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INFLUENCE OF DETERIORATION ON THE PRESERVATION OF MUD BRICK ARCHITECTURE BASED ON THE MONUMENTS FROM THE TELL EL-RETABA ARCHAEOLOGICAL SITE

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Abstract

Properties of mud bricks and reconstructed brick material from the Tell el-Retaba archaeological site in Egypt have been compared. The site is located in the transitional zone between humid sub-tropical and dry tropical climate. The influence of deterioration on changes of the physical and mechanical properties of mud bricks has been assessed as a factor of time. Effects of deterioration of the mud brick material have been presented: exfoliation as an effect of heating enhanced by colour, mud brick deformation and salt crystallisation as a result of cyclic watering and evaporation, and loosening of the structure caused by numerous factors. With brick age, decrease of bulk density and increase of porosity has been observed. The values of these parameters in the reconstructed brick material do not show a similar trend. Differences in grain size and mineral composition of the material used for brick production influenced not only the speed of deterioration processes but also the prevailing type of the process. Comparison of the properties of mud bricks and the reconstructed material indicates that mud bricks were characterised by good initial values. However, with time, the physical and mechanical properties of the mud bricks became significantly worsened following the long-term influence of deterioration processes.

Keywords*: Residential and defence structures; Physical and mechanical properties; Reconstruction of mud brick; Weathering processes; Nile Delta, Climate change*

Introduction

Worsening of the physical and mechanical parameters of building material in effect of atmospheric and anthropogenic factors is known as deterioration. The issues related with long-term deterioration processes on the physical and mechanical and structural properties of building material have been undertaken in various aspects by numerous authors [1-8]. The influence of atmospheric factors such as air temperature or humidity, wind, rainfall and microorganism activity that causes changes in the properties and structure of the building material is known as weathering. The weathering rate is strictly related with the climate zone and the duration of the influence of the dominating factors. Therefore, the most significant cause that influences the degree of atmospheric impact on the building material is the location of the object in a specific climate zone. This is the main factor influencing the type and intensity of the dominating weathering process. The speed of the weathering processes is also linked with the properties of raw material, such as grain size and mineral composition or structure.

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Atmospheric factors may be overlapped by anthropogenic factors such as environmental pollution or incorrect conservation of the object [7-10].

The commonly used building materials in ancient Egypt included stone, mud bricks and wood. The role of stone increased over the centuries and, due to the geological setting of the area, the typically used rocks were limestones and sandstones. Granite and basalt were applied to a lesser degree and mainly for decorative purposes [11-13]. Mud bricks were also a commonly used building material. They were produced from alluvial sediments of the River Nile. Alluvial mud accumulated on river terraces occurred within the entire delta and particularly in Lower Egypt it was used to produce sun-dried mud bricks. In turn, in Upper Egypt, above Esna, alluvial deposits of the Nile contain much more sand and are not favourable for direct production of mud bricks [14].

The beginnings of mud brick usage as a building material in Egypt reach back to the Predynastic Period (Nagada II culture, c. 3500 – 3200 B.C.) and are represented for example by funeral chambers in the T cemetery at Nagada whose walls were plastered. Further development and refinement of the technology of mud brick production contributed to the development of architecture, firstly of sacral objects, e.g. the mastabas in Sakkara from the 1st Dynasty, and later also residential and defence architecture [15]. Monumental mud brick architecture of ancient Egypt, including vast palace and temple complexes, is still poorly known due to the large degree of destruction, as observed in numerous archaeological sites both in Upper and Lower Egypt. Only foundations of these objects or small remains of their walls are preserved in such archaeological sites as Tell el-Amarna, Western Thebes, Karnak or Memphis [13].

The locality of the mud brick object was related to the source of the raw materials used for its construction. Most objects built of mud bricks, regardless their age, were constructed on the Nile floodplain or within the delta. Due to climate change and regulation of seasonal floods after the construction of the dam in Aswan, at present their remains are often found within the desert. Tombs and accompanying objects of cult are the most common constructions.

