Investigation on Mass Production of Adobe Bricks

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***Abstract*—Adobe construction is the oldest building form on earth; it has been supporting the human evolution for more than 5000 years. Adobe has the advantage of cheap resources and the wide availability regardless of location. It is the most environment friendly construction method since it is fully recyclable and does not emit any greenhouse gasses.**

This study concentrates on the mass production of adobe bricks, taking adobe construction to the next level from being a random and non-uniform to engineered and precise. During 6 months of research and implementation, various studies were conducted to produce a constant production method which sustains certain properties of the brick and terminates the previous variation found in the native production methods.

***Index Terms*—Adobe Bricks, Mass Production, Brick Drying, Clay Bricks**

I. Introduction

Adobe construction has been, is and will continue to be a certainty. Even though this material has clear advantages of costs, aesthetics, acoustics and heat insulation and low energy consumption, it also has some disadvantages such as being weak under earthquake forces and water action. However, the technology developed to date has allowed a reduction in its disadvantages, stressing its most valuable advantages.

The recommendations presented herein are applicable to adobe constructions in general, but they are especially oriented to popular housing, aiming to enhance the quality of the life standards for the poor people around the world.

Therefore, it does not include solutions involving the use of stabilizers (cement, lime, asphalt, etc.) to improve the strength or durability in order to keep the making of the brick as easy as possible. Also for making the strengthening very economical, no use of the expensive materials (concrete, steel, wood, etc.) has been indicated to enhance the characteristics of the adobe unit.

II. Literature Review

Adobe is a natural building material made from sand, clay, water, and some kind of fibrous or organic material (sticks, straw, and/or manure), which the builders shape into bricks using frames and dry in the sun. Adobe buildings are similar to cob and mud brick buildings. Adobe structures are extremely durable, and account for some of the oldest existing buildings in the world. In hot climates, compared with wooden buildings, adobe buildings offer significant advantages due to their greater thermal mass, but they are known to be particularly susceptible to earthquake damage. [1]

A. Composition

An adobe brick is a composite material made of clay mixed with water and an organic material such as straw or dung. The soil composition typically contains clay and sand. Straw is useful in binding the brick together and allowing the brick to dry evenly. Dung offers the same advantage and is also added to repel insects. The mixture is roughly half sand (50%), one-third clay (35%), and one-sixth straw (15%) by weight. [3]

B. Adobe Bricks

Adobe, or sun-dried mud brick, has a long history of widespread use by the Indians, Spanish-Americans, and Anglo-Americans in the southwest United States, where annual precipitation is low. However, the use of adobe need not be restricted to arid and semiarid climates if buildings are properly protected or certain soil stabilizers are used. In fact, examples of earth-wall construction can be found from New England to South Carolina in climates that are far from arid or semiarid. Modern residences of earth-wall construction have been built since 1920 in Washington, D.C., Illinois, Michigan, Arkansas, Oklahoma, Colorado, North Dakota, Wyoming, Idaho, and in all the southwest states.

The introduction of the wooden form by the Spanish colonists in the late 1600s permitted the adobero (adobe maker) to control the size and weight of the bricks, which in turn allowed for greater construction flexibility. Many sizes of adobe bricks with considerable variation in weight have been produced in the Southwest. It was reported that the brick weights from early California and New Mexico adobe structures varied from 30 to 100 lbs.

TABLE I. Different Adobe Bricks in size with their nominal weight

Dimensions (inches)	Weight (lb)
4 x 8 x 16	30
4 x 9 x 18	38
4 x 12 x 18	50
5 x 9 x 18	48
5 x 12 x 18	60
6 x 12 x 14	100

The adobe bricks that are produced today in New Mexico vary from the small mosque-type Egyptian brick of 3 x 5 x10-inch size, which weighs 8 lbs and is used in the construction of domes and arches, to the Isleta Pueblo terrón brick of 7 x 7 x

14-inch size, which weighs 35 lbs. The principal size manufactured (97%) today by the majority of adobe producers in New Mexico is the 4 x 10 x 14-inch brick that averages 30 lbs in weight. Other sizes of bricks are made that are usually produced only in limited quantities or on special order. [2]

C. Adobe Soils

Adobes can be made from a variety of local soils, but the most suitable soil found in the Rio Grande valley is a sandy loam composed of approximately 55–85% sand and 15–45% finer material (generally more silt than clay) and usually containing caliche (pedogenic or formed-in-the-soil calcium carbonate). A balance of particle sizes is essential to ensure a quality adobe. Clay gives strength to the adobe, but in excessive amounts will cause shrinkage; sand or straw is added to decrease the shrinkage and prevent. [2]

D. Adobe Mortars

During the building of the adobe wall, adobe bricks and pressed-earth blocks are joined together with water-adobe- soil mixture that hardens and becomes firm upon drying. The New Mexico Building Code allows the use of earth mortar if it is composed of the same materials as the bricks. The majority of adobe-brick and pressed-earth-block producers can furnish this screened adobe soil. [2]

E. Thermal Properties

An adobe wall can serve as a significant heat reservoir due to the thermal properties inherent in the massive walls typical in adobe construction. In tropical and other climates typified by hot days and cool nights, the high thermal mass of adobe levels out the heat transfer through the wall to the living space. The massive walls require a large and relatively long input of heat from the sun (radiation) and from the surrounding air (convection) before they warm through to the interior and begin to transfer heat to the living space. After the sun sets and the temperature drops, the warm wall will then continue to transfer heat to the interior for several hours due to the time lag effect. Thus, a well-planned adobe wall of the appropriate thickness is very effective at controlling inside temperature through the wide daily fluctuations typical of desert climates, a factor which has contributed to its longevity as a building material. In addition, the exterior of an adobe wall can be covered with glass to increase heat collection. In a passive solar home, this is called a Trombe wall. [3]

