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Archaeometric Study and Restoration Implementation of Archaeological Roman Adobe Bath at Karanis – Fayoum, Egypt

Mahmoud Abd El Hafez M. Adam

Conservation Department., Faculty of Archaeology, Cairo University, 12613 Giza, Egypt.

HIGHLIGHTS

- Adobe architecture is an eco-friendly architecture. Its splendor appeared in Roman era in the city of Karanis, Fayoum.
- Mud brick and fired brick are the main building materials of the Roman bath at Karanis.
- Atmospheric weathering and neglect of conservation are the main deterioration factors to the bath building.
- A preventive conservation plan should be developed for the Roman bath site.

GRAPHICAL ABSTRACT

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ABSTRACT

The Roman bath is located in the city of Karanis in the Fayoum Governorate. The archaeological site is about 300 m from the asphaltic road linking the cities of Cairo and Fayoum. The present site consists of the remains of adobe walls, some of which are fired bricks. In some of the walls of the building the lower parts were built of fired bricks, while the upper parts of the walls were built of mud bricks. The building was severely damaged as a result of its presence in the harsh desert environment as well as the lack of conservation for a long time.

* **Corresponding author:** **mahmoud_adam@cu.edu.eg**

This research paper aims to identify and evaluate the risks that threaten the archaeological site, and these were conducted through using analytical means on the building materials to identify the composition and properties of the studied building materials. The results were utilized to make modern mud bricks and mortars for the purposes of restoration and reinforcement of the archaeological bath. XRD, XRF, FTIR, PLM and SEM-EDX have been used in the current study to analyze and examine the archaeological samples of building materials. After completing the analytical and diagnostic studies, this paper presented the most important practical aspects of carrying out the restoration works of the archaeological bath site, which included general cleaning of the site, completion, reconstruction, treatment of cracked walls, filling the gaps between fired bricks, capping and protecting the upper parts of adobe walls and troweling with mud plaster.

1. Introduction

Mud brick (or adobe) is the oldest building material used by man, since pre-dynastic times. In Roman times in Egypt fired (burnt) bricks, which are more resistant than adobe, were widely used. There are many buildings that were built of mud and fired bricks in many regions of the world, especially Egypt. Historically, the use of soil (the basic components of adobe) as a building material dates back to prehistoric times [1]. The term "Adobe" is given to mud buildings, and therefore it includes, from the researcher's point of view, buildings constructed of both mud bricks and fired bricks. Fired brick is the same as mud brick, but it in an advanced stage, which includes burning in kilns at high temperatures up to 1000 °C [2]. The use of earth for construction in the form of mud bricks (Adobe) was very common in Egypt, especially in rural areas, where the river Nile precipitated thick layers of mud. These layers were used in the past for manufacturing different forms of mud blocks used in building works. On the contrary, in desert areas, there were large amounts of shales or clays, which played an important role in the construction process of adobe buildings throughout the ages [3].

In the Roman era many buildings were constructed of mud brick and fired brick, or in other words both types were used side by side rick. It is also possible to say that the preliminary use of fired brick in Egypt, had actually started in those times, or more precisely, it became common, yet most likely, before this date [4].

Karanis (at the present day known as *Kom Aushim*) is one of the old cities which was famous in the Roman era. It is in the fertile region of Fayoum, near "Lake Moeris", which is fed by a branch of the Nile. The first settlements in the area were in prehistoric times, and agriculture was introduced as early as the Pharaonic era, during the Old Kingdom (Fig. 1). The city of *Karanis* occupies a unique position in the annals of Egyptian and Graeco-Roman archaeology. Although no more than a rustic agricultural village in Fayum oasis, but it is very important because it provides a microcosm of life as it was lived by ordinary people in Egypt under Greek and Roman rule. The history of *Karanis* spans over seven centuries, from the middle of the third century BCE to the end of the fifth century AD. This was an era of significant social, economic, political, and religious change throughout the Mediterranean - a period that saw not only the fallout from the conquests of Alexander the Great but also the rise, dominance and eventual decline of Rome. Actually, *Karanis* was established by Ptolemy II Philadelphus (285–247 BC) as part of his scheme for the settlement of Greek mercenaries and so that he could exploit the great potential of the fertile Fayoum depression [5].

It is worth mentioning that the ancient site of *Karanis* lies approximately 70 km southeast of Cairo. The site includes one of the most important buildings, the Roman bath that was built of mud bricks and fired bricks. This Roman bath represents a wonderful model for the Roman public baths that were found in Egypt, and is characterized by its uniqueness from an architectural point of view, as it includes multiple rooms for different uses despite its small size [6]. (Figs. 2, 3a, b).

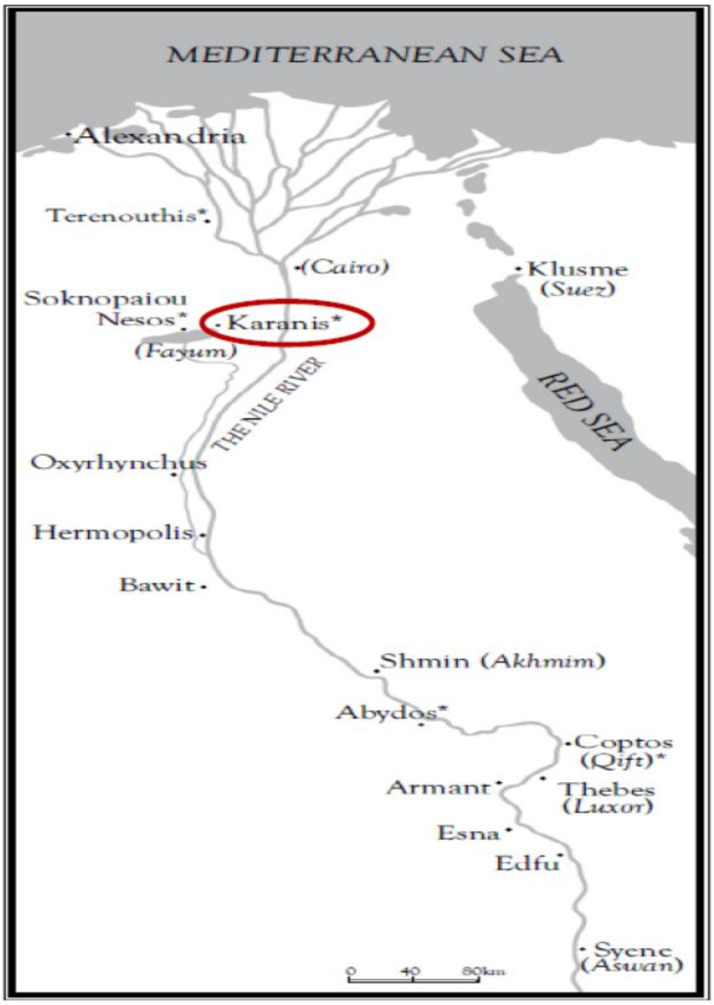


Fig. 1. A map shows Egypt in the Roman period. [5]

Fig. 2. General view of the Roman bath in Karanis.