Some of the essential materials for the production of mud bricks were clay (cohesive) sediments, e.g. alluvial muds or lacustrine sediments periodically supplied by the Nile flood waters, commonly occurring in the delta and in close vicinity of the constructed objects [13, 16]. Improvement of mud brick properties was maintained by the addition of various components, such as sand, gravel and straw chaff. Mud bricks are relatively easy to produce as building material. Their properties cause that mud bricks were widely used in ancient times and at present. However, mud bricks are very sensitive to mechanical damage and atmospheric factors, such as temperature change due to the effect of insolation or water influence, e.g. rainfall or soaking caused by groundwater level changes. Low strength of mud brick material to atmospheric conditions causes destruction of objects raised from mud bricks and the need for their continuous conservation [8, 13]. During their exploitation, such objects were repaired on an ongoing basis, while when abandoned they were subject to progressive degradation. In the case when they were covered by desert sand, such objects were cut off from atmospheric factors and only in a minor degree were exposed to further deterioration processes. Progressive increase of the degradation rate of mud brick objects took place after the sand was removed, i.e. during archaeological excavations. Such exposed mud brick constructions should be immediately secured and subject to conservation.

Despite the fact that in ancient Egypt mud bricks were one of the most commonly applied building material for over 3000 years, the number of monuments that exist till present is only a small fraction of objects constructed during that time. Furthermore, their preservation conditions are very poor, and the saved fragments usually represent the lowermost parts of the mud brick constructions. This is a large problem for such monuments, not only in the Nile valley but also other parts of Africa and other continents, where mud brick architecture is common. The reasons for such significant destruction include:

a) properties of the used raw materials and the applied technology of production, which are responsible for the values of physical and mechanical parameters of the produced bricks;

b) location of the mud brick objects in relation to climatic zones;

c) local microclimate;

d) climate changes during the operation of the object and after its abandonment;

e) activity of organisms, and

f) anthropogenic factors, including usage and conservation of the object during its operation, usage of the object after its abandonment, or activities, which expose the mud brick constructions, e.g. archaeological excavations.

A trigger that inclined the authors of this research to undertake interdisciplinary geoarchaeological investigations in the Tell el-Retaba archaeological site was the need of explaining the reasons of the poor preservation condition of the mud brick constructions. We tried to understand what is the influence of deterioration processes on the preservation conditions of objects built of mud bricks? The preliminary results of these investigations and the impact of environmental factors on mud bricks from this site have been presented by *S. Rzepka et al* [17] and *J. Trzciński et al* [18].

Taking into account the problem and its causes, the investigations were concentrated on determining the influence of deterioration processes on the geological-engineering properties of mud bricks. Relationships between mud brick properties, characteristics of sediments used for their production, as well as technological aspects of the production were explored. Particular attention was drawn on the influence of changing climatic and anthropogenic factors on these properties. Multifactor analysis of the obtained results resulted in determining the range of changes taking place in the material properties during several thousand years, the trend of these changes and their rate. This was possible by reconstructing the mud brick material with the application of an ancient production technology and testing its properties. The measurable effects of these investigations are rules for preparing mud brick replicas. Such rules will be a valuable source of information for monument conservators, who undertake activities linked with the reconstruction of mud brick material or reconstruction of mud brick objects.

Experimental studies

Tell el-Retaba site

Tell el-Retaba is an archaeological site located in NE Egypt, 35km to the W of Ismailia (Fig. 1). The site lies in the middle of Wadi Tumilat, a shallow valley running from the Nile Delta to the Bitter Lakes. The valley was one of the routes between Egypt and Syro-Palestine. The route was strongly fortified in the New Kingdom times (16^{th}-11^{th} century BC). The studies were concentrated on the analysis of mud bricks from three walls and two domestic buildings from this period.

The first archaeological investigations in Tell el-Retaba were conducted by *E. Naville* [19] and *E.M.F. Petrie and J.G. Duncan* [20]. Several Egyptian missions and an American mission worked on the site in the 20^{th} century. Complex archaeological investigations including excavations, archaeological, geophysical and geological prospections are conducted by the Polish-Slovak Archaeological Mission since 2007 [17, 21-23]. Detailed geoarchaeological studies confirmed that local clays, sands and gravels occurring around the fortress were using for mud bricks production at Tell el-Retaba [16].