F. Adobe Wall Construction

When building an adobe structure, the ground should be compressed because the weight of adobe bricks is significantly greater than a frame house, and may cause cracking in the wall. The footing is dug and compressed once again. Footing depth depends on the region and its ground frost level. The footing and stem wall are commonly 24 and 14 inches, much larger than a frame house because of the weight of the walls. Adobe bricks are laid by course. Each course is laid the whole length of the wall, overlapping at the corners on a layer of adobe mortar. Adobe walls usually never rise above two stories because they are load bearing and have low structural strength. When placing window and door openings, a lintel is placed on top of the opening to support the bricks above. Within the last courses of brick, bond beams are laid across the top of the bricks to provide a horizontal bearing plate for the roof to distribute the weight more evenly along the wall. To protect the interior and exterior adobe wall, finishes can be applied, such as mud plaster, whitewash or stucco. These finishes protect the adobe wall from water damage, but need to be reapplied periodically, or the walls can be finished with other non-traditional plasters providing longer protection. [3]

III. Earthquake Performance

In addition to its low cost and simple construction technology, adobe construction has other advantages, such as excellent thermal and acoustic properties. However, most traditional adobe construction responds very poorly to earthquake ground shaking, suffering serious structural damage or collapse and causing a significant loss of life and property. In the 2001 earthquakes in El Salvador, 1,100 people died, more than 150,000 adobe buildings were severely damaged or collapsed, and over 1,600,000 people were affected. That same year, an earthquake in the south of Peru caused the deaths of 81 people, the destruction of almost 25,000 adobe houses, and damage to another 36,000 houses. In the latest 2003 Bam earthquake, more than 26,000 people died and over 60,000 were left without shelter, primarily due to the collapse of adobe houses.

Adobe buildings are not safe in seismic areas because their walls are heavy and they have low strength and brittle behavior. During strong earthquakes, due to their large mass, these structures develop high levels of seismic forces, which they are unable to resist, and therefore they fail abruptly. Typical modes of failure during earthquakes are severe cracking and disintegration of walls, separation of walls at the corners, and separation of roofs from the walls, which can lead to collapse. [4]

IV. SOIL INVESTIGATION

The objective of any soil classification system is to predict the engineering properties and behaviour of a soil centred on a few simple laboratory or field tests. Those test results are then used to classify the soil and set it into a several groups that have soils with similar engineering characteristics.

Soils often exist in nature separately as sand, gravel; which usually they establish a mixture with varying particle distribution sizes. However soils can be defined according to their geotechnical characteristics into coarse grained soils and fine grained soils; coarse grained soils contains grains larger than 75 μm and the fine grained soils contain grains smaller than 75 μm.

Several samples were obtained from various areas around and inside Famagusta City in North Cyprus. Tests were performed on those samples in order to decide which one will best serve the needs of the project. These tests include:

- Atterberg Limit
- Sieve Analysis (Dry and wet sieving)
- Hydrometer Test

The locations from which the samples were acquired are:

- Minarelikoy Village, Degirmenlik region (GPS Coordinates: 35°13'40" N - 33°28'00" E)
- Famagusta – Karpass Road (FK Road) (GPS Coordinates: 35°09'30" N - 33°54'13" E)
- Teknopark Yard - Famagusta (GPS Coordinates: 35°08'36" N - 33°54'00" E)

A. Particle Size Distribution

Sieve analysis was used to determine the grain size distribution of soils where the fines grain size distribution was obtained through hydrometer analysis. Sieve and hydrometer analyses are essential for determining the grain size distribution of soils, because coarse and fine grains are found together in soils. [5]

1) Dry Sieve Analysis

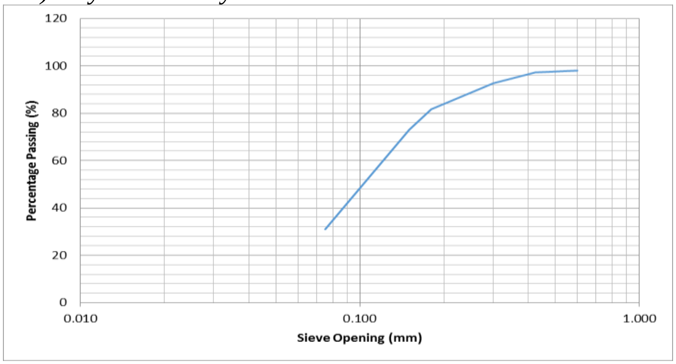

Fig. 1. Minarelikoy Soil Grading Curve

Fig. 2. Famagusta-Karpass Road Soil Grading Curve

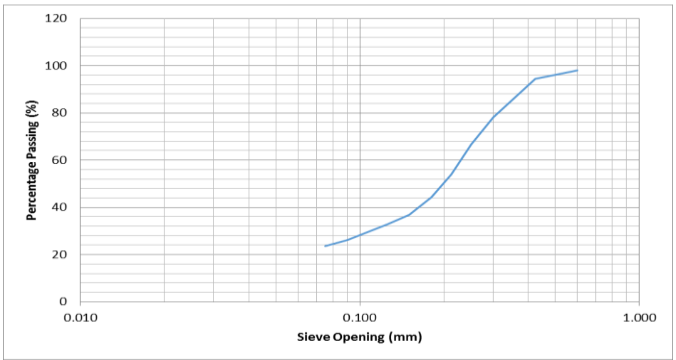

Fig. 3. Teknopark Soil Grading Curve

2) Wet Sieve Analysis

The test involves sieving a 100 g grinded soil sample through 75 µm sieve and washing the sample over the sieve until all the particles smaller than 75 µm pass through. Then the remaining amount is collected, dried and weighed. This weight indicates the percentage of sand particles within the sample, by subtracting it from 100%, the amount of clay and silt is found. Table II shows the results obtained from this test.