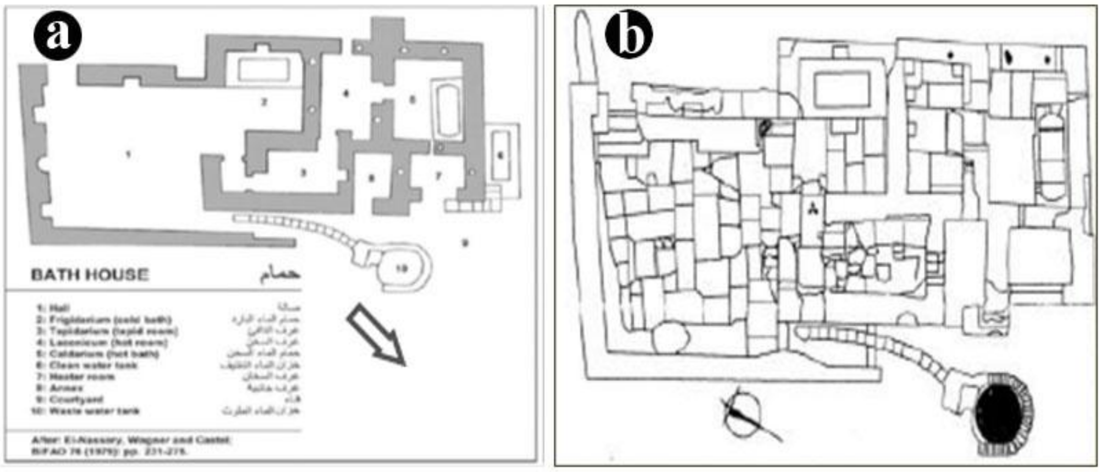


Fig. 3. (a, b) Plans of the Roman bath, showing the locations of the different rooms. [6]

The presence of the Roman bath building in the middle of desert environment unfortunately has led to the presence of many manifestations of serious damages. Also the neglect of restoration and conservation works of the site for long times increased the impact of the damage. This necessitated the intervention by restoration and conservation works to protect the site from further destruction.

2. Materials and Methods

2.1. General description of the investigated site

The current site of the Roman bath is nothing more than ruins of walls that were built from mud brick, and some of them built of fired bricks. It was observed that in some parts of these ruins, the lower parts of the walls were built of fired brick, and the upper parts of the same walls were built of mud brick. Mud brick, which is a local building material, is was the oldest building material used by man since the prehistoric times and is still used till now. The use of fired brick in construction work distinguishes the Roman period; especially in baths, because of the ability of fired brick to resist the moisture effects.

The site suffers from the damaging effects of the desert environment impacts, therefore are many deterioration manifestations [7]. As for building technique, the building was built by compaction of fired brick courses in the lower parts of walls and then completing the building by mud brick blocks. Some walls were completely built of fired bricks and others built of mud bricks. Sandy sediments covered many of the lower parts of the walls. The height of remaining walls does not exceed three meters height. The walls building was characterized by big thickness of either fired brick or mud brick walls (thicker than 60 cm). It is obviously from the current planning of bath that this bath consisted of connected rooms. There was an oven to heat waters, which was used in bathing (showering).

2.2. Building materials

2.2.1. Mud brick

Mud bricks or adobes, i.e., sun-dried bricks, are the oldest environmental local building materials, which have been commonly used for the purposes of building in ancient Egypt. Mud brick manufacture in ancient Egypt dates back to the period before the dynastic era. It is believed that the oldest use of mud bricks dates back to eight or ten thousand years ago. Although it was found in Egypt in the pre-dynastic era, there are also mud bricks belonging to Naqada era as found in two royal tombs at Abydos. Mud brick was more common in the tombs of the first and second dynasties in Saqqara and Abydos. Adobe architecture, in general, has many environmental advantages: local availability, cost effective, ease of implementation and good thermal insulation [8].

The initial preview of the site showed that the Roman mud bath was made from the soil close to the site of the building. There are many additives that had been intentionally added to the soil in order to improve the strength and durability properties of the produced mud bricks. Most of the adobe bricks in the site are yellowish in color, some blocks are light grayish brown and orange-tinged, and this depends on the kind of soil used in the manufacturing process and found in the construction site. As for the size of the mud bricks used in the archaeological site, it seems clear that there is a diversity in the sizes of the bricks, while there were blocks of the size of (35 × 17 × 10) cm, which is the common size in the mud buildings that date back to the Roman era, there were also other blocks of (10.5 x 13.8 x 25.5) cm. It seems that this diversity in sizes was accompanied by a diversity in use as well [9]. (Fig. 4a).

2.2.2. Fired brick

Fired brick is the advanced stage of mud brick, both of them have the same original composition, which is the earth substance, that passed through the same stages in terms of soil preparation, manufacture, additives added to improve adobe bricks properties, whether they are organic or inorganic additives, the stage of fermentation, blunging, shaping, and drying under the sun rays. However, the fired brick has another stage, which is the stage of burning (firing) in special kilns, which leads to the transformation of the vulnerable mud brick blocks into very hard and durable fired blocks. The burnt bricks are difficult to disintegrate due to excess moisture, unlike the unburned mud brick, which are characterized by their extreme sensitivity and complete vulnerability to the sources of moisture. The burning process of mud bricks requires very high temperatures up to about 1000 °C (typically, the firing temperature of fired bricks in Roman times ranged from 750 to 900 °C).

Some physio-chemical changes occur during firing process as follows: when clay-based materials are fired in a kiln, any hygroscopic moisture is driven off at temperatures between 100 and 200 °C. If organic matter and iron pyrites are present, oxidation takes place at temperatures between about 300 and 400 °C. Combined water inside the structure of clay minerals (water of crystallization) is usually released at temperature range 500 to 550 °C, while carbonates such as calcite and dolomite dissociate with the release of carbon dioxide in the temperatures between 750 and 950 °C. The significant changes relating to the development of fired brick properties involve the complete breakdown of the lattice structure of the clay minerals, followed by the formation of new crystalline compounds and glassy phases. The temperature at which vitrification (glass formation) takes place varies according to the nature, type and properties of the clay minerals. Vitrification usually starts at about 900 °C (montmorillonitic composition) and is completed at about 1050 °C (for many brick clays) or about 1100 °C in the case of more refractory fireclays (kaolinitic composition). During vitrification stage, many non-clay minerals such as quartz, oxides or iron, lime compounds and alkalis (oxides of sodium and potassium) become incorporated in the fired body [10].

The colors of fired bricks used in construction of the Roman bath varied greatly. There are light red blocks, dark red blocks and black blocks, as a result of the burning at high temperature (over heating), or due to the direct exposure to the fire during the burning in the ovens. The different colors of fired bricks in the site reflect the burning conditions. The color of the brick pastes is induced by the oxidation state of the iron ion. This in turn depends on the more or less oxidizing atmosphere of the furnace. In the presence of little oxygen and carbon monoxide there is a gray or black coloration due to the presence of Fe(II). This reducing action may be partly due to the presence of organic fragments inside the clay which, due to partial combustion, generate CO (this is the case of red bricks with a black core). Conversely, an atmosphere rich in oxygen oxidizes iron to Fe(III) resulting in a red or yellow color of the brick paste [11]. As for the sizes of fired brick blocks, the sizes in the site are similar to the sizes of the mud bricks referred to previously, there are different sizes as well, and there are fired bricks of less thickness, which were used in the construction of vaults (Fig. 4b).

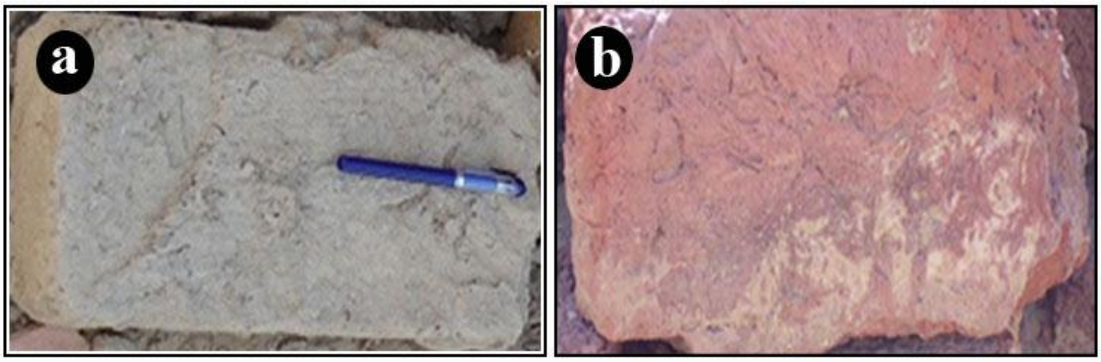


Fig. 4. Shape and dimensions of mud bricks and fired bricks at the archaeological site (a) Mud brick blocks, (b) Fired brick blocks.