The oldest settlement in the site is from the late phase of the Second Intermediate Period and 1^{st} half of the 18^{th} Dynasty (17^{th}-15^{th} century BC) (Table 1). Later, the site was abandoned. Subsequent settlement took place at the beginning of the 19^{th} Dynasty (beginning of the 13^{th} century BC). At that time a fortress surrounded by a huge brick wall was constructed (Petrie's "Wall 1"). The fortress surrounded by "Wall 1" existed only for several tens of years. By the end of the 19^{th} Dynasty, the defensive walls and the inner constructions were in perish. At the beginning of the 20^{th} Dynasty (1^{st} half of the 12^{th} century BC), in Ramesses III times, the ruins were levelled and a new, larger fortress was constructed on the site; the fortress was surrounded by a much larger brick walls referred to as "Wall 2" and "Wall 3" (Fig. 2). The fortress of Ramesses III existed for over 100 years. During the Third Intermediate Period, the defensive walls were already ruined [17, 21-30].

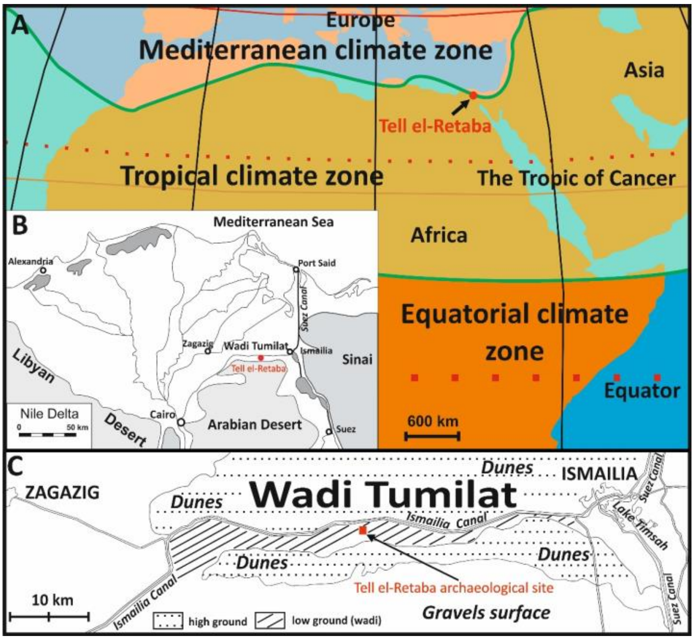

Fig. 1. Location of the Tell el-Retaba archaeological site: A – with regard to the climate zones of Africa, Southern Europe and Western Asia, B – in the Nile delta, C – in Wadi Tumilat.

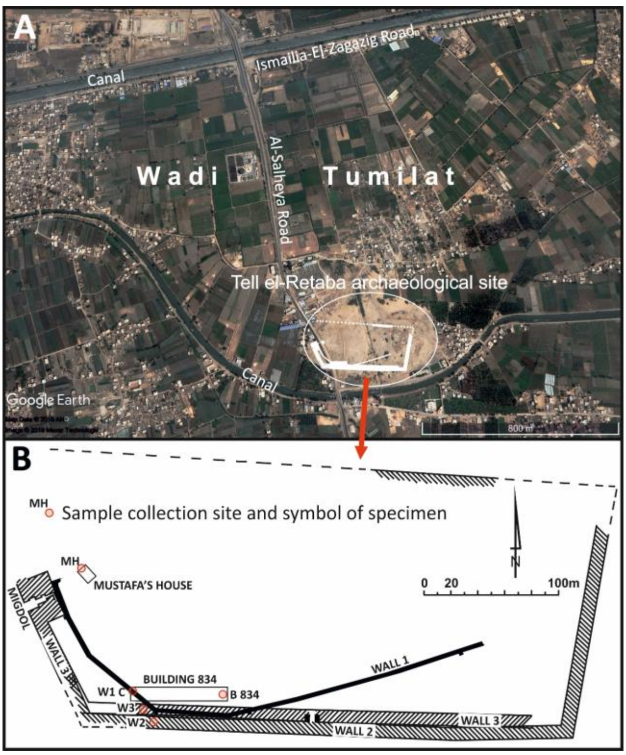

Fig. 2. Tell el-Retaba archaeological site: A – location of the site with outline of fortress walls (map from Google Earth), B – location of the mud brick material collected for studies from defence and residential structures - outline of fortress walls after Petrie and Duncan [24].