TABLE II. WET SIEVE ANALYSIS RESULTS

Sample	Sample Weight (g)	Weight of Sand Particles (g)	Percentage of Sand (%)	Percentage of Clay & Silt (%)
Minarelikoy	100	23.3	23.3	76.7
F-K Road	100	4.9	4.9	95.1
Teknopark	100	5.7	5.7	94.3

3) Hydrometer Analysis

A hydrometer analysis is the process by which fine-grained soils, silts and clays, are graded. Hydrometer analysis is performed if the grain sizes are too small for sieve analysis. The basis for this test is Stoke's Law for falling spheres in a viscous fluid in which the terminal velocity of fall depends on the grain diameter and the densities of the grain in suspension and of the fluid. The grain diameter thus can be calculated from the knowledge of the distance and time of fall. The hydrometer also determines the specific gravity (or density) of the suspension, and this enables the percentage of particles of a certain equivalent particle diameter to be calculated. [6]

The results obtained from the hydrometer test are reported. Table III shows the hydrometer test data for the sample taken from Minarelikoy village and its particle size distribution for those smaller than 75 micron is shown in Figure 4.

B. Atterberg limit

The Atterberg limits determine the nature of fine grained soils depending on the water content. The Atterberg limits can be used to distinguish between silt and clay, and their types. [7]

1) Determination of liquid limit

The liquid limit of a soil is defined as the moisture content at which the soil is sufficiently fluid to flow a specified amount when lightly jarred 25 times in a standard apparatus. Tables IV - VI and Figures 5-7 detail the results acquired using this test.

After studying the above limits, the optimum water content was found and tabulated in Table VII.

2) Determination of plastic limit

The plastic limit of a soil is defined as that moisture content at which a thread of soil can be rolled without breaking until it is only 3.2 mm in diameter.

After obtaining the results from the Atterberg Limits tests, the soil type can be classified by using the plasticity index along with the optimum water content on the plasticity chart shown in Figure 8. The soil type is then determined to be silty organic with low plasticity. [8]

TABLE III. HYDROMETER ANALYSIS RESULTS FOR THE SOIL OBTAINED FROM MINARELIKOY

Test Start													
1/4/12 14:12:14													
Date	Elapsed time (sec)		R_h	Temperature (°C)	ρ_ω (g/cm³)	ν (g sec/cm²)	M_t	Rh+cm	Hr (cm)	B (cm sec)	D (mm)	K (%)
1/4/12 14:12:14	15	1296000	32.5	18.5	0.998505	0.106720	-0.2377650	33.1	5.976	1163161.20	0.0681	92.71
1/4/12 14:12:14	30	2592000	31.5	18.5	0.998505	0.106720	-0.2377650	32.1	6.211	1163161.20	0.0491	89.50
1/4/12 14:13:14	60	5184000	31	18.5	0.998505	0.106720	-0.2377650	31.6	6.329	1163161.20	0.0350	87.89
1/4/12 14:14:14	120	10368000	30.2	18.5	0.998505	0.106720	-0.2377650	30.8	6.518	1163161.20	0.0251	85.32
1/4/12 14:16:14	240	20736000	24.5	18.5	0.998505	0.106720	-0.2377650	25.1	7.860	1163161.20	0.0195	67.01
1/4/12 14:20:14	480	41472000	15.5	18.5	0.998505	0.106720	-0.2377650	16.1	9.979	1163161.20	0.0156	38.10
1/4/12 14:27:14	900	77760000	13.5	18.6	0.998486	0.106438	-0.2207142	14.1	10.450	1160078.41	0.0116	31.73
1/4/12 14:42:14	1800	155520000	12.3	20.9	0.998005	0.100258	0.2028068	12.9	10.733	1092397.57	0.0081	29.24
1/4/12 15:12:15	3600	311040000	11.2	20.8	0.998027	0.100515	0.1831635	11.8	10.992	1095216.14	0.0058	25.64
1/4/12 16:12:16	7200	622080000	10.2	20.8	0.998027	0.100515	0.1831635	10.8	11.228	1095216.14	0.0041	22.43
1/4/12 18:12:18	14400	1244160000	9.2	20.8	0.998027	0.100515	0.1831635	9.8	11.463	1095216.14	0.0030	19.22
1/5/12 14:12:14	86400	7464960000	5	19.8	0.998242	0.103144	-0.0071757	5.6	12.452	1124010.75	0.0013	5.12
1/6/12 14:12:14	172800	14929920000	5	20.4	0.998114	0.101554	0.1056934	5.6	12.452	1106600.08	0.0009	5.48
1/7/12 14:12:14	259200	22394880000	5	20.4	0.998114	0.101554	0.1056934	5.6	12.452	1106600.08	0.0007	5.48