2.2.3. Mortars and plasters

Mud mortar was used in order to connect the mud brick blocks with each other.Initial visual investigation proved that the components of mud mortar were similar to the mud brick components. It is known that mud mortar and mud brick were made from the same local soil in the surrounding site; lime mortar was used for the connecting of fired blocks to each other. By preliminary examination of the lime mortar samples, it was found that they consist of lime and sand, in addition to the presence of fine fractures of fired brick. It also appears that a very small percentage of fired brick powder was added to the lime mortar used in the construction process of the Roman bath. It is worth mentioning that silt as well as fine to coarse grained sand are inherited components of the local desert soil that has apparently been used as mineral aggregate for the mortar. The residues of mud and lime plaster were found on some walls of this bath, especially the walls constructed of fired bricks [9]. Moreover, the Romans used lime mortars that have the ability to withstand moisture. Artificial pozzolans such as brick fragments, ground terracotta and roof tiles were used in the mortars and plasters of many Roman structures. Those mortars known as "*Cocciopesto*" or "*Opus Signinum*" were used for walls as plasters exposed to severely humid environments such as baths or foundations. Furthermore, specialists define "*Cocciopesto*" as a waterproof building material used as wall and floor covering in water tanks and aqueducts. It is characterized by fragments of crushed or ground terracotta from tiles, bricks or pottery mixed with a lime-based binding substance like modern cement [12].

2.2.4. Other building materials

The use of sandstone in the Roman bath building was very limited, it was used only in the bathtub, and as lintels on the entrances of some rooms.

2.3. Deterioration factors and manifestation of the Roman bath building

There were many deterioration manifestations of the Roman bath building, which are due to a lot of reasons, the most important reasons are: its location in harsh desert environment, and the neglect for long times without any intervention to restore and protect the site. These reasons led to many deterioration manifestations, such as (**Fig. 5a– f**):

- Covering the bath site with sandy sediments and garbage.

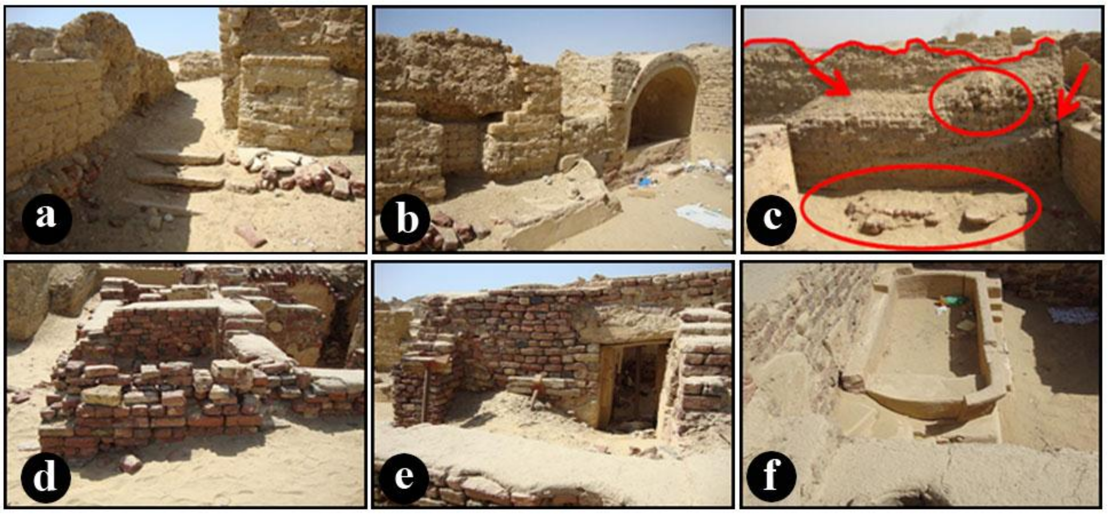


Fig. 5. Some deterioration manifestations of the Roman bath (a) The main entrance of bath building was covered by sand and dust, dismantling of stairs and disintegration between fired brick blocks, (b) The main hall of bath building, it is clear the presence of garbage, decomposition and fall of mud plaster, loss of the wooden lintel for the niche, falling of mud brick courses from the upper parts of the wall, and a general weakness in the mud brick walls due to environmental factors, (c) The floor, terrace "Mastaba" and walls were covered with sand and mud fragments, the terrace was eroded, rain water and wind storms caused erosion of the walls, the upper courses of walls were totally eroded and crushed, (d) Disintegration and general weakness in the fired brick walls, (e) Covering the tepid room by sand due to wind storms, breaking in the stone lintel of the tepid room, threatening the fired brick building, there are temporary supports for walls. (f) Fractures and missing parts in the bathtub.

- Dismantling of stairs of the main entrance.
- Severe erosion and under-cutting of mud brick walls.
- Various cracks in the building walls.
- Disintegration, separation and falling of some fired brick blocks.
- Loss of binding mortar in the fired brick walls.
- Falling of mud and lime plasters.
- Breaking in the stone lintels.
- Fractures and missing parts in the bathtub.
- Decomposition of upper courses of bath walls.
- Deformation of the overall shape of the site [7], [9].

2.4. Methods

A number of samples of different building materials were collected from the archaeological site for the purpose of examination and analysis, to identify their chemical and mineralogical components, as these components reflect the nature of the building materials, and their physio-chemical properties, and this is necessary when choosing and preparing the restoration materials for the archaeological site. The used analytical techniques were:

2.4.1. X-ray diffraction analysis (XRD)

The mineralogical analysis of the samples was performed by X-ray diffraction using A "Philips" X-ray diffractometer (PW 3071, with analysis program: Match 2014+ PDF4 2015) (CuKα 40 kV, 30 mA) in order to identify the mineralogical composition of the archeological mud brick, fired brick, mud mortar and lime mortar samples. XRD patterns were measured in the range of 5 to 75° (2θ).

2.4.2. X-ray fluorescence (XRF)

Chemical analysis of the samples was performed by X-ray fluorescence using X-MET7500 MINING ANALYSER (Oxford Instruments) to identify the chemical composition (elemental oxides) of mud brick and fired brick samples.

2.4.3. Fourier transform infrared (FTIR)

FTIR analysis was performed on the mud brick samples using: FTIR 460 plus – Jasco – Japan – Range. 400-4000 cm^{-1}, in order to identify the functional groups in the samples.

2.4.4. Polarizing microscopy (PLM)

A polarizing microscope (Zeiss) 2010 with operating conditions: magnification in plane-polarized-light 25 was used to study the thin sections of archaeological fired brick samples.

2.4.5. Scanning electron microscopy (SEM-EDX)

Scanning electron microscopy of the archaeological samples was performed using: SEM quanta FEG 250 FEL, USA, equipped with an energy dispersive X-ray detector, in order to investigate the morphology of studied mud brick and mud mortar samples and study their elemental compositions. As well as, Tescan - Vega. 2018 Scanning electron microscope (Magnification at 30 Kev 1x1000.000x. The samples are coated with gold) was performed to study the morphology of studied archaeological fired brick samples [13].