Table 1. Changes of hydrological conditions in the Nile Delta with regard to settlement intervals in the Tell el-Retaba archaeological site.

Period		Age	History of settlement	Hydrology of the area after Butzer [31]
Late Period		7th-4th century BC	Lack of remains	Medium floods in 5th century BC
Third Intermediate Period		11th-7th century BC	Open settlement	High floods between 9th and 7th centuries BC
New Kingdom	Beginning of 20th Dynasty	1. half of 12th century BC	Ramesses III builds fortress with “Wall 2”, “Wall 3”, Building 834 and entrance gate (100 years of operation)	Low floods and narrowing of lake limits (famine)
	1. half of 19th Dynasty	Beginning of 13th century BC	Ramesses II builds fortress on plateau with “Wall 1” (several tens of years of operation)	High floods with occasional low floods, widening of lake limit
	2. half of 18th Dynasty	14th century BC	Abandonment of settlement for 100 years	
	1. half of 18th Dynasty	16th-15th century BC	Egyptian settlement with Mustafa’s House	
Second Intermediate Period		18th-16th century BC	Hyksos settlement	
Middle Kingdom		2133-1786 BC	?	Catastrophic low floods (famine) and narrowing of lake limits
First Intermediate Period		2181-2133 BC	?	
Old Kingdom		2686-2181 BC	?	
Early Holocene		? – 2700 BC	?	High floods and widening of lake limits – lake sediments including mineral-organic clays and silts
Pleistocene		-	-	Fluvial sands and gravels of a braided river

Climatic conditions in the area of the site

Wadi Tumilat is located in the south-eastern part of the Nile Delta at the boundary with the desert. The area is located in the transitional zone between two climate zones: 1) humid sub-tropical (Mediterranean) zone, dominating in the north of the country and in the Nile Delta, and 2) dry tropical zone, which influences the remaining area (Fig. 1A). Explaining the influence of deterioration factors responsible for mud brick weathering in the area requires determination of the typical features of both climate zones.

The dry tropical zone is characterised by low precipitation, high summer temperatures and low humidity. The Mediterranean climate zone has relatively more intense rainfall, especially during the winter, high summer temperatures, mild winters and higher humidity. In Wadi Tumilat rainfall is rather low and irregular, annually reaching from 25 to 50mm/m^2. Rains usually occur between October and May. During the summer temperatures are high and humidity is low. In the winter, the climate becomes more temperate. Clouds are common, the rain intensity is low, and morning and evening dews are frequent. Humidity becomes higher. Annual temperature almost never falls below 0°C [24].

The prevailing wind direction in entire Egypt is from the north-east. Between March and May, a warm, dry wind, known as Khamsin, blows from the desert to create intense silt-sand storms. Very large insolation is characteristic of the area. During the summer, the sun shines at angles from 80° to 90°, which causes heating of the sun lighted surface even up to 70°C. Due to strong insolation in the areas of the Eastern and Western Deserts and Sinai, evaporation prevails in these areas above infiltration. In effect, salts dissolved by rainfall are not discharged inwards but rather recrystallized in the sub-surface zone [25].

Methods

The influence of deterioration processes on mud brick properties has been analysed based on material from selected defence and residential objects (Fig. 3), whose location is presented in Fig. 2B. The methodology described by *J. Trzciński et al* [18, 26] has been used in the analysis of physical and mechanical parameters (Fig. 4). The mud brick material has been reconstructed to determine the properties that the bricks had directly after production. The reconstruction included some aspects of mud brick production, such as water content, consistency and compaction of the mixture and drying [27]. The reconstruction allowed to determine the physical and mechanical parameters of the mud bricks directly after production and to compare them with the present-day parameters of the original mud bricks.

