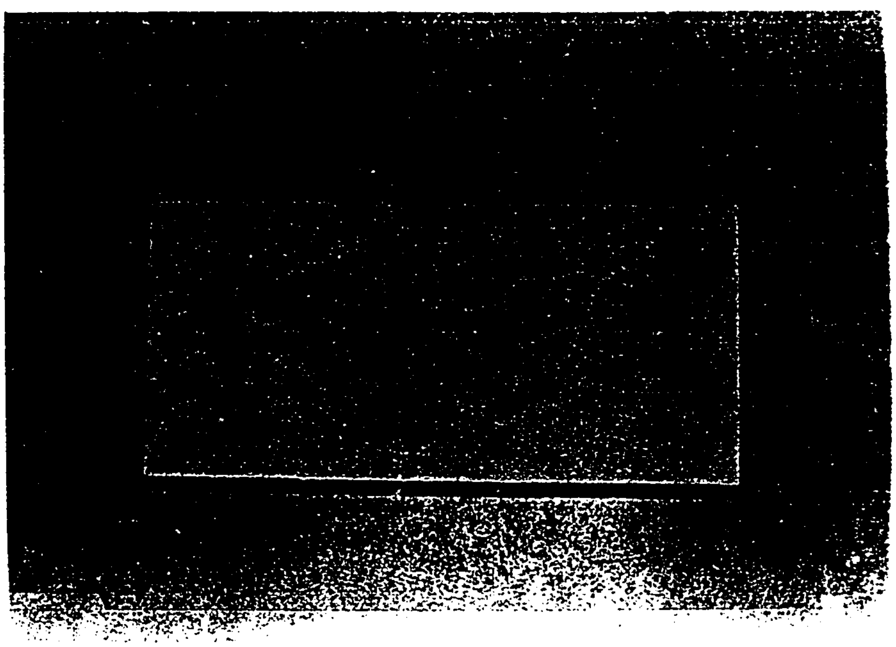


Figure 4.17 Sample of a brick with 5% palm tree fibre.

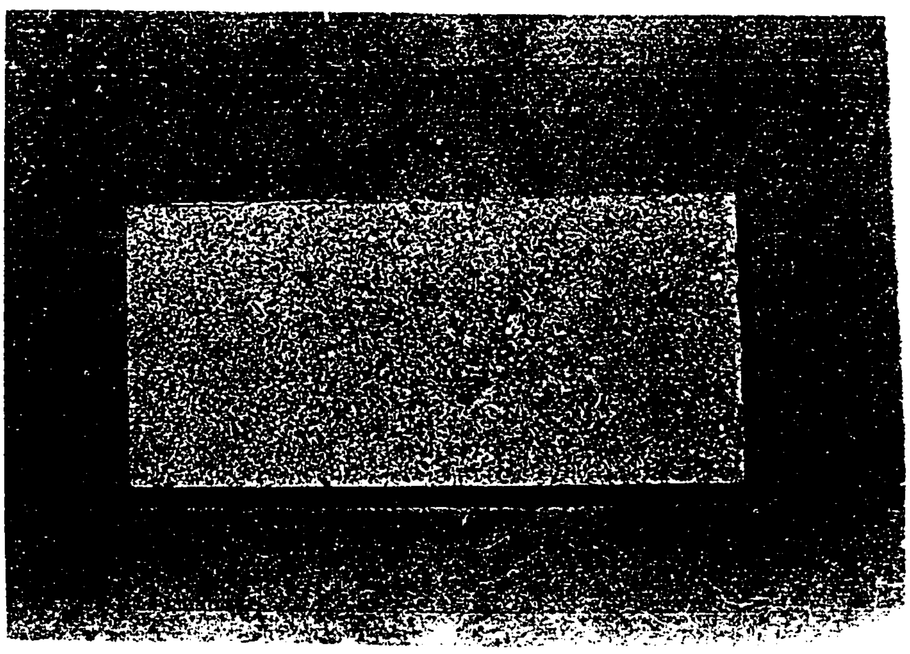


Figure 4.18 Sample of a brick with 5% emulsion and 5% palm tree Fibre.

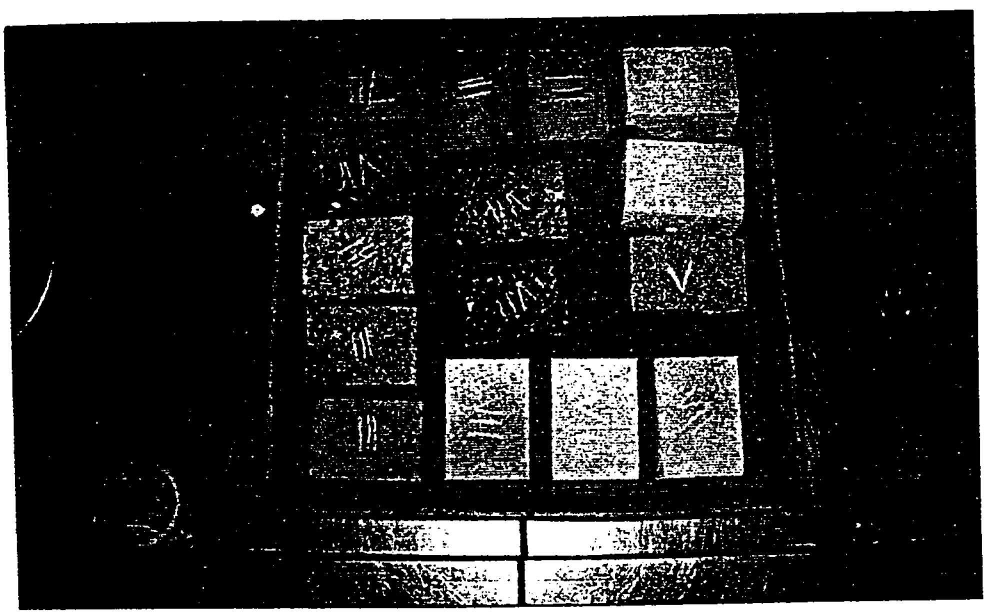


Figure 4.19 Samples for absorption test- bricks with 3, 5, 7% cement and 3 and 7% emulsion.

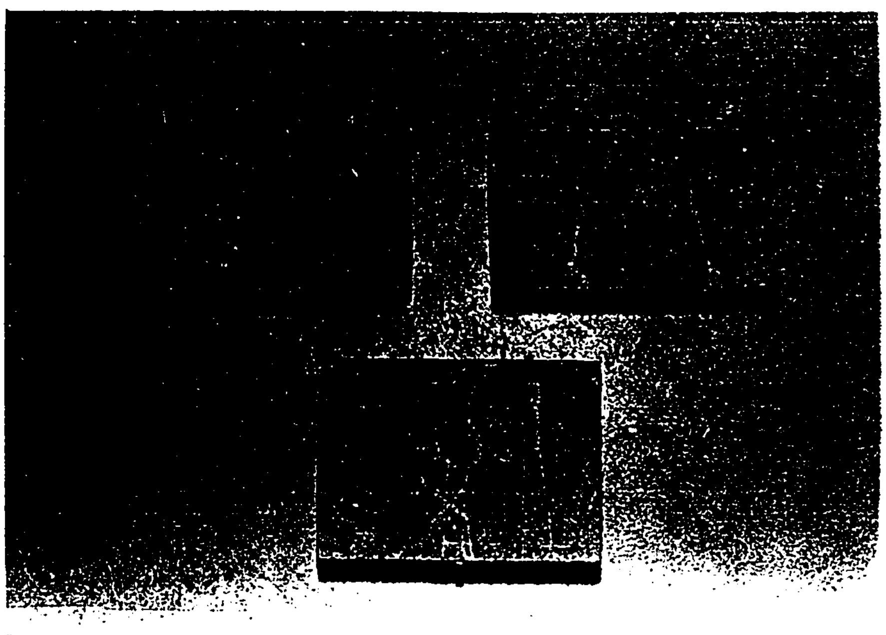


Figure 4.20 Samples for absorption test - bricks with 5% emulsion.