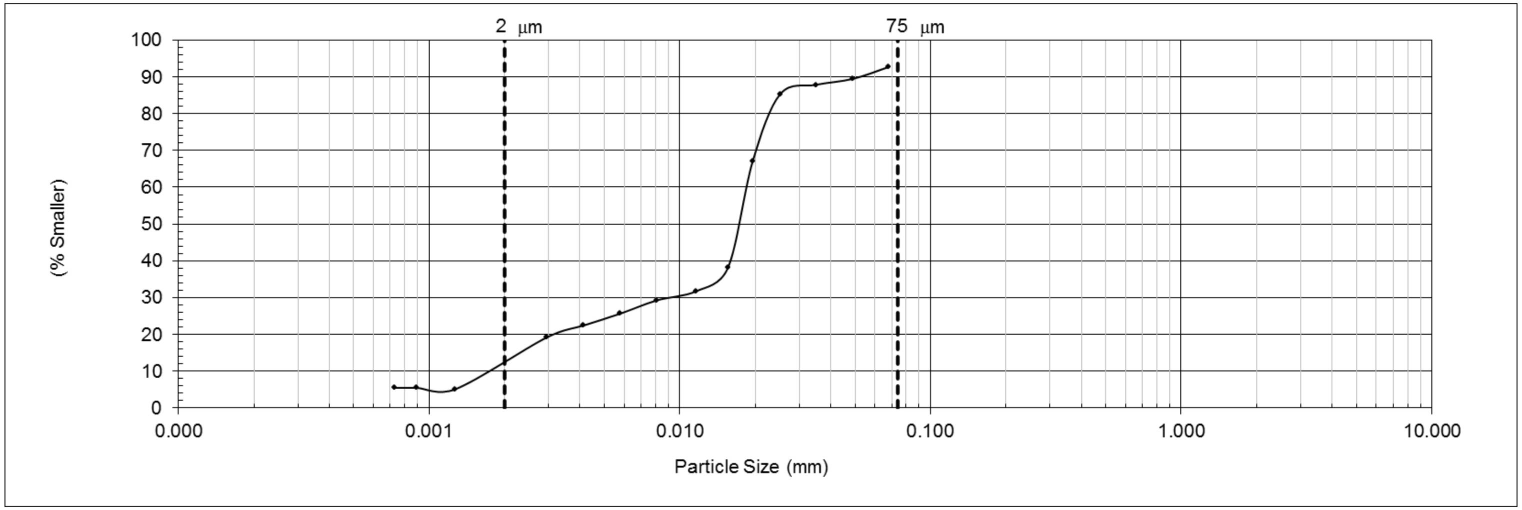

Fig. 4. Minarelikoy Grading Curve (For Particles Smaller than 75 micron)

TABLE IV. LIQUID LIMIT DATA FOR MINARELIKOY SOIL

ID	Mc	Mw	Md	# of Drops	Water Content (%)
1	6.65	28.97	24.2	114	27.2
2	6.59	26.75	22.2	62	29.2
3	6.67	15.84	13.6	60	32.3
4	6.63	12.16	10.7	42	35.9
5	6.67	22.73	18	17	41.8

TABLE V. LIQUID LIMIT DATA FOR FAMAGUSTA-KARPASS SOIL

ID	Mc	Mw	Md	# of Drops	Water Content (%)
1	9.83	19.31	17.12	74	30.0
2	6.67	26.32	21.82	48	29.7
3	9.48	32.62	27.13	37	31.1
4	18.91	29.84	27.04	17	34.4
5	9.9	23.29	19.79	13	35.4

TABLE VI. LIQUID LIMIT DATA FOR TENKOPARK SOIL

ID	Mc	Mw	Md	# of Drops	Water Content (%)
1	22.75	56.39	48.1	44	32.7
2	20.1	29.95	27.5	30	33.1
3	9.73	25.36	21.4	22	33.9
4	6.74	16.38	13.9	16	34.6
5	6.76	22.26	18.1	14	36.7