Application of the material that was used for mud brick production for the reconstruction has allowed for obtaining an identical grain size and mineral composition. Small changes in the initial chemical composition of the mud bricks resulted mainly from the weathering of some minerals, decomposition of organic matter or introduction of additional substances during object operation. These changes had only minor influence on the properties of the reconstructed material. Repeated or multiple usage of the same mud brick material during settlement in the area should also be taken into account. Mud bricks from objects which underwent destruction or were left over by previous users could be repeatedly used for the production of new mud bricks. Such material was only to a small degree subject to modification by admixtures improving mud brick properties, applied in the contemporary technology of their production.

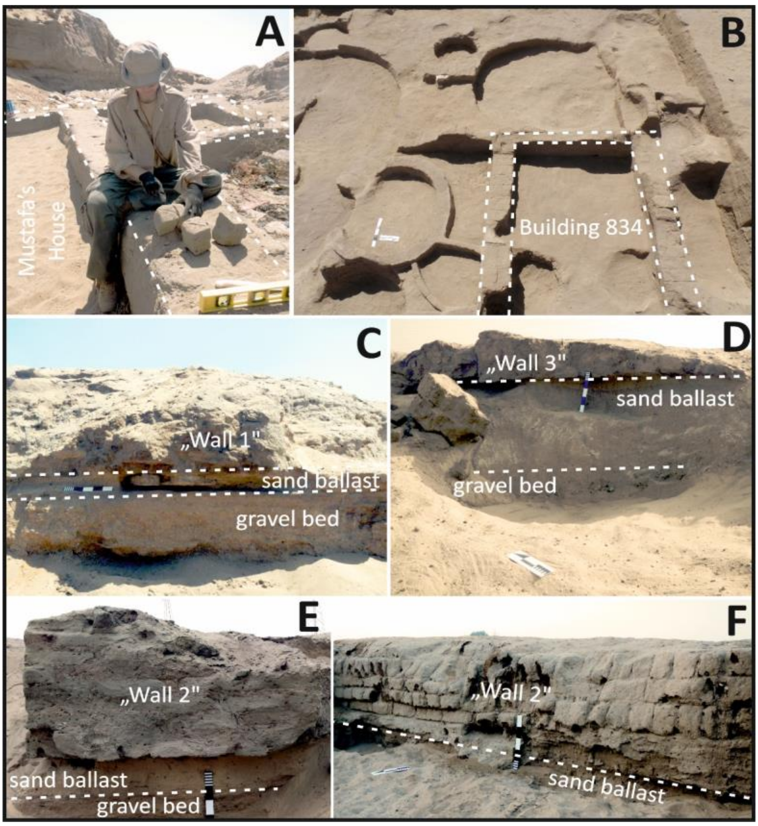

Fig. 3. Defence and residential structures in Tell el-Retaba archaeological site: A – Mustafa's House, B – Building 834 (photo from the collection of Polish-Slovak Archaeological Mission), C – "Wall 1", D – "Wall 3", E – "Wall 2" (cross-section), F – "Wall 2" (in the front). Localisation (Fig. 2B).

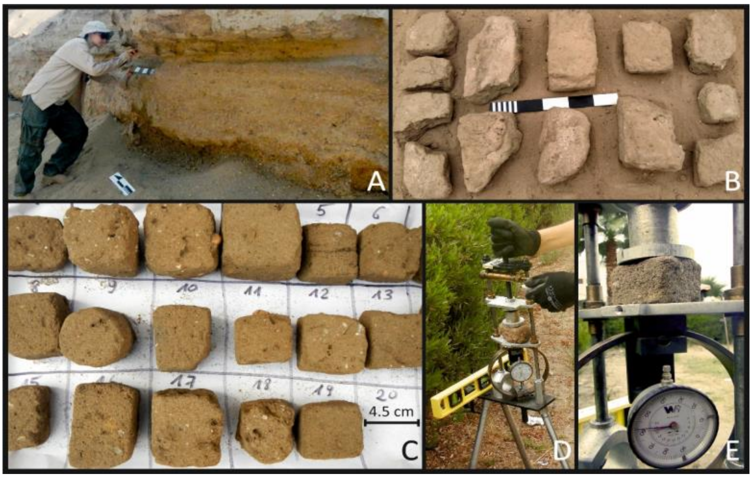

Fig. 4. Methodology of mud bricks analysis: A – fragment of "Wall 1", B – selected bricks, C – samples for laboratory analysis, D – general view of apparatus for compressive strength analysis, E – sample during analysis of uniaxial compressive strength.