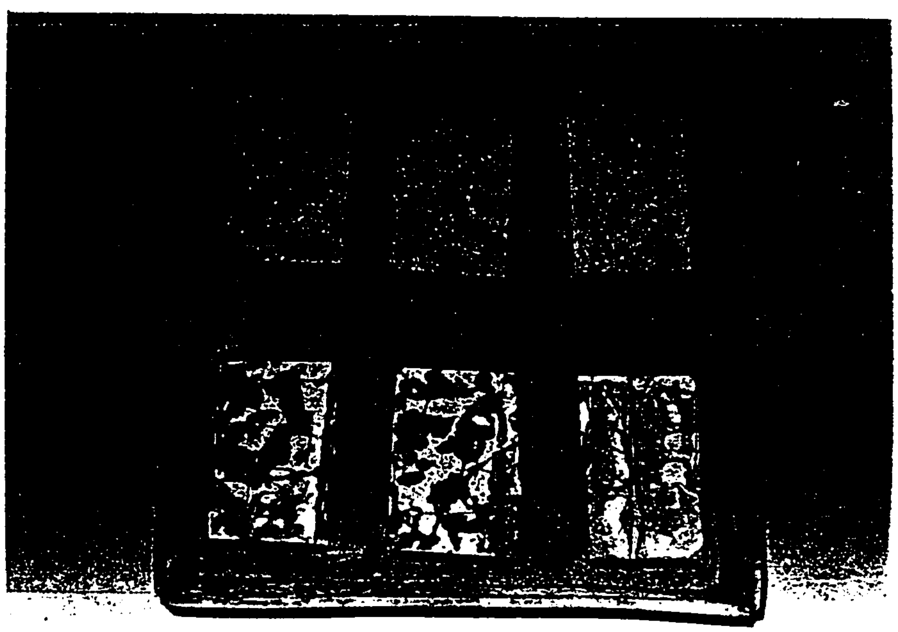


Figure 4.21 Samples on test for absorption . *Top row - bricks with 5% emulsion and 5% palm tree fibre, bottom row - bricks with 5% palm tree fibre.*

4.6 Result Analysis and Discussion

From the test results of bricks without additives, it is seen that as the soil constituents are changed the strength changes. The same clay content of 15% with different combinations of marl and sand produced bricks of different strengths. Also the same phenomena is observed when the sand content is kept the same with varying clay and marl contents. The average strength of the bricks are well below the optimum strength requirement. The compressive values are given in Tables 4.7 and 4.8. However, within the same mix strength variation is minimal.

Although the purpose of additives is for increasing the performance of the bricks - strength, absorption and shrikage. The addition of emulsion has little effect on the compressive strength. However, absorption is highly reduced with emulsion. On the other hand, cement reduces the strength by alarming rate. As the cement percentage is increased from 3% to 7% strength increase is observed but still below the strength of the mix without additives. Of the four mixes, the mix with 5% emulsion and 5% palm tree fibre has attained the maximum strength of 201 psi. The adobe codes from the southwset of United States dictates an average of 300 psi of compressive strength. On physical examination, the bricks had no cracks. Also physical examination revealed that the bricks with the bitumen emulsion as additive were far more stronger than the bricks without the additives. In terms of absorption, emulsion, 5 and 7% cement and 5% palm tree fibre plus 5% emulsion (Table 4.9) had low rate of absoroption.

While adding cement as additive, it is expected that the compressive strength will increase; but the reverse phenomenon occurs. The resulting negative effect of cement as additive and overall low compressive strength with additives required further investigation as to why it is happening. almost all research papers on adobe and mud based materials research suggest improved strength and quality of the bricks upon addition of stabilizing agent. The only exception was a part of Uzomaka's (25) report where a strength retarding effect was observed with cement. The soil, however, was high in clay and no sand was mixed with the soil.

Ahmed.(4) in his extensive study on the Qatif soil, charactizes the it as Montmorillonitic clay in minerological composition. While Al-Tayyib, et al (24) reported 70% Dolomitic composition of Marl from Dhahran and Quarzite composition of the sand. A clay soil containing montmorillonite mineral is a highly expansive soil. Gillot (11) remarks that cement stabilization of soil becomes uneconomic with soil containing montmorillonite mineral. Moreover, A typical characteristic of montmorillonte is it controls soil behavior and reduces cohesion of the soil particles. Thus, no considerable improvement was observed with the stabilizers.

Chapter 5

ECONOMIC FEASIBILITY

5.1 Adobe Economics

In the building construction process, the cost is an important aspect. Building materials are selected by comparing the costs of the similar and viable materials. It has been established in the literature review that adobe, as a material for walls, vaults and domes is viable in terms of strength. Therefore, to ensure its economic viability in the Eastern Province, a cost comparison with other building blocks is necessary.

The most common types of building blocks available in Saudi Arabia are

Concrete Masonry Units (CMU);
Calcium Silicate Blocks; &
Clay Blocks (Burnt)

There is a basic difference between these building bricks and adobe. While these bricks are being manufactured by the building industries, adobe is yet to be popular for industrial production in Saudi Arabia. Adobe bricks are to be produced by hand labor with wooden or metallic moulds.

There are simple machines available that can produce compressed adobe brick. But this still needs manual labor. All of above mentioned types of blocks have the same dimensions of 40x20x20 cms. The adobe blocks can be of different sizes. depending on the mould sizes. The compressed block making machine produces the adobe blocks of 30x15x10 cms size.

For the purpose of cost comparison, the Al-Rahmah Mosque of the KFUPM Campus has been taken as a case study. The mosque is a fine example of the traditional and vernacular architecture of Saudi Arabia. At present, the mosque has become a ruin of the traditional architecture. To revive the tradition, interests have grown to renovate and rebuild the mosque. This case study has taken one of the students' projects, as a design solution, for rebuilding the mosque. Figures 5.1 through 5.3 shows the design solution in plan and model. The mosque remodelling design has a repetitive series of columns and arches. This economic study takes into consideration of only the part that is proposed to be added to the existing mosque - which is the arcades on the front of the mosque.