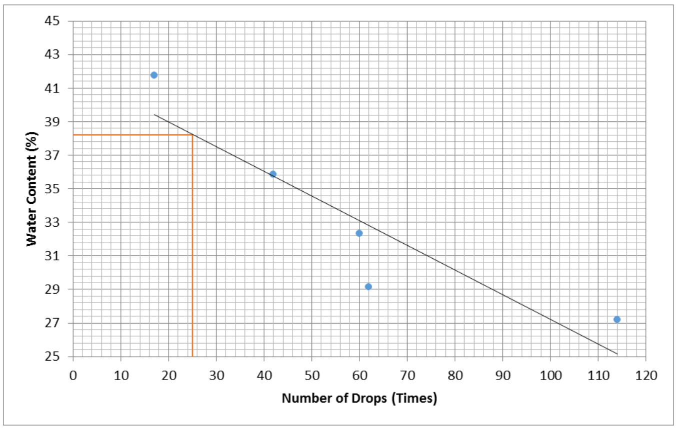

Fig. 5. Determining Optimum Water Content for Minarelikoy Soil

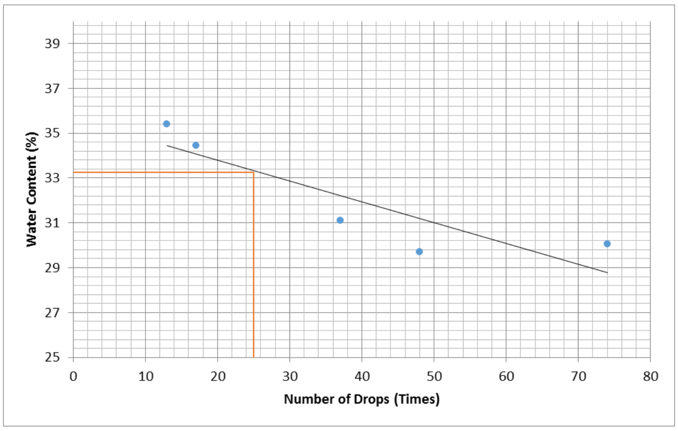

Fig. 6. Determining Optimum Water Content for Famagusta-Karpass Soil

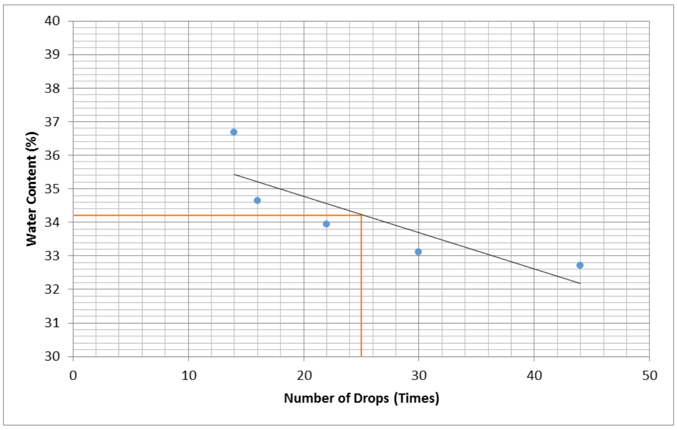

Fig. 7. Determining Optimum Water Content for Tenkopark Soil

TABLE VII. HYDROMETER ANALYSIS RESULTS FOR THE SOIL OBTAINED FROM MINARELIKOY

Sample	Optimum Water Content (Liquid Limit)
Minarelikoy	38.20
Famagusta-Karpass Road	33.25
Teknopark	34.20

TABLE VIII. HYDROMETER ANALYSIS RESULTS FOR THE SOIL OBTAINED FROM MINARELIKOY

ID	Mc	Mw	Md	Plastic Limit	Plasticity Index
Minarelikoy	6.58	13.93	12.4	25.8	12.4
FK Road	9.88	13.44	12.76	23.6	9.65
Teknopark	6.71	14.62	13	26.3	7.9

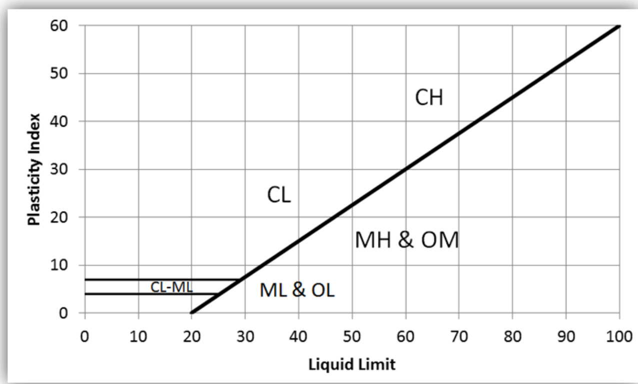

Fig. 8. Soil Classification Chart

C. Determination of Shrinkage Limit

The linear shrinkage of the soil is measured from the sample before and after drying it to determine how much the soil will shrink after drying. [9]

After performing the preceding tests, the soil chosen for the test was the Famagusta-Karpass road sample, for the amount available to be used in production.

Other soil samples were also used for production with the same production methods and proved to be successful and useable in mixing and production of adobe.

V. Testing Apparatuses

For the mixing purposes; several lab tools were used. Since the mix has no chemical reactions; any mixer or even hand-mixing can be applied. In this particular project; hand-mixing in a trolley was used to perform the mixing procedure. The moulds consisted of a wooden frame with an initial size of (35 x 25 x 10 cm) which was lately changed to (25 x 15 x 10 cm) for few reasons that were faced during casting. Under the mould, a portable metal plate was used to hold the bottom surface of the brick over the oven mesh. For levelling the surface, a straight-ended trowel is used.

For some trial mixes; the normal concrete mixer was used, but the resulting mix did not meet the specifications and the soil particles were not properly mixed with the water. That inconvenience was due to some defects in the available mixer in the laboratory. The drying process is carried out in a laboratory oven of 120 lt. capacity and 200°C maximum temperature.

A local-made metal mould is also used to make holes in the bricks in an attempt to reduce the weight and the time needed for the bricks to dry. The mould was made up of 6 cylinders with a uniform diameter of (42 mm) and uniform distribution over the brick's surface area. The mould was designed to be portable and to fit for all the moulds with the size of (25 x 15 x 10 cm). Another attempt to reduce the time required for the bricks to dry was to use a mesh with small openings so that the bricks can be placed over it directly without the need for a steel plate to hold it.

For the soil investigation purposes; several apparatus were used including:

- Hydrometer Test Apparatus
- Liquid Limit Test Apparatus
- Shrinkage Limit Apparatus
- Sieves Set with Sieve-Shaker

VI. Brick Specifications

A. Normal Bricks

The normal brick has been designed with dimensions that comply with the standard sizes of other bricks. The dimensions are 250 x 150 x 100 mm. the brick's weight is between 7.4 to 7.6 Kg when wet and 5.9 to 6.1 Kg when dry.