3. Results and Discussion

3.1. X-ray diffraction analysis (XRD)

The results of mineralogical analysis by X-ray diffraction (XRD) of mud brick samples (Fig. 6a) showed that they contain quartz mineral (SiO_2) and plagioclase feldspar "anorthite" ($CaAl_2Si_2O_8$) in large proportions, which reflect the addition of a high percentage of sand within the mixture of mud brick. The mineral anorthite is one of the plagioclase feldspars, that are common in the sandy soil composition of desert areas such as the soil of Fayoum region. The mineral calcite ($CaCO_3$) was also found in a good proportion, and it is most likely that lime was intentionally added to the components of the mud bricks when manufacturing in order to improve the cohesive properties of the produced mud bricks, as well as, lime makes the clay mixture softer, which facilitates the process of blunging and manufacture. Moreover, some minerals were found as impurities in a small percentage, such as diopside ($MgCaSi_2O_6$), which may be found in the components of the soil naturally. Another possibility is adding fired brick powder to the clay mixture used to manufacture the mud bricks, as this mineral is one of the distinguishing minerals of fired bricks. As well as, the mineral halite (NaCl) may have been found in mud bricks as one of the products of damage, and this does not prevent the presence of a percentage of it in the local soil naturally.

With regard to the mineral components of the archaeological fired bricks, the mineralogical analysis by XRD proved that the fired bricks are of medium to high burning type, according to the mineral components that appeared in the analysis, the most important of which are: spinel ($MgAl_2O_4$), quartz (SiO_2), diopside ($MgCaSi_2O_6$), hematite (Fe_2O_3) and mullite ($Al_2O_3SiO_2$) (Fig. 6b), some of these minerals gave the fired bricks their red color. It is well known that the quartz mineral mainly exists in the components of all muds or clays. Some minerals, such as diopside and mullite, appeared in the high burning temperatures. Moreover, calcite reacts with silica to form diopside at 850 °C, while mullite appears at 950 °C [9], [14], [15]. It is worth noting that the mineral composition of mud mortar did not differ from the mineralogical composition of mud brick, and this is common in adobe architecture, as the mud mortar was composed in the studied samples of anorthite ($CaAl_2Si_2O_8$), quartz (SiO_2), albite ($NaAlSi_3O_8$) (both albite and anorthite are plagioclase feldspar minerals) and halite (NaCl) (Fig. 6c). As for the lime mortar, it was mainly composed of lime and sand, and for this reason the main minerals were: calcite ($CaCO_3$) and quartz (SiO_2) (Fig. 6d). It is noteworthy that the mortar used for the construction of fined brick walls consist of a fine white-yellowish calcium-carbonate matrix. The main mineral aggregates embedded in the matrix are the local quartz sand and fine gravel in different grain sizes. The dominant feature is the low content of silt and very fine sand in the mortars and plaster. Silt and fine to coarse grained sand are inherited components of the local desert sand, which seems clear to be the sand that was used as mineral aggregate for the mortar. It is clear from the apparent examination of the lime-mortar samples that it is fine-grained, and this means that the sand was sieved well before mixing with the lime binder [9]. The results of X-ray diffraction (XRD) contributed a major role in the preparation of modern mud bricks for the purposes of restoration, reinforcement and reconstruction of the Roman bath building, as well as preparing mud and lime mortars appropriate for restoration purposes.

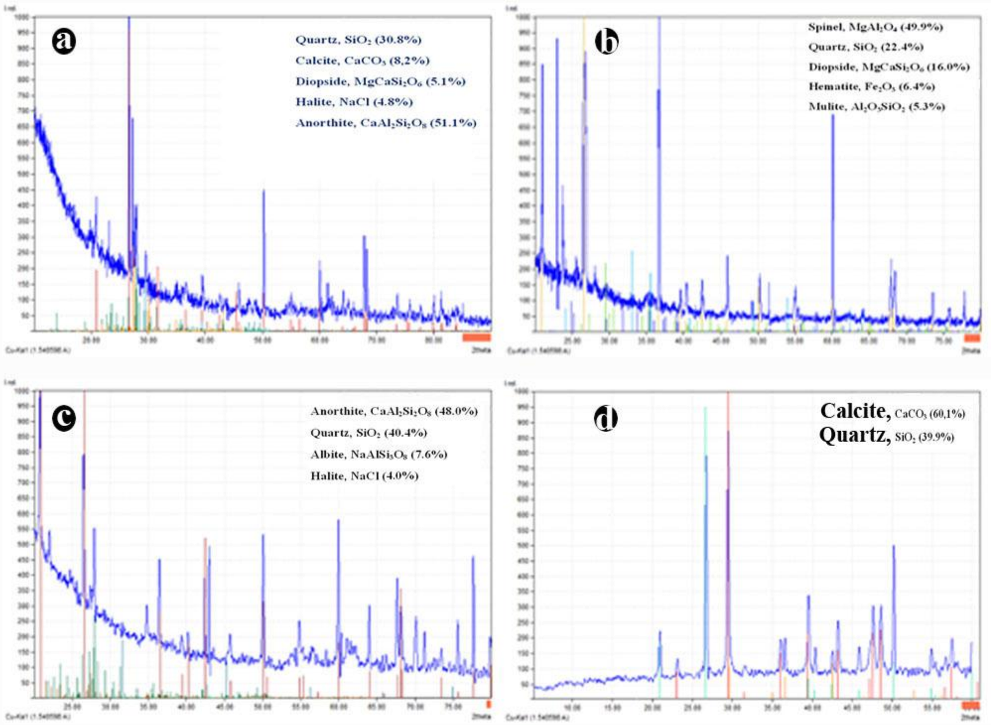


Fig. 6. XRD patterns of the studied samples (a) Mud brick, (b) Fired brick, (c) Mud mortar, (d) Lime mortar.

3.2. X-ray fluorescence analysis (XRF)

XRF analysis is an important quantitative analytical tool used for elemental analysis of constructing materials such as mud brick, fired brick, mortars and plasters in the archaeological buildings. Moreover, XRF is commonly used for analyzing major oxides such as silicon dioxide (SiO_2), titanium dioxide (TiO_2), aluminum oxide (Al_2O_3), ferric oxide (Fe_2O_3), manganese oxide (MnO), magnesium oxide (MgO), calcium oxide (CaO), sodium oxide (Na_2O), potassium oxide (K_2O) and phosphorus pentoxide (P2O5). X-ray fluorescence analysis was conducted to identify the percentages of the elemental oxides in existing mud brick and fired brick samples. Silicon dioxide (SiO_2) is found due to clay, sand and gravels, while the presence of calcium oxide (CaO) indicates the amount of lime that was often added during the manufacture of mud bricks to improve its properties. Although, it is well known that a percentage of this lime is naturally present in the soil from which the bricks are made, as one of the accessory components in the soil. magnesium oxide (MgO), potassium oxide (K_2O) and sodium oxide (Na_2O), usually refer to the clay components in bricks, while iron oxide (FeO) indicates the soil content of iron oxides, which play an important role in determining soil properties and color. Loss of ignition (L.O.I) refers to the elements and volatiles lost during the burning process Aluminum oxide (Al_2O_3), which could possibly be carbonates, organic matter, moisture content or other elements [16]. In the current study, results of (XRF) analysis were confirmed by the results of (XRD) analysis as a guide for the preparation of new mud bricks to be used in restoration works. XRF results of mud brick and fired brick samples are shown in Tables 1 and 2.