Reconstruction of the mud brick material has been made based on selected mud brick parameters, i.e. bulk density and shrinkage. Amount of water that is required for obtaining a mixture with an appropriate consistency has been calculated [27]. Particular stages of material reconstruction and preparation for further analysis are presented in Figure 5. Dry material was gently crushed with a pestle with a rubber cap and next water was added to obtain a soft plastic paste with an appropriate consistently (Fig. 5A).

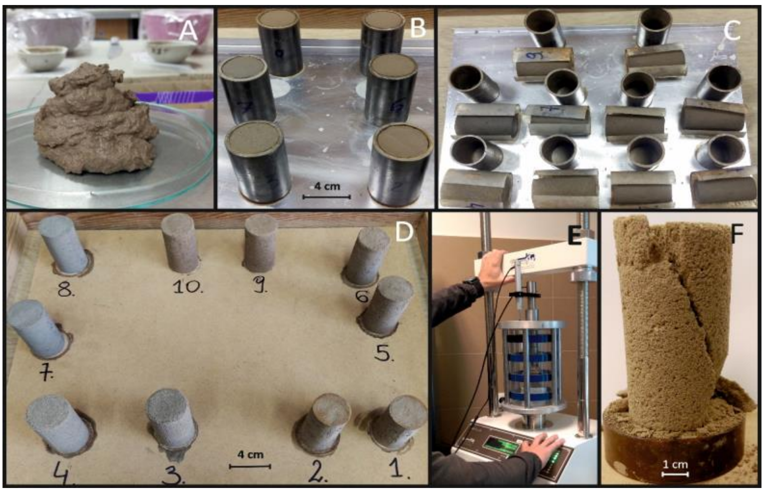

Fig. 5. Methodology of reconstructed brick material analysis: A – preparation of mixture, B – material placed in steel pipes, C – drying of formed samples, D – preparation of samples for compressive strength analysis, E – uniaxial compressive strength analysis, F – sample destruction after compressive strength analysis.

The paste was inserted in a steel pipe lined with thin plastic foil, to reduce adherence of the material to the pipe wall during drying (Fig. 5B). After stabilisation and initial drying, the samples were taken out of the pipe and dried for several days to an air-dried state (Fig. 5C). Next, the samples were additionally dried at 45 ºC for three days. After complete drying, the upper and lower surfaces of the samples were levelled so that they became parallel, and later the samples were weighed, measured and photographed (Fig. 5D). Normalised cylinder samples were subject to analysis of uniaxial compression strength according to the norm PKN-CEN ISO/TS 17892-7: 2009 [28] and their destruction was documented (Fig. 5E and F). The procedure was made in four repetitions in order to obtain a better statistics of the results.

The methodology applied for testing the properties of the original mud bricks and the reconstructed mud brick material differed in the applied instruments and the shape of the samples [18]. These differences did not have much influence on the obtained results. In both cases, uniaxial compression strength was calculated with regard to norm differences for samples with irregular and regular shapes.

Results and discussion

Factors, processes and effects of deterioration, and counteracting their consequences

Effects of mud brick deterioration have been documented during fieldwork. Exfoliation of mud brick surfaces has been observed on the exposed wall fragments (Fig. 6A).