B. Hollowed Bricks

After the normal brick became stable and repeatable, modification to the brick's shape were discussed and the idea of hollowing the brick was adopted to increase the area of evaporation and reduce the material needed to cast the unit, this would save resources and reduce the production time.

Reduction in volume was designed to be in 6 cylindrical voids with an exterior diameter of 42 mm and depth of 150 mm. The cutter was designed to be attachable to the mould and then removed when volume cut is finished.

The cutting process was done by leaving the brick in the mould into the oven for 3 hours at 50°C to allow the brick to gain some strength and cohesion to survive the cutting process, then the brick is taken out and the cutter is installed onto the mould. After cutting the brick the mould is removed and the brick is returned into the oven at 200°C for 6 hours.

Weight was reduced by approximately 25% and the production time by 3 hours but Due to the lack of workmanship, the mould was not precisely designed and therefore extraction of the cut material harmed the stability of the brick allowing cracks to occur directly.

VII. Mix Design

A. Soil Proportions

Designing the mix for an adobe brick starts with a determination of the percentages with which clay, sand and water contribute. Since there is no engineering background on the subject, a survey was carried out on the methods followed by the citizens of North Cyprus. These methods mainly consist of mixing the virgin soil with water without proper implementations of the water/soil ratio or any other core requirements for the assurance of having a constantly correct substratum; instead, inaccurate, locally developed, methods for determining the correct substratum were followed. These methods include:

- Hand-palm test, which involves grasping a handful of the mix, squeezing it in the palm, and then allowing it to free-fall from the hand. If it sticks to the palm, the right consistency is achieved.
- Falling ball test, which includes shaping a handful into a ball, then dropping it from an approximate height of 1 meter. The test succeeds if the ball does not shatter into pieces.

These methods were found to be not in relation with the characteristics of the soil itself but more to the water content of the mix, therefore, more precise and accurate tests like sieve analysis and hydrometer test were used to study the soil and determine the modifications necessary if needed.

The lack of scientific background on the subject forced the implementation of trial and error method in order to determine the right proportions which will be adopted as constant design characteristics and therefore reach a stable and repeatable mix which succeeds each and every time.

After studying the results obtained from the soil investigations; various mixes were batched so as to determine the best proportions for the adobe brick. Sand used in the research to modify the mix is unwashed sea sand.

Adobe bricks were produced with different percentages of clay and sand as shown in Table IX.

TABLE IX. Mixing Proportions

Mix ID	Proportions		
	Sand	Clay	Ad-Mixtures
Mix I	30	70	-
Mix II	50	50	-
Mix III	70	30	-
Mix IV	40	60	-
Mix V	70	30	0.5% Superplasticizer
Mix VI	70	30	5% Cement 0.5% Superplasticizer

Fresh properties of the mix were distinguishable and the effects of each contributing material were varying as its percentage changed. Main effects of clay on the mix are decreasing the deformation because of the high plasticity it provides, higher compressive strength and increasing the drying time. Increasing the sand proportion in the mix increases the workability, decreases the plasticity and therefore the brick becomes more deformable.

In matter of drying, bricks with high content of clay need more time to dry and are very sensitive to heat; clayey bricks (containing 60% and 70% clay) exhibited low workability and were too plastic and therefore vulnerable to shaping and moulding. Big cracks were appear on relatively low temperatures and therefore were decided not feasible to be produced.

On the other hand, high sand content bricks showed more workability and ease of moulding and demonstrated better heat resistance and a relatively less drying time in oven.

In the comparison of drying shrinkage, clayey bricks would show extensive shrinking, and that is one of the main reasons which made it very hard to be produced in oven where high temperature results in rapid loss of moisture and therefore fast shrinkage, which yields into huge shrinkage cracks which developed into full splitting of the brick. Sandy bricks, on the other hand, have much less drying shrinkage, making it very compatible for high temperature oven production.

After batching various mixes with the specified percentages mentioned previously, mix III with 30% clay with 70% sand proportions proved to be the most fitting for the purposes of the conducted study.

B. The Water Ratio

Water used in the study was normal tap water, Water is the most crucial contributor to the success of the mix, and an addition of even 100 grams over the optimum water content may affect consistency of the fresh mix which crucially disturbs the workability and the ability of the brick to hold its shape.

After trying numerous water contents, the optimum water/soil ratio was determined to be 23.1% of the dry content mass.

Admixtures were used to study the ability of enhancing the brick's specifications and abilities. These admixtures are cement and superplastesizer. The method of addition and the effect of each of them are explained below:

- **Cement:** cement was added to the mix in a percentage of 5% to the total brick weight. The cement was first dissolved in water and added to the dry contents at once with the decided water amount. Reasons of addition are to:
  - ✓ take advantage of the early setting property,
  - ✓ reduce the drying shrinkage to a minimum value and possibly ;
  - ✓ Increase the compressive strength.

After casting and production of cement enhanced bricks, tests showed that cement's contribution to the compressive strength was not significant, drying shrinkage values reduced but by relatively small values.

- **Superplasticizer:** Glenium was used as a Superplasticizer. The addition of this admixture to the fresh mix increased the plasticity of the mix but increased the drying time.