Table 1. XRF analysis results and (LOI) of mud brick samples (wt. %)

Ag_2O	Al_2O_3	CaO	Cl^-	Fe_2O_3	K_2O	MnO_3	Nb_2O_5
0.11	**7.63**	**7.86**	**5.94**	**17.79**	**4.22**	**0.27**	**0.23**
SO_3	**SiO_2**	**SrO**	**TiO_2**	**ZnO**	**ZrO_2**	**Rb_2O**	**LOI**
6.64	**44.79**	**0.24**	**2.27**	**0.68**	**0.42**	**0.02**	**9.30**

Table 2. XRF analysis results and (LOI) of fired brick samples (wt.%)

Al_2O_3	**CaO**	**Cl**	**Fe_2O_3 $^{tot.}$**	**K_2O**	**MgO**	**Na_2O**
13.00	**8.43**	**4.63**	**11.27**	**1.61**	**2.40**	**5.87**
SO_3	**SiO_2**	**SrO**	**TiO_2**	**ZnO**	**ZrO_2**	**LOI**
2.08	**41.32**	**0.078**	**1.65**	**0.015**	**0.054**	**6.86**

3.3. Fourier transform infrared spectroscopy of mud brick samples (FTIR)

FTIR spectroscopy was used to characterize the minerals and organic content of the archaeological mud brick. The FTIR spectrum of mud brick samples are presented in **Fig. 7**, and Table 3 lists the characteristic infrared bands of mud brick samples. The results confirmed the presence of kaolinite as a basic clay mineral in the mud bricks, moreover, the results confirmed the presence of silica, which is a clear indication of the abundant use of sand in the mud brick manufacturing. Furthermore, the results showed that the mud brick contained an organic substance of cellulosic origin, which reflects the use of straw among the components of mud brick, and perhaps other plant materials were used beside the straw, but most likely that the use of straw in the manufacture of mud brick was more common, especially in that period. As for the water in the samples, as proven by the analysis, it represents the mixing water or combined water, and it may refer to water acquired as a result of climatic factors in the environment of the archaeological site (i.e., seasonal rains) [17], [18].

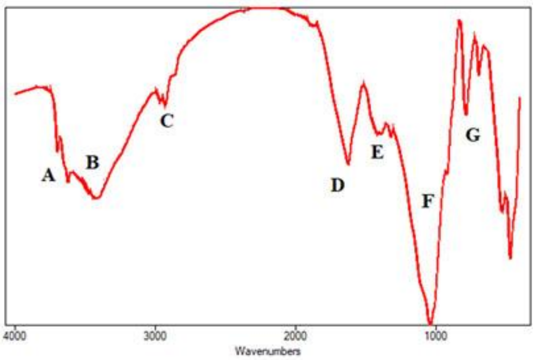


Fig. 7. FTIR spectrum of mud brick samples from Roman bath in Karanis.

3.4. Polarizing microscopy (PLM)

Fired brick samples from the archaeological site were examined by the polarizing microscope to identify the kind and nature of the bricks. According to El-Gohary et al. in a similar study, the results showed that the materials used in brick manufacturing are, in fact, strongly related to the local materials common in Fayoum environment. Moreover, the materials are characterized by amorphous or vitreous structure. Furthermore, the studied samples include some non-clay minerals, such as, quartz, carbonate minerals (usually calcite), iron oxides, fragments and mafic minerals; and some additive components are mostly lower than the clay matrix [19].

The PLM results obtained of studied fired components of the archaeological fired brick samples shown in Fig. 8 a, b showed the presence of quartz as very fine to fine-grained (sand and silt size), rounded to angular in shape, cemented by clay minerals and iron oxides. Mafic minerals occur as very fine to fine-grained, flaky and prismatic crystals scattered in the samples. Clay minerals are deformed as a result of thermal processing. Some parts of the samples are stained by iron oxides. The samples are highly porous due to the presence of remarkable irregular pore spaces and cavities in the brick.

Table 3. FTIR bands of mud rick samples from Roman bath in Karanis

	Function Groups	Wavenumber cm^{-1}	Assignment
A	Anti-symmetric O-H stretching	3702-3625	Kaolin
B	OH stretching	3424	Organic Materials and Water
C	C-H2 asymmetric stretching	2925-2972	Organic Materials
D	Conjugated C=O stretching + H-O-H absorption	1631	Organic Materials + water
E	CH bending	1424	Organic Materials
F	C-O stretching + asymmetric Si-O-Si stretching	1044	Kaolin + Silica + Organic Materials
G	Si-O stretching + CH Rocking	690-784	Kaolin + Silica + Organic Materials

Organic Materials = Cellulose.

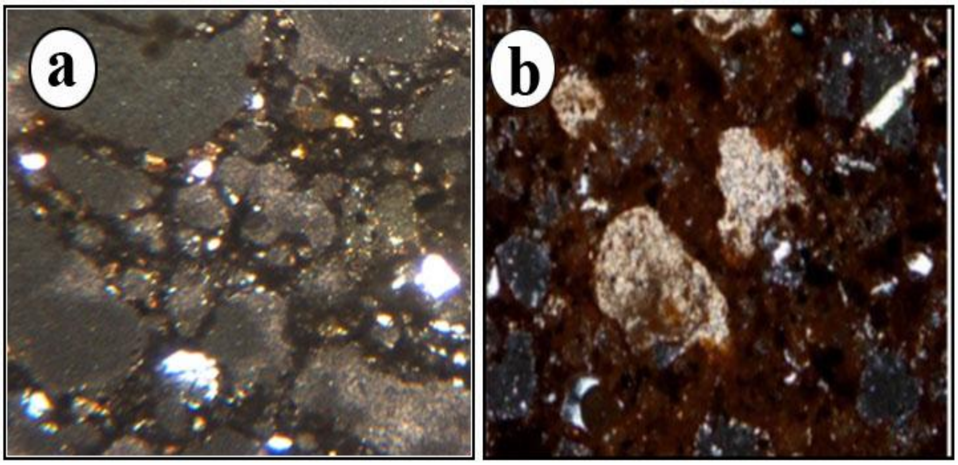
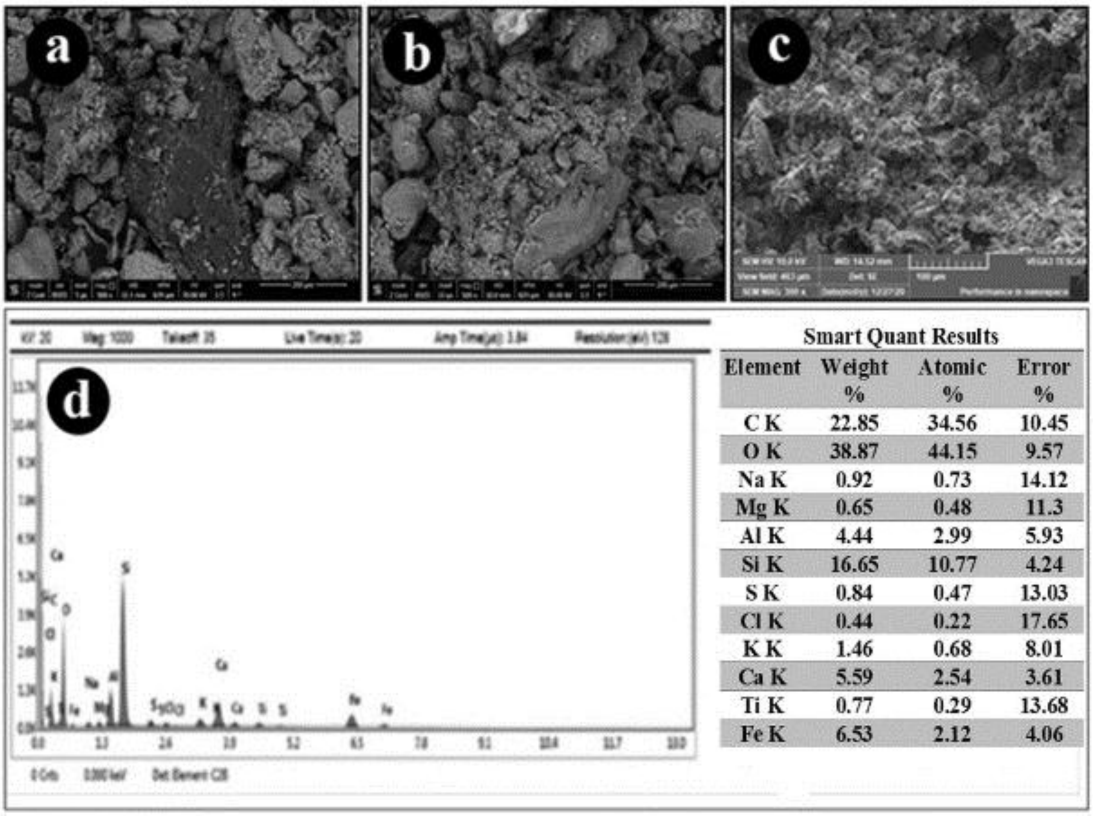