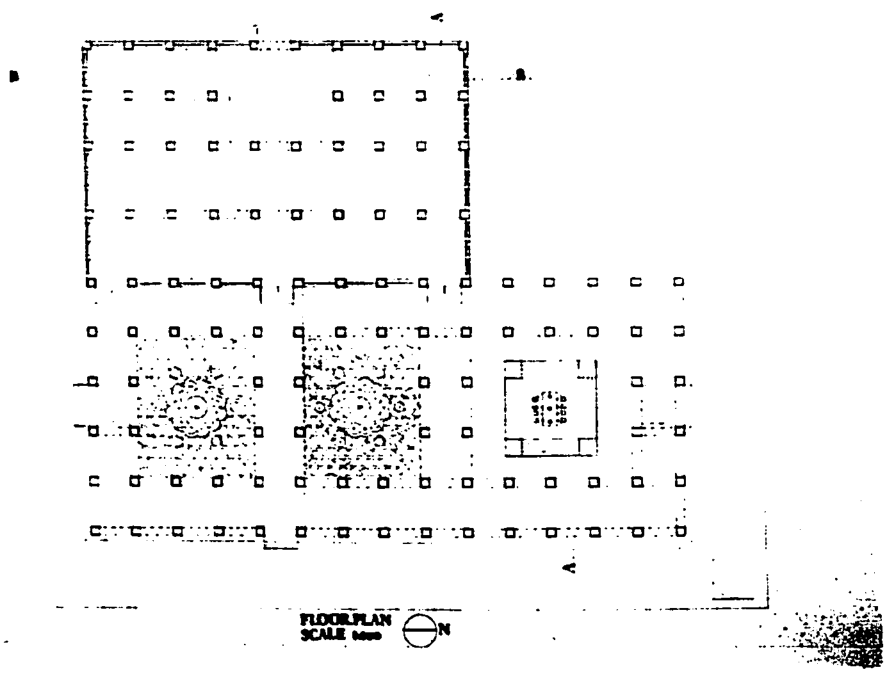


Figure 5.1 Plan of Al-Rahmah mosque.

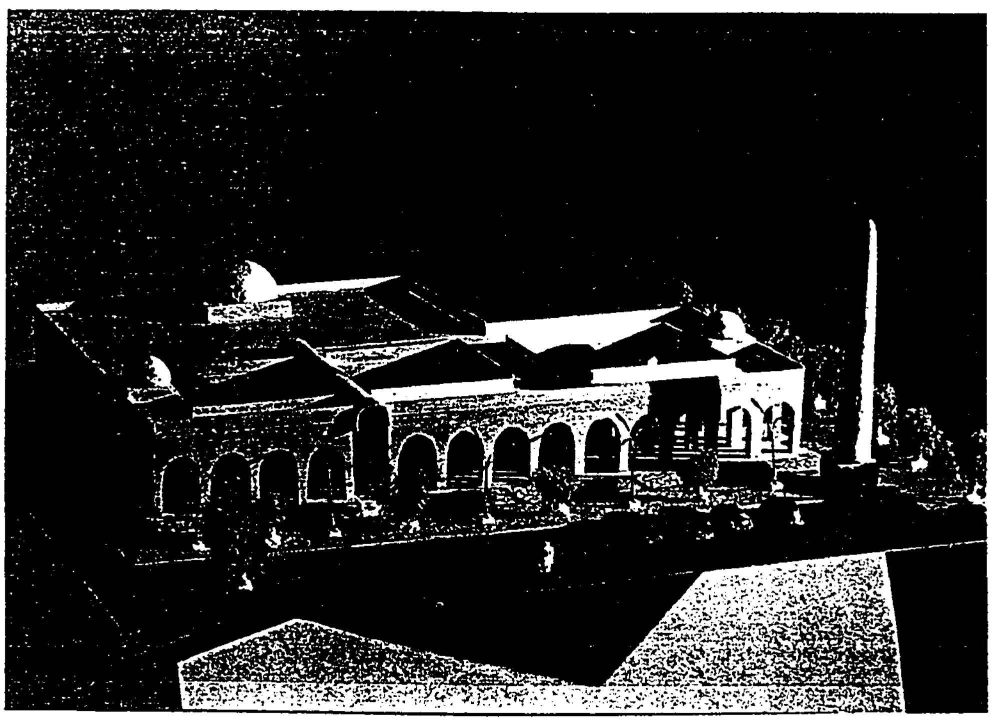


Figure 5.2 Model of Al-Rahmah mosque.

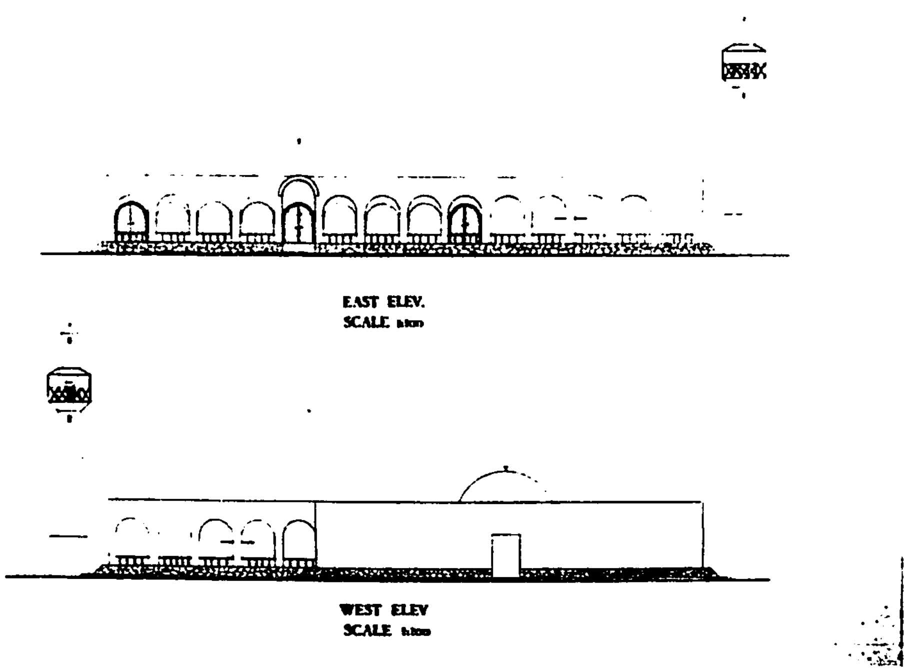


Figure 5.3 Elevation and Section Al-Rahmah mosque.

5.2 Various Costs Factors

A number of cost factors are involved in a construction project. The first is the land cost. Then there are land development cost, architectural design cost, construction cost and maintenance cost. For a project, the land cost and the design cost remains the same, the variation occurs in construction cost when different alternatives are considered. also the maintenance cost will vary depending on the type of materials and methods of construction. This cost will be discussed later in life cycle cost. The construction cost includes materials, labor, and plant and equipment cost. The contruction cost factors are discussed here.

5.2.1 Material Cost

The cost of the materials needed for the construction - bricks, concrete, steel, etc. In the case study of the mosque, the basic material concerned is the bricks. Most often, the transportation costs of the materials to the site are included in the material costs. In cases where it is not included, the transportation cost has to be considered separately.

5.2.2 Labor Cost

The labor cost on the construction site is another important aspect of construction cost. Labor cost for the production of the adobe bricks is another part of the labor cost. Although productivity of labor will vary while using different types of bricks, for all practical reasons we can ignore this variation - assuming labor productivity to be the same for the different types of bricks.