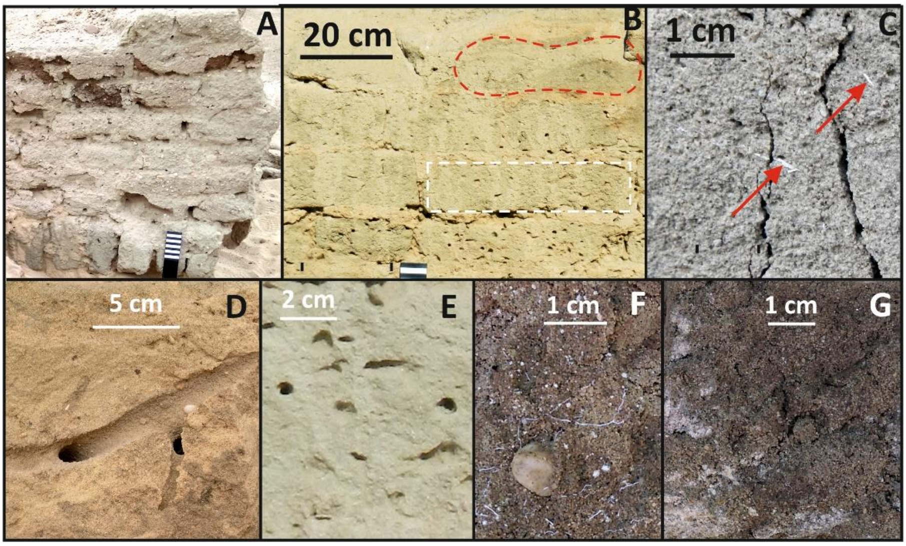

Fig. 6. Manifestations of mud brick deterioration (see text for details): A – exfoliation, B – deformation visible in the wall of Mustafa's House (white dashed line indicates non-deformed brick, red dashed line indicates deformed brick), C – salt crystallization (arrowed), D – borings, E – borings, F – salt crustallization (white threads and points), G – saline efflorescence on the surface.

Exfoliation resulted from the effect of insolation weathering during exposure of the objects for the last few years after their unearthing during archaeological excavation works. The effect is linked with the cyclic process of heating and cooling of the sub-surface layer, which is heated more intensely than the deeper parts of the mud brick. Thermal expansion of minerals is observed. Cyclic temperature changes cause the formation of stress on the contacts and their destruction, which causes loosening of the brick structure, leading to the formation of surface-parallel fractures, and chipping of single grains and particles. Similar processes took place also during exploitation of the objects by the ancient Egyptians. To a lesser degree exfoliation occurred on the wall surfaces of residential objects, because they were much lower than the defence walls and usually located within the fortress, which gave them additional protection against heating. A mud layer, which was used to cover the external walls, acted as additional protection. Object walls with a NW to NE exposure also did not heat as intensely. Mud brick colour directly influences the effect of heating and exfoliation (Fig. 7). A darker-coloured mud brick warms up more intensely than a lighter-coloured brick, therefore thermal stress is higher and, in consequence, loosening of the mud brick material takes place on a larger scale. Mud brick colour and its significance in the ancient Egyptian constructions have been discussed recently by *M. Zaremba et al* [16]. Analysis of isochronous objects (W2, W3 and B 834) built of variously coloured bricks shows that brick deterioration is caused by brick colour and object location. The fortress walls, being a protection for the objects within the fortress against the impact of atmospheric conditions, were at the same time most liable to these conditions.

Fig. 7. Mud brick colours: MH – light grey, W1 C – grey-brown, W2 – light grey, W3 – brown (arrows indicate imprints of plant fragments), B 834 – dark brown. Symbols of objects as in Fig. 2B.

Diurnal changes of air humidity induce the formation of stress in the brick structure. Swelling and shrinkage of the brick material in a diurnal cycle results in micro stress. These factors cause loosening and weakening of the internal brick structure. Particularly sensitive to these factors were bricks from the core of “Wall 1” (W1 C), which are characterised by the presence of extremely hydrophilic clay minerals [27].

During detailed field work, wall fragments with deformed bricks have been observed for example in Mustafa’s House – MH (Fig. 6B) [27, 29]. The deformations bear traces of water influence caused by intensive rainfall, resulting in bricks moistening. Similar brick deformations, caused by rise of groundwater level, have been observed by *J. Trzciński et al* [26]. Numerous traces of salt crystallisation have also been observed both on brick surfaces and on fresh fractures (Fig. 6C-E). This fact additionally documents the process of cyclic moistening and drying of the mud brick material in strong insolation conditions.