Fig. 8. PLM photomicrographs of studied fired brick samples (a) Showing quartz in rounded shape of very fine to fine-grained size, in addition to clay minerals and carbonate as cement materials, moreover iron oxides, pores and cavities are shown (25 X, CN.), (b) Showing quartz in rounded to angular shape, iron oxides, concretions of carbonates or clays floating in the clay cement, fragments and mafic minerals (10 X, CN.)

3.5. Scanning electron microscopy (SEM-EDX)

Scanning electron microscope supported by a semi – quantitative (EDX) unit was used in this study to identify the morphological features of mud brick, mud mortar, and fired brick, as well as elemental analysis of mud brick samples. SEM investigation showed the morphology of the internal structure of mud brick, mud mortar, and fired brick. It is clear that both mud brick and mud mortar were subjected to severe weathering in the desert regime, as the mud bricks contain many pores and voids. Weathering is also evident on quartz (sand) grains. Some quartz grains have sharp angles, while most quartz grains have rounded edges due to weathering. Many grains of quartz and other mud brick components are disintegrated, and the same manifestation is observed in mud mortars as well (Fig. 9a, b). Moreover, SEM investigation of fired brick showed a relative homogeneity with some blanks due to weathering processes and the lack of good kneading as well as the lack of good pressing of mud components within the wooden mould used in the brick manufacturing, as shown in Fig. 9c. Through the results of the elemental analysis with (EDX) unit for mud brick samples, it was noted that silica is the main component of the samples. Iron, calcium, aluminum and potassium were found in various percentages (Fig. 9d) [19], [20].



Element	Weight %	Atomic %	Error %
C K	22.85	34.56	10.45
O K	38.87	44.15	9.57
Na K	0.92	0.73	14.12
Mg K	0.65	0.48	11.3
Al K	4.44	2.99	5.93
Si K	16.65	10.77	4.24
S K	0.84	0.47	13.03
Cl K	0.44	0.22	17.65
K K	1.46	0.68	8.01
Ca K	5.59	2.54	3.61
Ti K	0.77	0.29	13.68
Fe K	6.53	2.12	4.06

Fig. 9. SEM-EDX results of studied samples (a) SEM photomicrograph of mud brick, (b) SEM photomicrograph of mud mortar, (c) SEM photomicrograph of fired brick, (d) Energy dispersive X-ray (EDX) spot analysis of mud brick samples

4. Restoration and preservation procedures

In order to executive procedures for the restoration works at the Roman bath building in the city of *Karanis*, Fayoum, the field study, and the results of investigations and analyses were used. The restoration procedures included many technical works to restore many aspects of damage in the bath building.

4.1. Mud brick manufacturing for the purposes of building completion

To complete the missing parts of mud brick walls, mud brick blocks were manufactured, with similar original characteristics, components of raw materials and size of the ancient mud bricks. Table 4 shows the ratios of components involved in mud brick mixture. The ingredients were mixed well in the dry state, then a sufficient amount of water was added for good workability, and the mixture was left for several weeks until fermentation was complete. It is worth noting that the same fermentation method was used to prepare the mortars used in the restoration work. Fig. 10 shows the stages of preparing the mud mixture for manufacturing mud bricks, and preparing the mortar mixtures used in different restoration works.

4.2. General cleaning of the site and removal of garbage

The site was cleaned from the rubbish and waste, as shown in Fig. 10. Before any restoration works, the garbage was removed and the site was cleared of accumulated sand, dust, broken bricks and all residues in order to reveal the floors, foundations and the lower parts of walls and to facilitate movement to and from the bath building (Fig. 11 a–f).

4.3. Filling the gaps between fired brick blocks

The mortars between fired brick blocks in the bath building were disintegrated due to atmospheric weathering, which resulted in a lot of spaces between the fired brick blocks, and made the walls structurally weak. It is worth noting that some experimental samples of the filling mortars were made with different components, to choose the most suitable one in terms of the original components and the general appearance. Table 5 shows the ratios of components involved in the mortar that was used to fill the spaces between fired brick blocks. The process of filling the gaps between the fired brick blocks with a modified mortar was carried out as shown in Fig. 12, and the restoration works were carried out on the fired brick walls according to the following steps:

- Cleaning the walls mechanically and removing the decomposed mortar using coarse brushes, scalpels and metal sticks.
- Opening the gaps between fired brick blocks using soft brushes.
- Wetting the gaps between fired brick blocks by fresh water.
- Applying the above-mentioned mortar; shown in Table 5.
- Finishing and removing excess parts of the mortar.

4.4. Restoration of mud brick (adobe) walls

4.4.1. Treatment of the cracked adobe walls

Due to negligence and lateral loads, some vertical cracks occurred in the walls causing serious structural damage. In order to treat the problem of cracked walls, and to maintain the continuity of the walls "*reconnection*", wooden beams were used to make a connection between both sides of the crack. The treatment process took place as follows; firstly, the cracks were cleaned accurately by brushes and air blower, then a rectangular hole was dug in the lower part of the cracked wall. After that the hole was cleaned mechanically and wetted with fresh water. The preparation process was concluded by putting a thick layer of mud mortar at the base of the hole and inserting the wooden beam in the core of the wall and putting another thick layer of mud mortar above the wooden beam so as to have "*the wooden beam sandwiched between the layers of mud mortar*". It was necessary to complete the missing parts of cracked wall with new mud bricks, and make wooden beams long enough (45 cm in both sides of the cracked wall). Additionally, it was necessary to treat the wood to protect it from attacking insects using Clorzane 48%

EC which was applied on the wood by brush. The above-mentioned method of treating was repeated on the upper part of the cracked wall [21], [22]. Fig. 13 shows the cracked walls and the steps of treatment and restoration.

Table 4. Ratios of components involved in mud brick mixture

No.	Component material	The ratio relative to the weight of the dry mixture
1-	Crushed clay	35
2-	Salt-free sand	40
3-	Slaked lime	9
4-	Fired brick powder	8.5
5-	Ash	2.5
6-	Chopped straw	5
7-	Fresh water	sufficient quantity

Fig. 10. Stages of preparing the mud mixture for manufacturing mud bricks, and preparing the mortar mixtures used in different restoration works (a) Sieving the ingredients and purify them from impurities, (b) Fermentation process, (c) Kneading process.

Fig. 11. Different parts of the bath building during and after carrying out cleaning works (a) Removal of garbage, (b, c) Removal of accumulated sand and fragments, (d, e, f) Different parts of the site after general cleaning.