5.2.3 Plant and Equipment Cost

In a construction project, plant and equipment take up part of the total cost of the project. In heavy construction this forms a major cost, for example, roads and highways construction, bridges, multi-storyed structures, etc. The building of the mosque involves simple construction method. The whole idea behind incorporating traditional method and earth construction is simplicity. In earth construction, plant cost is minimal as the bricks can be produced in open square. The drying of the bricks require simple shade that can be made at the least cost. The equipment for producing the bricks is a simple brick making machine which has been used for making the bricks for this thesis. For this case study it is assumed that the existing facilities at KFUPM will be used. Therefore, plant and equipment cost is assumed to be negligible.

5.3 Cost Analysis

In the analysis of costs, three types of costs are involved. These are

1. Unit Cost;
2. Per Square Meter Floor Area Cost; and
3. Life Cycle Cost.

Of these costs, unit cost of the material and life cycle cost can be indicative of the economic feasibility of the project. Reduction in the material cost will result in the reduction of the project cost. If the long run cost , that is, maintenance cost of the building can be reduced will also be an economic factor for a project. These two types of costs are discussed below :

5.3.1 Unit Cost

Whlie comparing similar materials, the per unit costs of the materials are considered first. In this economic analysis, the materials considered are -
CMU Blocks,
Clay Burnt Bricks,
Calcium Silicate Tiles and
Adobe Blocks.

The first three types of blocks are available in the local market and are sold by per m^2. The costs of these block are as follows :

CMU Blocks............... SR 12.50 / m^2

Clay Burnt Bricks........ SR 18.75 / m^2

Calcium Silicate Tiles... SR 27.00 / m^2

The above costs, by the factories, are established taking into account the following factors :

a. Cost of basic materials; e.g. cement/sand for CMU blocks.

b. Transportation cost of these materials to the production site.

c. Labor cost in the production process.

d. Establishment cost of the production plant.

e. Certain percentage of profit.

Since there is no commercial production of adobe in Saudi Arabia, the adobe blocks are to be produced specifically for particular projects. For estimating the cost of producing adobe blocks for the Al-Rahmah mosque the number blocks required for the columns and arches are estimated. Figure 5.4 shows the detail of a typical arch on columns.

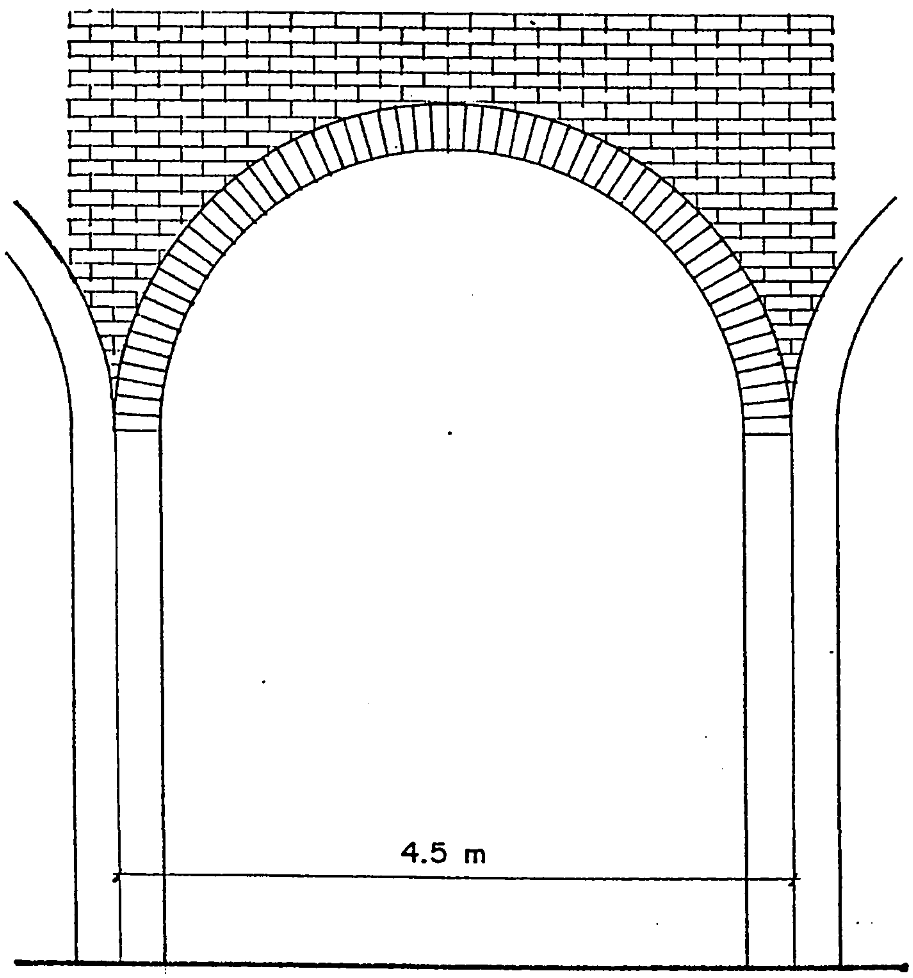


Figure 5.4 Detail of an arch on columns.

A) Material Estimate for Adobe :

i) Columns : 66 nos.

36 courses high, 8 blocks / course	= 36x8x66	= 19,008

ii) Arches : 80 nos.

4 skins, 60 blocks / skin	= 4x60x80	= 19,200

iii) Work over arches : 80 nos.

4 skins, 166 blocks / skin	= 4x166x80	= 22,400
Total (add 5% wastage)		= 96,000

Total sq.m. of blocks = 96,000/22.3 per sq. m. = 4,305 sq m

Amount of sand needed : 96,000 bricks x 5 Kg/brick x 60%

= 290,000 Kg

Sand in m^3 (1420 Kg/LCM) 205 m^3

Amount of clay needed : 96,000 bricks x 5 Kg/brick x 15%

= 72,000 Kg

Clay in m^3 (1660 Kg/LCM) 44 m^3

Amount of marl needed : 96,000 bricks x 5 Kg/brick x 25%

= 120,000 Kg

marl in m^3 (1250 Kg/LCM) 96 m^3

No. of truck loads required...