VIII. Mixing Procedure

The procedure starts by taking the required amounts of the sand, clay and water, and for some cases, the additives and ad-mixtures. The soil is first placed in the trolley and dry-mixed. After that, water is added and the paste is properly mixed with the hands for few minutes. For better mixing, and after the experience gained during the work in the last 2 semesters; it would be better to put the sand in the trolley first then place the clay over it. In this way, the water will easily be mixed with the particles leaving fewer amounts of un-mixed parts which will make the hand-mixing much easier.

Fig. 9. Mixing the adobe by hand

The soil/water ratio is quite sensitive. Excess water can be easily felt while hand-mixing the soil; vice versa, less water amount makes the mix too dry and very hard to be mixed.

After proper mixing, the paste is then casted into the wooden moulds which would be already greased to insure no sticking between the mould and the brick and would produce a smooth surface and exhibit ease of removal. Improper placing of the mix into the moulds will result in porous and weak brick; thus the bricks should be filled carefully with the paste. The top surface is then smoothened with the trowel. Then the mould is removed and the brick is placed in the oven to dry.

The other way that was tried for mixing the soil and water was using the normal concrete mixer. But due to some problems in the machine; the mix was not properly done. The procedure is the same as the hand-mixing, except that it would be done using the mixer instead of the hands.

On the attempt to reduce the weight and the time needed for the brick to dry, hollowed bricks were casted. The outcome can be seen in Figure 12.

Fig. 10. Moulding the adobe into the wooden mould

Fig. 11. Moulded Abode Brick before going through the drying process

Fig. 12. Hollowed Brick Molding

IX. PRODUCTION

After moulding and finishing the surface of brick, the brick enters the production phase in which it would be oven heated to a certain temperature to lose its water content and gain hardness and strength.

In order to determine the most fitting way of production, several methods were implemented. These methods vary with:

- The stage at which the mould is removed.
- Initial temperature on which the brick is heated.
- Final temperature on which the brick spends most of its drying time.

First, the bricks were left into moulds and were directly heated at 110° C for 24 hours.

Second process was to remove the moulds right after casting and then putting the brick into 110° C.

Third process was performed after directly removing the mould; the brick was put at 50°C as an initial temperature for 3 hours and then put to the final temperature of 150°C for 24 hours

Fourth process was by directly removing the moulds after casting and then putting the brick at an initial temperature of 80°C for 3 hours then raising it to a final temperature of 200°C for 9 hours.

Fifth process was done by unmoulding the brick and leaving it outside in day temperature (Average 22° C) for 24 hours, then in 50°C for 24 hours and 24 hours at 110°C.

Sixth Process was similar to the 5th process except that the final temperature was 150°C.

Fig. 13. Drying Process in the Oven at 150°C

A. Analysis of the Production Processes

Process one: putting the brick at a high temperature suddenly proved to be ineffective; the brick would show signs of cracking at early stages. The effect of leaving the mould was very negative because the heat was not distributed equally to the sides of the brick; only the upper face was in contact with heat and that made the drying process start from top to bottom. The unequal drying resulted in having a top layer of around 3 cm dry earlier; this layer starts to shrink causing a complete separation from the rest of the brick.

Process two: with the mould removed directly after casting, the brick was inserted in the oven at 110° C. drying process was very rapid resulting in complete separation of the brick at the middle.

Process three: the gradual heating of the brick made the bypassing of thermal cracking possible, the brick held its shape perfectly and at the end of the production time it was crackles and uniform.

Process four: with the success of process three, the final temperature was raised to 200° C and it succeeded, the production time was reduced significantly.

Process five and six were successful but the production time was too long therefore they were not adopted.

X. TESTING

After successfully mixing the bricks and obtaining the best paste; some rheology tests were carried out on the fresh mix. Moreover; after drying the bricks, other tests were also done on the bricks. Those tests are carried out in order to determine whether the water/soil ratio is within the correct ranges or not.

The already existing information regarding the adobe mixing and bricks do not give clear indications on how to test the mix while it is fresh; thus some tests were tried, especially those done on the wet soil and fresh concrete mixing. The rheology tests carried out on the adobe mix were:

- **Modified Liquid Limit:** The normal procedure was followed using the adobe mix. Only the number of drops was taken under consideration. The more workable mix, the less the number of drops. For the best mix, the number of drops was found to be within the range 15 – 20 drops.

Fig. 14. Determining the Liquid Limit for the used Soil

- **Modified Vicat Apparatus:** This test is usually carried out on the cement paste to determine its setting time or the time that the cement start hardening in. For the purpose of this project; the test was tried on the fresh mix of adobe but it did not give dependable results since the mix contains relatively large particles of sand which help the needle to completely sink in the paste.
- **Shrinkage Test:** This test is conducted in order to understand the behaviour of the paste under heat and to determine the amount of the shrinkage to be expected. The test involved placing the adobe mix into the shrinkage mould used for clay soil. Then the specimen was placed in the oven at 50°C for 24 hours. The specimen length is taken as 140 mm. Two mixes were tested for shrinkage determination. The first mix was containing 70% sand and 30% clay and the second mix consisted of 50% sand and 50% clay. The results obtained from the shrinkage limit on the mixes are shown in table X.