Table 5. Ratios of components involved in mortar used for filling the gaps between fired brick blocks

No.	Component material	Ratio (by weight)
1-	**Crushed clay**	**1.5**
2-	**Salt-free sand**	**4**
3-	**Slaked lime**	**3**
4-	**Ash**	**0.2**
5-	**White cement**	**0.2**
6-	**Brick powder (Humra)**	**1.5**
7-	**Fresh water**	**To attain good mix consistency**

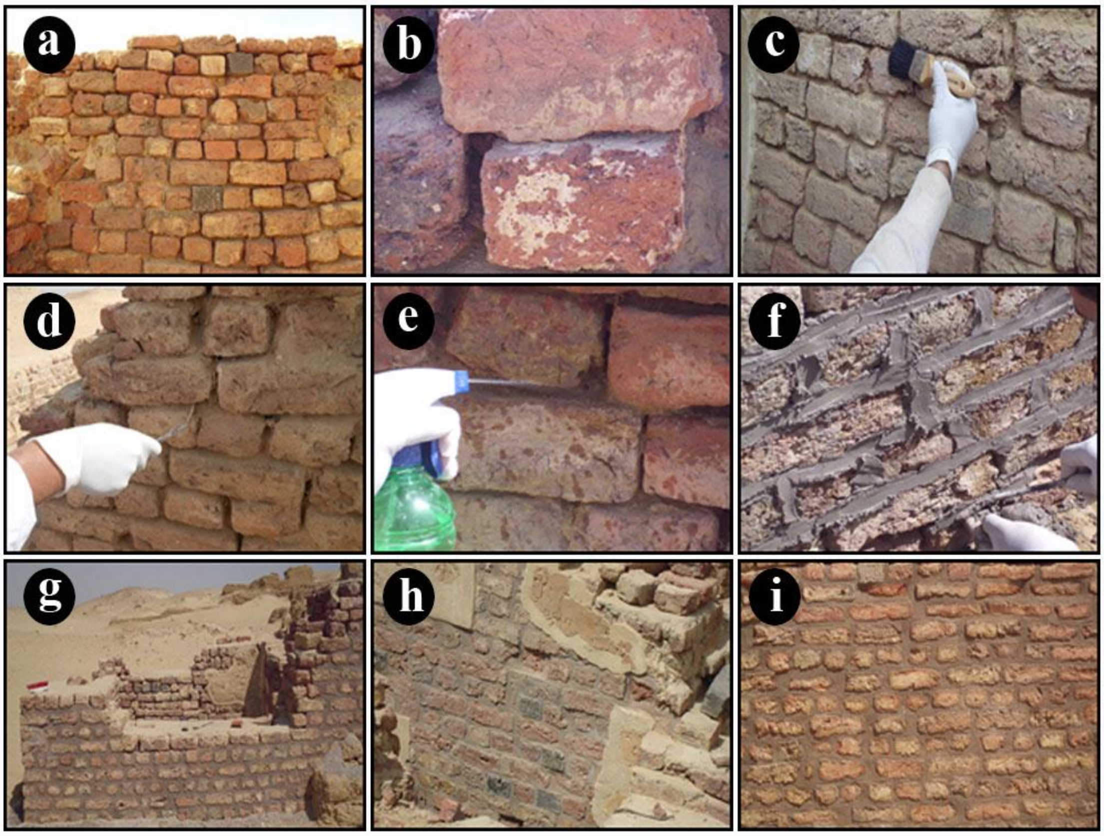


Fig. 12. Fired brick walls before, during and after restoration works and filling voids between brick blocks (a) Showing the gabs between fired bricks, (b) Detailed from the previous image, (c, d) Cleaning the walls mechanically and remove the decomposed mortar using coarse brushes, scalpel and metal sticks, and opening the gaps between brick blocks, (e) Wetting the spaces between brick blocks by fresh water, (f) Applying the modern filling mortar in the gaps, (g, h, i) The walls after finishing the filling process between brick blocks.

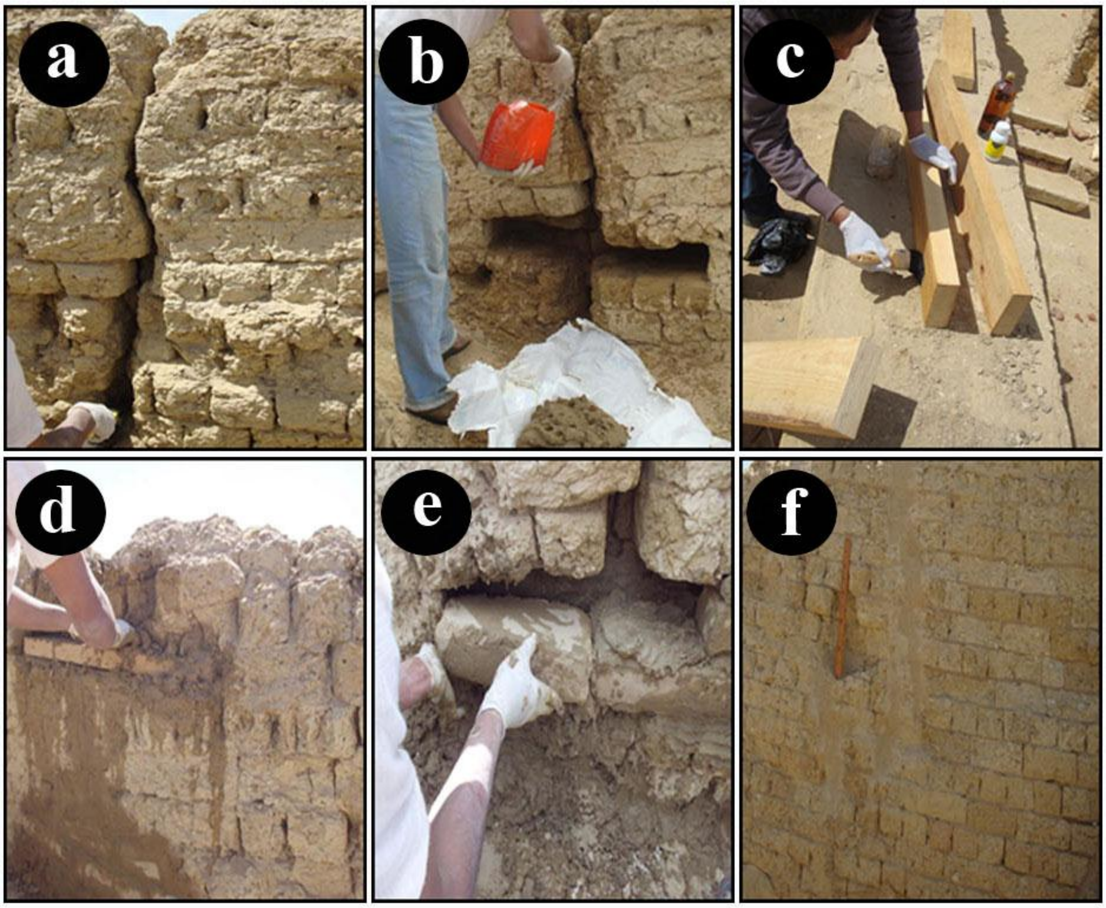


Fig. 13. Mud brick walls before, during and after treating the cracks (a) A cracked wall before treatment, (b) Making a rectangular hole in the wall perpendicular to the crack, (c) Treating the wood beams with the pesticide, (d, e) During reconnecting the cracked wall using wood beams with mud mortar and mud bricks, (f) The cracked wall after treatment.

4.4.2. Filling the missing parts of adobe walls with modern mud bricks

There were many missing parts in the mud brick walls due to atmospheric and biological weathering. These empty places in the walls resulted in a structural riskiness in the building, so the rubbish and fragments were removed and the spaces were opened using coarse and fine brushes, scalpels and metal sticks. After that, the missing areas were wetted by water, then filled with mud bricks and mud mortar (*this mortar has the same components of the modern mud brick as shown in* Table 4. Fig. 14 shows the missing parts in mud brick walls and the method of restoration and filling of the spaces.