Capacity of truck	5 m^3 (heaped)
loose	
Sand - 205 / 5	41 loads
Clay - 44 / 5	9 loads
Marl - 96 / 5	20 loads
Total	70 loads

The truck rent is SR 100.00 per load

B) Cost Estimate for Adobe **:**

The costs of CMU blocks, clay tiles and calcium silicate tiles are known. To estimate the cost of adobe blocks material, labor and transportition costs have to be calculated.

i. Material Cost **:** The basic materials for adobe (clay, marl & sand) are found in their sites which can be collected without any costs. The cost of bitumen emulsion is SR 200.00 per 200 kg containers. Again, palm tree fibre is free of cost.

ii. Transportation Cost **:** Tranporting these materials from their natural sites to the production site, which is the project construction site or very near to it, requires hauler trucks and a front loader. Using a 1.0 cu. m. capcity of loader with cycle time of five minutes (26), it is needed only for two hours to load 41 truck loads of sand. However, the the renting of the loader is at the rate of SR 50.00 per hour for a minimum of three hours. For simplicity of calculations it is assumed that all the materials (sand, clay and marl) can be transported to the production site at the same time. This may not be true in reality due to the fact that there may not be enough space to store 205 cu. m. of sand along with the other materials. The loader cost is then SR 150.00 each for sand, clay and marl. Therefore, the total transportation cost comes out to be as follows :

Cost of Loaders :	3 sites X SR 150.00	= SR 450.00
Cost of Trucks :	70 trucks x SR 100.00	= SR 7000.00
Total cost of Transportation		= SR 7450.00

iii. Labor Cost : Using the brick making machine, 1000 bricks can be produced per day by four labors. With this productivity it will take 96 working days to produce the required number of bricks. The work of the labors will include pulverizing (if necessary) the materials, mixing, watering, making the bricks, stacking and curing as well (7). Taking the cost of labor at the rate of SR 1000.00 per month and 26 working days per month the labor cost is as follows :

96 / 26 x SR 1000.00 x 4 labors = SR 14,800

assuming the labors will be working elsewhere after this job.

If one supervisor is employed to look after the job at the rate of SR 2000.00, the supervisory cost is

Supervisory cost : 96 / 26 x 2000 = SR 7,400.00

iv. Establishment Cost : Since the mosque rebuilding project will be an in-house job for KFUPM, the establishment cost is not taken into consideration.

v. Unit Cost of Adobe : Total cost of producing the bricks includes labor, material and transportaion cost. Adding these costs and dividing it by the m^2 will give production cost of adobe per m^2 as follows :

Material cost(emulsion as additive)	= SR 24,000.00
Total labor cost	= SR 22,200.00
Total tranportaion cost	= SR 7,450.00
Total Production cost	= SR 53,650.00

Per m^2 cost of adobe bricks is 53650 / (96000 / 22.3 bricks per m^2)

= SR 12.46 / m^2

This cost is a little less than the cost of CMU bricks - the least costly brick of the three other alternatives.

5.3.2 Life Cycle Cost

To determine the life cycle cost present worth and annual equivalent methods are used. In order to calculate the life cycle cost, there are certain assumptions that have to be made the design or materials to be evaluated and also the conditions of economy under which a building of particular use will be operative. These assumptions include prices in future, rates of interest, building life and building component life and levels of taxation. (23)

5.3.2.1 Prices in Future

Price changes in the future occurs in two ways :

1. Changes in relation to the value of currency; and
2. Changes in relation to the conditions of their supply and demand.

As value of currency falls prices of goods and services increase. Price changes during inflationary period happens in the ratio as that of inflation. In other words, the real costs of goods measured in terms of resources or in terms of each other do not change. Thus real costs of materials remain unaffected by inflation. On the other hand, price changes due to materials' supply and demand is difficult to forecast. There are techniques to deal with the uncertainty of future prices. However, it is generally assumed that future prices of materials remain unchanged. (23)

5.3.2.2 Rates of Interest

Building developers usually borrow money to finance a building project or divert the money from other alternative uses. Interest, here, is the rate at which the money is borrowed, or the average return which the money can earn from other alternative investments. The average return can, of course, be different than the predicted return. A better method is to use true rates of return and either the actual life or the life over which foreseeable predictions can be made. This approach is useful for houses, office buildings, shops etc. A true rate of interest is important as it affects the decision to be taken. A low rate of interest will mean lower cost of servicing the capital and a worthwhile investment now to reduce costs in future. High rate of interest will lower construction standards as the resulting higher costs of operation and maintenance are heavily discounted. In cases of public buildings, it is sometimes arguable to take into account the interest factor as public organizations do not borrow money for construction of their buildings. However, it is important to consider a rate of return for the investment as money can always be put to other uses. For economic analysis, the rate of interest is often considered a variable for money put to alternative uses may earn different returns. Hence, usually a low, a high and a median value of interest rates are used in economic analysis. (23)

5.3.2.3 Life of Building and Building Components

Cost comparisons among the alternative designs, various building materials and components are made within the pattern set by the life of the building as predicted. The prediction should be realistic and the predicted life should normally be a period over which investment is recoverable. Usually, the life of a building is substantial - sixty to eighty years. A predicted shorter period of life (five to ten years) can affect the annual equivalent of the initial cost of the building. Errors in costs and decision making are more likely to occur if the predicted life is substantially shorter. As buildings may last many years, building components need to be replaced several times over the life of the building and repair and maintenance is also necessary to be carried out regularly. In cost comparison, it is implied that comparison is necessary not only of present costs, but also of the repair and maintenance costs occuring at different periods during the life of the building. (23)

5.3.2.4 Taxation

The effect of taxes is an important issue. However, it does not apply in the particular case of Saudi Arabia. Hence, this issue is not considered in the economic analysis.

5.3.2.5 Assumptions for Life Cycle Cost Analysis.

This life cycle cost study involves rebuilding of a mosque - a building for public use. The cost comparisons are among the selection of materials for the superstructure : Adobe and Clay Burnt Bricks. Construction labor cost is assumed to be the same. Labor productivity may vary with the choice of the material - it will have minimum effect on the overall cost. Although inclusion of these costs along with other non-variable construction cost may change the annual equivalent, the present worth remains unaffected. The maintenance cost of the building will vary as different materials are used for the wall treatment. In the case of Clay Bricks the walls are treated with oil based paint, repainted every four years. In case of Adobe, the walls are treated with lime solution every two years. The future prices of these materials are assumed to remain unchanged. The rates of interest to calculate the present worth and annual equivalent worth are assumed at 5%, 10% and 15%. Economic analysis is calculated over a 20 years period as this will be a good indicator of the economics.

5.3.2.6 Calculations

For calculations, the prices are taken from a local contracting firm. These prices are quotation cost of the contractor and may vary. The labor productivity values are taken from Dutta (7). Tables 5.1, 5.2, 5.3 and 5.4 gives the materials and cost estimate for adobe bricks and clay burnt bricks.

Table 5.1 Materials estimate for adobe bricks construction.

Particulars of Items	No.	Length, m	Width, m	Height/ Depth, m	Quantity	Notes
1. Excavation for columns	66	1.00	1.00	1.00	66 cu m	
2. Foundation						
Concrete	66	1.00	1.00	0.20	13.2 cu m	
Brickwork in mud mortar upto plinth	66	0.9	0.9	1.5	80.19 cu m	
Mud mortar	--	--	--	--	24 cu m	30 cu m/100 cu m
Backfilling	66	3.8	0.05	0.8	10 cu m	
3. Brickwork-columns, arch,work over arch						Void below arch deducted from continuous wall
Wall 1	11	15.0	0.6	7.0	693	
		minus void	11.61*40	=464	229 cu m	
Wall 2	4	24.0	0.6	7.0	403	
		minus void	11.61*20	=232	171 cu m	
Wall 3	1	20.0	0.6	7.0	84	
		minus void	11.61*5	=58	26 cu m	
Wall 4	1	35.0	0.6	7.0	147	
		minus void	11.61*9	=104	43 cu m	
Total wall brickwork					469 cu m	
					4690 sq m	
Mud mortar					28.14 cu m	0.6 cu m/100 sq m
4. Roof						
Vault	1	5.18(mean)	0.3	25	38.9 cu m	
Dome	2	3.0(span)	volume 5.1	cu m	10.2 cu m	
Mud mortar	--	(247+62)	sq m		1.9 cu m	0.6 cu m/100 sq m
5. Floor						
Backfilling	1	55.0	24.0	0.65	858	
		minus	66*.9*.9*.65	=35	823 cu m	
2 layers of brick	1	55.0	24.0	2 layers	2640	
		minus	2*66*.9*.9	=107	2533 sq m	
Mud mortar	--				81 cu m	3.2 cu m/100 sq m
6. Plastering, 12 mm with mud mortar	--	1869 sq m			37.3 cu m	2 cu m/100 sq m all surfaces
7. Painting, 3 coats of lime	--	1869 sq m			560.7 kg	all surfaces

Table 5.2 Materials estimate for clay burnt bricks construction.