TABLE X. SHRINKAGE VALUES FOR THE ADOBE MIX

Sample	L0	L1	Shrinkage
70% Sand + 30% Clay	140	134.5	4%
50% Sand + 50% Clay	140	128.9	8%

- **Drop Test:** This test was processed using the mould of the Vicat Apparatus which has a diameter 80 mm and height of 40 mm. The mould was filled with the adobe paste and then allowed to free-fall from a height of 500 mm. The diameter of the paste fallen was then measured and a range for the correct mix was set to be between 120 mm and 135 mm. A specimen in a range smaller than the specified one indicates that the mix is too dry, and a result within a range higher than the specified one indicates that the water/soil ratio is high.

Compressive Strength Test:

After completing the mix design, casting the bricks and drying them in the oven, they are subjected to compression in order to measure the ability of the brick to carry the load. The brick of the dimension 250 x 150 x 100 mm is placed into the compressive strength testing machine and it was tested using two different approaches. The first approach is to measure the strength in accordance with the crack deviation; that is the machine is to stop when any crack is detected in the brick. The second approach is to manually crush the brick to report the ultimate strength that the brick can carry.

The results of the compressive strength test are detailed in Table XI.

TABLE XI. COMPRESSIVE STRENGTH FOR THE CASTED ADOBE BRICKS

Sample	Compressive Strength (MPa)	
	Crack Deviation	Manual Crushing
Brick #1[1]	2.026	1.987
Brick #2[1]	2.103	1.962
Brick #3[2]	3.427	2.995
Brick #4[2]	3.267	2.881
Brick #5[2]	3.060	2.968
Brick #6[2]	3.269	3.176

[1]*: The brick consisted of 70% sand and 30% clay. It was placed in the oven for 12 hrs at 110°C.*

[2]*: The brick consisted of 70% sand and 30% clay. It was placed in the oven for 3 hrs at 80°C and for another 9 hrs at 200°C.*

XI. REPAIR AND RECYCLING OF ADOBE PRODUCTS

Survival of adobe buildings depends on repair and maintenance, because adobe is made of earth material that will deteriorate at some point due to the erosive action of rainwater.

Adobe units can be repaired easily by using the same mix of the adobe units then adding the repair material to the deteriorated part, however adobe is a sustainable building material; it is a friend of the environment from the production of raw materials to demolition, the following reasons explain why adobe is sustainable:

A. Resource efficiency:

The main raw material of adobe is soil, soils are available everywhere and there is no need for constructing a quarry to excavate which reduces the environment pollution.

B. Thermal insulation:

Adobe buildings have the ability to retain and absorb heat that's why it is highly energy efficient building material.

C. Minimal waste:

Adobe can be crushed and recycled into soil to be used in casting new bricks.

XII. ECONOMY

Adobe bricks are made of low cost materials and the production of adobe brick is also low, this makes adobe more economical on individuals who cannot afford the increasing cost of other building materials such as reinforced concrete buildings.

Cost estimation is done according to the north Cypriot price lists; this estimation was done as per the cost of 1 adobe unit.

The idea behind the project was to mass produce adobe, therefore the oven was chosen to be a big size oven, 1600 x 1600 x 1200 mm interior dimensions in which around 450 adobe units can be fit and dried at once.

The oven consumes 24 kW at maximum capacity, therefore for a production time of 12 hours it would consume 288 kW.hr and with a price of 0.38 TL per kW.hr this would result in a sum of 110 TL per batch.

Similarly, soil needed for a single brick production is 6.5 Kg, so 1 ton of soil would produce 150 bricks. With a price of 30 TL per ton the production cost of a single unit would be 0.2 TL/brick.

Water also will be needed for production; a single unit needs 1.62 Kg of water to reach the optimum consistency resulting in a production of 618 bricks for each m3 of water. Price of 1 cubic meter cube is 3.2 TL therefore a single brick would cost 0.0052 TL.

Summation of the previously mentioned prices would result into having a price of 0.45 TL/brick which is around 0.27 $/brick.

Compared to the normal clay brick, the adobe brick as unit is cheaper, stronger and more sustainable which makes it a possible competitor for other material based bricks. Further studies would improve the adobe brick to become better, cheaper, lighter and even more environment friendly.

XIII. CONCLUSION

Adoption of adobe as a construction material has never been more reliable, this research was conducted to improve both time and quality of the adobe brick in order to find a more sustainable way of construction and supporting the poor due to the relatively low cost of production and the ease of the process.

In this research, adobe brick was improved to reach stable and constant properties which allow it to compete with other material based bricks and even lead in some properties. For example; Compressive strength of the brick scored an average of 3.00 MPa which is almost 10 times higher than fired clay bricks.

Adobe brick is the most environment friendly among its competitors, the brick uses natural resources that are 100% recyclable, without any admixtures or special chemicals or treatments for production whereas other bricks need very high temperatures and emit greenhouse gases with a recycling cost higher than that of production.

This research transformed the production of adobe from a sun dependant process to a factorized one, adobe units can be produced all around the year with a reduction of production time from 28 days to only 12 hours. The production phase was designed to be very easy without any need for special equipment or skill, therefore low skilled labour can handle the process and this point is crucial to the cost of the production which was the defying factor throughout the research because this research was established to support poor people and pay tribute to our planet earth.

XIV. RECOMMENDATIONS

After stabilizing the mix design which resulted in a uniform output, further studies on the following subjects can be very helpful in upgrading the adobe construction and making it a worldwide accepted method:

- Thermal conductivity of adobe walls
- Weight reduction of adobe unit
- Usage of hay and straws to reduce crazy surface cracking
- Adobe mortar
- Using adobe mixtures as plastering material
- Usage of glass fibers and polymers for reinforcement.
- Seismic resistance of adobe structures.

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