4.4.3. Restoration and strengthening the niche in the entrance wall

This niche lies in the inner part of the entrance wall of the bath building, and was built of mud brick. The niche was mostly probably a wooden or stone lintel, but this lintel is now missing. It was also eroded and mostly damaged. The restoration process of the niche relied on putting a new disinfected wooden lintel and reconstructing the missing, eroded parts, using mud bricks and mud mortar. Fig. 15 shows the restoration works of the mud niche. It is worth noting that this restoration procedure can be considered as an initial restoration, because the entrance wall will be subjected to subsequent restoration, which is capping and plastering "troweling" with mud mortar.

Fig. 14. The method of restoration and filling the missing parts in mud brick buildings (a) Some disintegrated mud brick courses in the wall, need to be removed and rebuilt, (b) During rebuilding with modern mud bricks and mud mortar, (c) The wall after rebuilding.

Fig. 15. Steps of the initial restoration of the niche (a) The niche wall before restoration, (b) During restoration and inserting the wooden lintel, (c) The niche wall after initial restoration.

Table 6. Ratios of components involved in the mortar used for capping

No.	Component material	Ratio (by weight)
1-	**Crushed clay**	**1.5**
2-	**Salt-free sand**	**4**
3-	**Slaked lime**	**3**
4-	**White cement**	**1.25**
5-	**Chopped straw**	**5**
6-	**Fresh water**	**To attain to mix workability**

4.4.4. Capping and protecting the upper parts of adobe walls

In order to protect mud brick walls in the bath building from rain water and sun rays, capping and completing processes were carried out. This technique is known as "upper protection of the adobe walls"; the method of upper protection was carried out as follows:

- Cleaning the upper parts of mud brick walls, mechanically by brushes, putty knife and air blower.
- Removing the remains of mud brick and mortar.
- Wetting the upper/missing parts by spraying with fresh water.
- Completing the missing parts in upper courses of mud brick walls using modern mud bricks and mortar.
- Putting a thick layer of mud mortar on the upper course of the wall, this layer should fill all gaps.
- Spreading plastic sheets "Kartunal" on the above-mentioned layer of mud mortar [23].
- Putting a thick layer; 3-4 mm. approximately of modified mortar (its components are shown in Table 6 on the plastic "Kartunal" sheet.

It is worth noting that the plastic sheets and modified mortar make a protective layer to the upper parts of the adobe walls. Moreover, the plastic sheets will serve as an indicator when the upper mortar is damaged by the effect of rain water and sun rays, where the mud mortar layer is constantly renewed to ensure that the ancient walls are protected from damage [24]. Fig. 16 shows the steps of reconstruction and capping of upper courses.

Fig. 16. Steps of reconstruction and capping of upper courses in adobe walls (a) Some adobe walls, the upper courses of which were completely destroyed by rain water and other atmospheric agents, (b, c) During reconstruction and capping using mud bricks, mud mortar and plastic sheets, (d, e, f) Some adobe walls after reconstruction and capping.

4.4.5. Plastering "troweling" the mud brick walls with mud plaster

The main base in restoration of adobe buildings is keeping them protected from environmental factors (i.e., wind storms, sun light, rain water…etc.). The site of Roman bath/ *Karanis* lies in a desert environment, so it is continuously exposed to sandy storms and strong air motions, which lead to crushing of adobe surfaces. Therefore, it was necessary to apply mud plaster layers on the surfaces of mud brick walls to protect these exposed walls as long as possible. Components of the used mud plaster are shown in Table 7. The mud plaster was carried out on the adobe walls using a special tool known as "trowel", to cover the wall surfaces. A piece of sponge was used to add finishing touches. It was axiomatic that the adobe walls were cleaned mechanically by soft brushes and wetted by spraying with fresh water before covering with mud plaster "troweling" [25]. Fig. 17 shows the technique of troweling with mud plaster.

Table 7. Ratios of components involved in mud plaster used for troweling.

No.	Component material	Ratio (by weight)
1-	**Crushed clay**	**1**
2-	**Salt-free sand**	**5**
3-	**Slaked lime**	**2.5**
4-	**Chopped straw**	**4**
5-	**Fresh water**	**sufficient quantity**

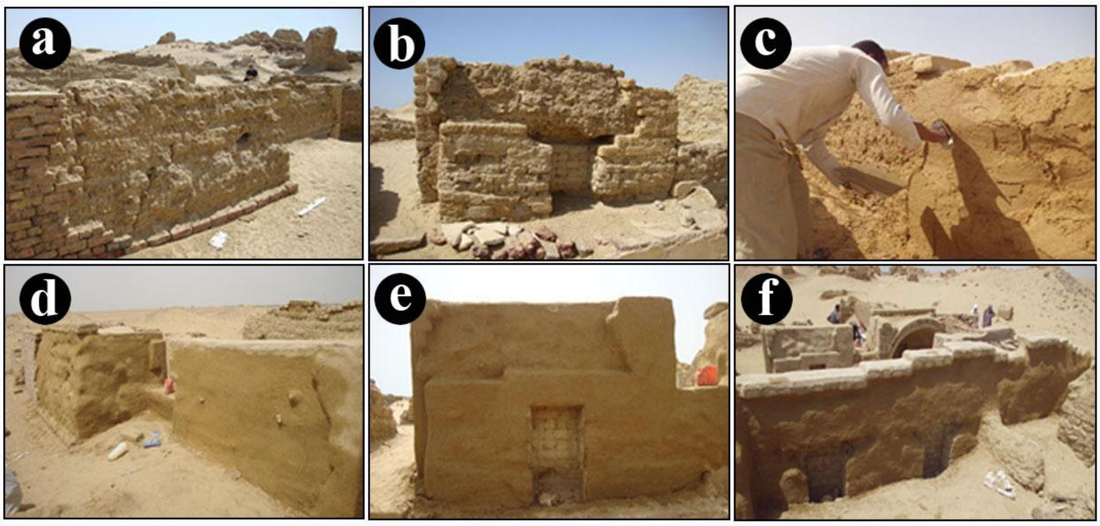


Fig. 17. The technique of troweling with mud plaster (a, b) Some mud brick walls before plastering, (c) During plastering "troweling", (d, e, f) Some mud brick walls after troweling with mud plaster.

5. Conclusion

The site of adobe Roman bath at *Karanis*, Fayoum is an important archaeological site, which must be preserved from damage and extinction. The site represents a unique example of traditional adobe architecture, which is eco-friendly architecture. The Roman bath was built from local building materials, whether mud brick, mud mortar, mud plaster, and fired brick. All mud materials are rich in sand and organic matter. The main factors of damage are climatic factors, especially rain water, wind storms, temperature variations, and sand dunes. The restoration works that were carried out on the Roman bath building included protection, reinforcement and risk reduction. These works are an important step in preserving the archaeological building. However, adobe buildings, due to their nature, are constantly damaged, especially due to severe environmental changes in the desert environment. Therefore, there are a number of recommendations that should be taken into consideration to ensure the long-term protection of the archaeological site, including the necessity:

- to constantly monitor the site and remove garbage, rubbish and sandy sediments.
- to renew the mud plaster to preserve adobe walls from disintegration due to weathering agents.
- to carry out windbreaks (planting trees, barriers...etc.) in the direction of wind to prevent harmful effects of sand dunes/ sediments on the archaeological site.

- to perform periodic conservation of the archaeological site, because of continuous exposure to weathering factors. This regular maintenance should include: first aid, disinfection and renewing capping and plastering layers.

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