Particulars of Items	No.	Length, m	Width, m	Height/ Depth, m	Quantity	Notes
1. Excavation for columns	66	1.00	1.00	1.00	66 cu m	
2. Foundation						
Concrete	66	1.00	1.00	0.20	13.2 cu m	
Brickwork in cement mortar upto plinth	66	0.8	0.8	1.4	60 cu m	
1:6 cement mortar	--	--	--	--	18 cu m	30 cu m/100 cu m
Backfilling	66	3.6	0.10	0.8	19 cu m	
3. Brickwork-columns, arch,work over arch						Void below arch deducted from continuous wall
Wall 1	11	15.0	0.6	7.0	693	
		minus void	11.61*40	=464	229 cu m	
Wall 2	4	24.0	0.6	7.0	403	
		minus void	11.61*20	=232	171 cu m	
Wall 3	1	20.0	0.6	7.0	84	
		minus void	11.61*5	=58	26 cu m	
Wall 4	1	35.0	0.6	7.0	147	
		minus void	11.61*9	=104	43 cu m	
Total wall brickwork					469 cu m	
				469*5	2345 sq m	
1:6 cement mortar					28.14 cu m	0.6 cu m/100 sq m
4. Roof						
Vault	1	5.34(mean)	0.4	25	53.4 cu m	
					267 sq m	
Dome	2	3.0(span)	volume 7.3		14.6 cu m	
					73 sq m	
1:6 cement mortar		(267+73)	sq m		2.0 cu m	0.6 cu m/100 sq m
5. Floor						
Backfilling	1	55.0	24.0	0.40	550	
		minus	66*.8*.8*.4	=17	533 cu m	
1 layer of brick	1	55.0	24.0	--	1320	
		minus	66*.8*.8*	=42	1278 sq m	
1:6 cement mortar					41 cu m	3.2 cu m/100 sq m
6. Plastering, 12 mm with 1:6 cement mortar		1869 sq m			37.3 cu m	2 cu m/100 sq m all surfaces
7. Painting		1869 sq m				all surfaces

Table 5.3 Cost estimate for adobe bricks construction.

Particulars of Items	No.	Quantity	Unit Cost per quantity	Total Cost SR	Notes
1. Excavation for columns	66	66 cu m	368.73	24336	
2. Foundation					
Concrete	66	13.2 cu m	3143.17	41490	
Brickwork in mud mortar upto plinth	66	801.9 sq m	12.46	9992	
Mud mortar	--	24 cu m	232	5568	
Labor	--	80.2 cu m	8.25 /hour	3529	0.1875 cu m/hour
Backfilling	--	10 cu m	152.3	1523	
3. Brickwork-columns, arch,work over arch					
Total wall brickwork	--	4690 sq m	12.46	58437	
Mud mortar	--	28.14 cu m	232	6528	
Labor	--	469 cu m	8.25	20636	0.1875 cu m/hour
4. Roof					
Vault	1	389 sq m	12.46	4847	
Dome	2	102 sq m	12.46	1270	
Mud mortar	--	1.9 cu m	232	441	
Labor	--	49.1 cu m	8.25	8120	
5. Floor					
Backfilling	823 cu m		232.46	191315	
2 layers of brick	--	2533 sq m	12.46	31561	
Mud mortar	--	81 cu m	232	18792	
Labor	--	2533 sq m	8.25	20897	
6. Plastering, 12 mm with mud mortar	--	37.3 cu m	232	8654	all surfaces
Labor	--	1869 sq m	8.25	15419	
7. Painting, 3 coats of lime	--	560.7 kg	1	561	
Labor	--	1869 sq m	8.25	1851	for 3 coats
Total Cost				303749	
		Contingencies	3% overall	9912	
		Supervision	8% overall	24300	
GRAND TOTAL				SR 337961 ~SR 338,000.00	

Table 5.4 Cost estimate for clay burnt bricks construction.

Particulars of Items	No.	Quantity	Unit Cost per quantity	Total Cost SR	Notes
1. Excavation for columns	66	66 cu m	368.73	24336	
2. Foundation					
Concrete	66	13.2 cu m	3143.17	41490	
Brickwork in cement mortar upto plinth	66	296	18.75	5550	
1:6 cement mortar	--	18 cu m	108.86	1959	
Labor	--	60 cu m	8.25	3173	
Backfilling	--	19 cu m	152.30	2894	
3. Brickwork-columns, arch,work over arch					
Total wall brickwork	--	2345 sq m	18.75	43969	
1:6 cement mortar	--	14 cu m	108.86	1524	0.6 cu m/100 sq m
Labor	--	469 cu m	8.25	20636	0.1875 cu m/hour
4. Roof					
Vault	1	267 sq m	18.75	5006	
Dome	2	73 sq m	18.75	1369	
1:6 cement mortar	--	2.0 cu m	108.86	218	
Labor	--	68 cu m	8.25	11220	0.05 cu m/hour
5. Floor					
Backfilling	1	533 cu m	232.46	123901	
1 layer of brick	1	1278 sq m	18.75	23963	
1:6 cement mortar	--	41 cu m	108.86	4463	
Labor	--	1278 sq m	8.25	10544	1 sq m/hour
6. Plastering, 12 mm with 1:6 cement mortar	--	37.3 cu m	108.86	4060	
Labor	--	1869 sq m	8.25	15419	1 sq m/hour
7. Painting	--	1869 sq m	26	48594	labor included
Total Cost				394288	
		Contingencies	3% overall	11829	
		Supervision	8% overall	31543	
GRAND TOTAL				SR 437660	
				~SR 437,700.00	

Economic Analysis has been performed over a period of 20 years with three rates of interests (i = 5 %, 10 %, 15 %). Both present worth and annual worth values have been calculated for adobe and clay burnt bricks. The formulas for calculating the present worth and annual worth are given below.

In general,

(1) P = F (P/F, i%, N)

where,

P = Present amount,

F = Future amount, and

P/F, i%, N = Single payment present worth factor occuring at N period in the future.

(2) A = P (A/P, i%, N)

where,

A = Annual amount,

P = Present amount, and

A/P, i%, N = Uniform series capital recovery factor.

The factor values are used from tables.

Besides their unit price difference, there is a difference of about SR 100,000.00 in construction cost (Table 5.3 and 5.4). Present worth value of adobe construction is SR 240,000.00 less costly than building with clay burnt bricks at 5 % rate of interest. At 10 % and 15 % rates of interests, the differences are SR 188,000.00 and SR 160,000.00. The annual equivalent worth is also greater in clay burnt bricks construction than that of adobe. The calculations are presented in Tables 5.5 and 5.6 and Figures 5.5 and 5.6. In the analysis, only the regular painting job as maintenance is considered. The painting costs are taken from Tables 5.3 and 5.4, added are 3 % contingencies and 8 % supervision to the costs. Other repairing or renovation costs are not included for it is difficult to forecast any such work. However, the analysis serves the purpose of comparison to some extent.

Table 5.5 Present worth and annual equivalent of adobe construction.

Year	Cost	Present Worth, SR i = 5 %	i = 10 %	i = 15 %
0	338,000	338,000	338,000	338,000
2	2,700	2,449	2,231	2,041
4	2,700	2,221	1,844	1,544
6	2,700	2,015	1,524	1,167
8	2,700	1,827	1,260	883
10	2,700	1,658	1,041	667
12	2,700	1,503	860	505
14	2,700	1,364	711	382
16	2,700	1,237	588	289
18	2,700	1,122	486	218
20	2,700	1,018	401	165
TOTAL PRESENT WORTH		354,514	348,946	345,861
ANNUAL EQUIVALENT		28,432	41,001	55,269

Table 5.6 Present worth and annual equivalent of clay burnt bricks construction.

Year	Cost	Present Worth, SR i = 5 %	i = 10 %	i = 15 %
0	437,700	437,700	437,700	437,700
4	54,000	44,426	36,882	30,877
8	54,000	36,547	25,191	17,653
12	54,000	30,067	17,204	10,093
16	54,000	24,737	11,750	5,773
20	54,000	20,353	8,024	3,299
TOTAL PRESENT WORTH		593,830	536,751	505,395
ANNUAL EQUIVALENT		47,625	63,068	80762

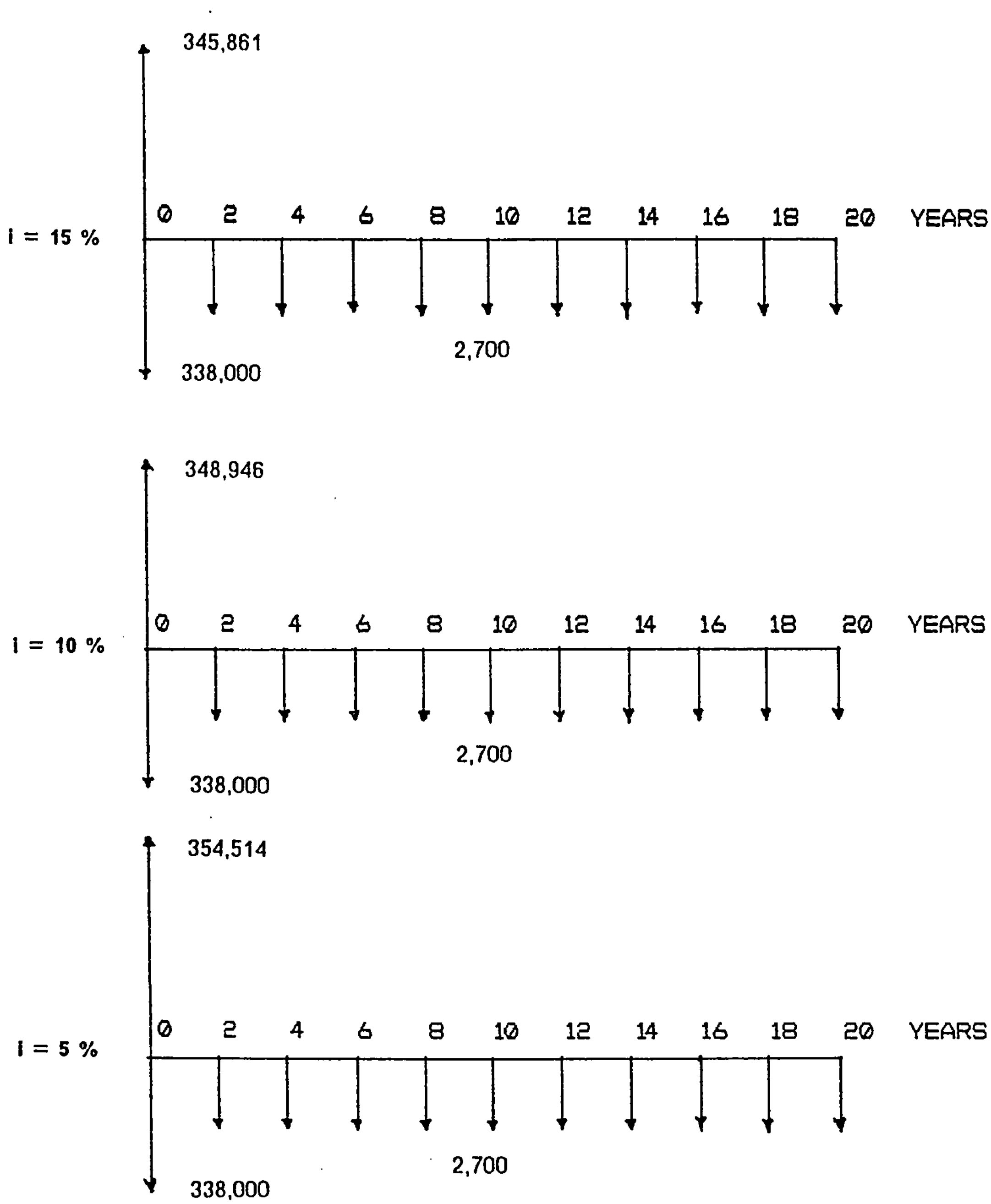


Figure 5.5 Cash flow diagram for adobe construction.

i = 5 %, 10 % , 15 %

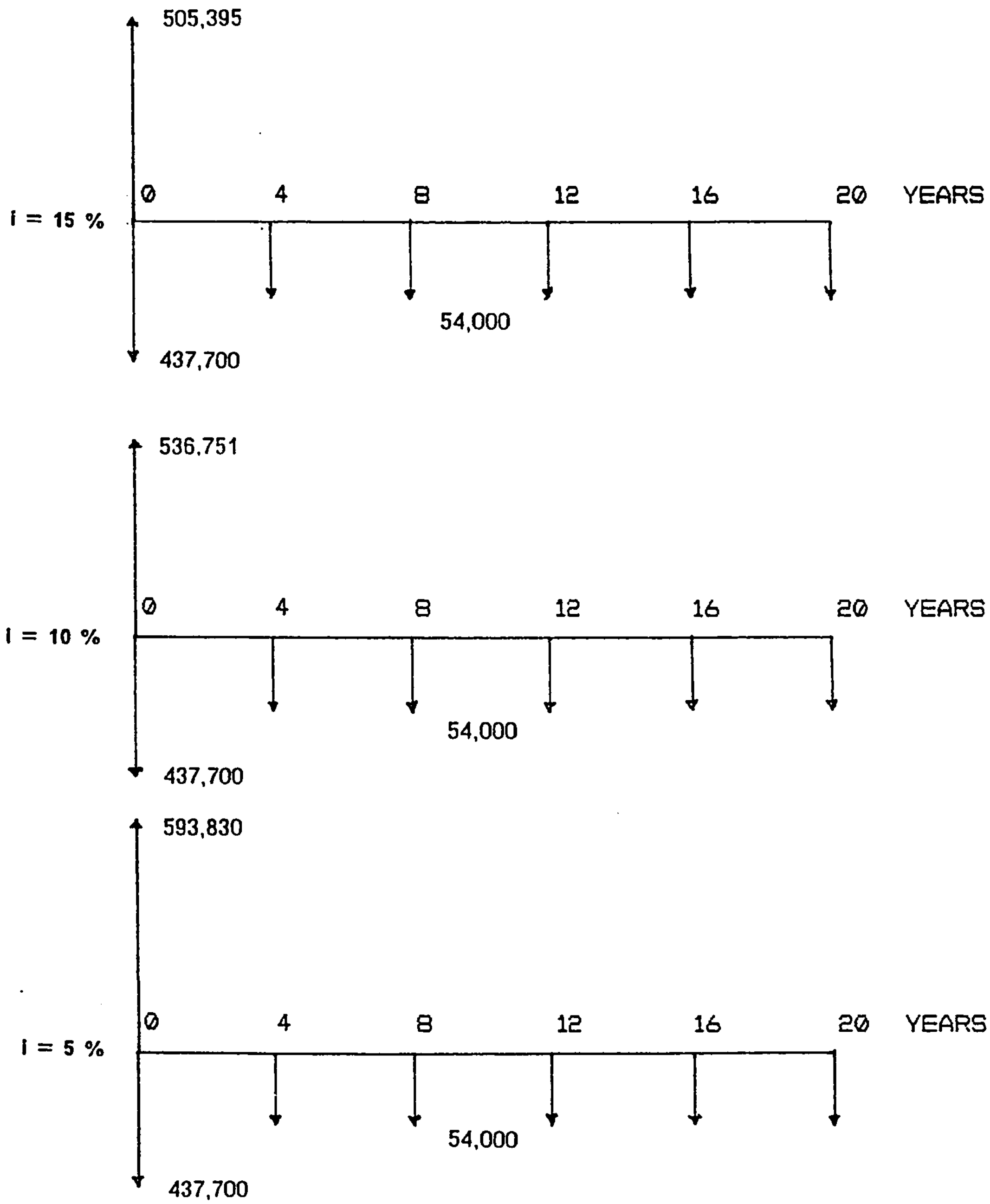


Figure 5.6 Cash flow diagram for clay burnt bricks construction.

i = 5 %, 10 % , 15 %

Chapter 6

SUMMARY, CONCLUSION and RECOMMENDATION

6.1 Summary of the Research

Chapter 1 gave a background of earth construction throughout history and various civilizations, shift towards modern materials in the wake of industrial revolution and revival after the energy crisis in the 70's. In recent years, interest towards earth construction has alsogrown in Saudi Arabia. The chapter discussed the objectives, scope and limitations, research methodology and significance of this study. Saudi Arabia has a traditional and historical background in construction with earth. It was this background and recent interests that encouraged to take up this research study on the feasibility of earth construction, in particular, adobe contruction in the eastern province as a case study.

Chapter 2 discussed the works of research interests and studies. The first part of the chapter described the various forms of earth construction. The second part discussed the research works at Grenoble in France, Hassan Fathy's Gourna Housing in Egypt, Janadria Exhibit-Centre in Earth in

Riyadh, Saudi Arabia and reviewed literature of contituent material and thermal study. A summary of the effects of additives on different soils in literature reviews was presented in the third part of the chapter.

Chapter 3 described the soil selection criteria by locating soil sites, finding soil constituents, various laboratory test methods to determine soil type and quality. The chapter also discussed the additives that are used to improve the strength and durability of adobe bricks.

Chapter 4 presented all the test results of the soil and the adobe bricks. The first part of the chapter discussed the soil test results of the two soils collected for this research. Soil mix proportions were also discussed together with the process of making the bricks. And finally, the chapter presented and discussed the test results of the adobe bricks without additives and with additives.

Chapter 5 discussed the economic feasibility of adobe bricks in the eastern province of Saudi Arabia. The Al-Rahmah mosque of KFUPM was taken as a case study for economic analysis. A unit cost of adobe bricks was determined for the eastern province using the two soils for comparing with the unit prices of other locally available building bricks. A comparative life-cycle-cost of building the mosque with adobe and CMU blocks was also performed.

6.2 Conclusion

This study attempted to look at the aspects of construction with adobe as an alternative material that has a historical and traditional background in Saudi Arabia. To investigate the feasibility of adobe buildings in the Eastern Province of Saudi Arabia two different soils from two sites has been explored.

The effects of additives of cement, bitumen emulsion and palm tree fibre on the compressive strength and absorption were also investigated. The compressive strengths were low as compared to the minimum value given in the adobe codes of the United States (1). A marked decrease in the compressive strengths with cement as additives has been observed. Further investigation indicated that this is happening due to the Montmorillonite mineral present in the clay which dictates soil mix behavior (4,10). However, there was no significant difference in the compressive strengths of the samples of the same mix proportions. The performance in terms of absorption and shrinkage has been excellent with the additives.

In the economic analysis, it has been seen that the use of emulsion increases the cost per m^2 of the adobe bricks from SR 6.88 to SR 12.46 The results have indicated that it is possible to use compressed adobe bricks stabilized with emulsion for better compressive strength and also absorption. With 5% emulsion, the cost per m^2 of adobe is the same as that of CMU bricks (SR 12.46 versus SR 12.50) However, it is cheaper than Clay Burnt Bricks (SR 18.75 per m^2) and Calcium Silicate Bricks (SR 27.00 per m^2). In the 20 years analysis, it is seen that construction with adobe is far less costlier than that of Clay Burnt Bricks.

6.3 Recommendations

This thesis is the begining of research in adobe in the Eastern Province. It is hoped that it will pave the way for research interests in adobe. In the light of this research and various studies done elsewhere on adobe, the following recommendations are made to carry out further research work :

i. Investigate the use of other alternative additives, such as lime, gypsum, etc. with the same soils used in this research.

ii. Find out methods to use palm tree fibre in an easier way as palm trees are abundant in Saudi Arabia.

iii. Investigate soils from other locations.

iv. Investigate different mix proportions of constituent soils.

v. Do a comprehensive study to obtain a better methodology for soil quality improvements.

vi. The use of alternative additives with varying percentages.

vii. Investigate the feasibility of uncompressed bricks with various soils and additives.

viii. Investigate the feasibility of compressed bricks with various soils and additives.

ix. make on site experiments to investigate the environmental effects.

x. Perform local thermal studies of adobe bricks in order to compare with the available data in literature and studies done in USA.

xi. Develop of a good maintenance criteria for mud constructions.

xii. Develop of a better construction techniques of mud constructions.

xiii. Formulate policies as to how it can be presented to government organizations, public and private sectors for making adobe popular.

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