During field studies, breaching of the material structure due to the activity of boring organisms was documented in mud bricks from “Wall 2” – W2 and Mustafa’s House – MH (Fig. 6F and G). Mud brick surfaces are covered by numerous oval holes, 1cm in diameter, whereas long, several centimetre-long networks of bored tunnels are visible in cross-section. The holes formed in the mud brick cause decrease of its strength.

The grain size composition of the mud bricks differs from the initial composition of the mixture used for brick production. These results from diagenetic processes related to drying up of the material, due to which aggregation, typically of the finest particles, usually takes place. Weathering may also cause aggregation, for example due to the formation of new crystalline phases, as well as a process opposite to aggregation – disaggregation, causing breaking up of the formed aggregates and grains. Physical and chemical processes, such as grain fracturing or weathering of feldspars, cause disintegration of the coarser grains and enrichment in finer fractions. These processes may also be reversed, when aggregation of smaller particles of the finer fractions takes place and coarser fractions are produced. An example of such process is the formation of various sizes of e.g. calcium carbonate concretions, or cementing of smaller grains typically in the clay and silt fraction, by salts secondarily crystallising from water solutions circulating in the pore space of the brick material. Circulation of solutions took place when the brick material was soaked with rainwater, dew water or groundwater when the groundwater level rose.

Chemical deterioration takes place in case of changes related with the decomposition of organic matter. The decomposition of small amounts of dried and disintegrated plant remains added to the mixture is evidenced by voids after plant fragments, often observed on fresh fractures of the bricks (Fig. 7).

Ancient Egyptians undertook actions focused on limiting the degradation processes, for example by application of protective structures. They built sinusoidal one-brick-thick walls, like those near Mustafa's House with a NE to SE orientation (Figs. 3 and 5) [29, 30]. Such wall did not only separate the area around the house but also protected it against the destructive activity of wind and sand – wind erosion. A similar example but on a larger scale was the complex composed of "Wall 2" and "Wall 3", which were built one next to another. It seems that "Wall 2" was a low platform and a sort of protection and shield for "Wall 3". Most probably it was a defence against potential flooding linked with high water levels in the Nile, which caused increase of water level in the nearby channels and local lakes. Flooding of low ground took place in such cases, which could have threatened the stability of "Wall 3" as a defence structure. Evidence that such case was taken into consideration during the construction of the second, larger fortress was the fact that the foundation of "Wall 3", located on the slope of an elevation composed of gravel, was made on a high ballast to level its height with the foundation of "Wall 1" [17]. Raising of the foundation level was made because of repeated cases of flooding of the area around the fortress, which took place during the construction and exploitation of the first fortress with "Wall 1" [18]. Ancient Egyptians performed an on-going reinforcement of the strained constructions, for example by building reinforcements as in the case of the inner and outer extension of "Wall 1".

Insolation weathering on the brick surfaces and washing out due to rainfall are related with subsequent exposure of the fragments of buildings resulting from the present-day human activities. Removal of the protective sediment cover from the remains of the fortress resulted in subsequent, direct impact of deterioration processes. Besides, building exposure to weathering, duration of this exposure, and lack of maintenance of the buildings when the settlement was abandoned were of high significance for the qualitative and quantitative effects of mud bricks deterioration. Loosening of brick structure could have been caused also by increase of porosity due to the decomposition of plant remains in the lake deposits and decomposition of straw chaff added to loosen the mixture.

Climate change had high impact on the environment, especially on the hydrological conditions in the Nile Delta and the anthropogenic activity in the area, significantly dependent on the annual inundation of the Nile [31]. These changes caused increase or decrease of the water level in the Nile, which resulted in high or low water levels in all tributaries crossing the delta. Changes linked with high and low Nile floods presented by *K.V. Butzer* [31] have been confirmed by isotopic analysis [32]. According to archival data, climate did not change significantly over the last few centuries in the Nile Delta and in the Wadi Tumilat region [23]. In the Pleistocene, a braided river filled the delta with fluvial sediments, mainly sands and gravels (Table 1). Small elevations (plateaux) were formed, which were used for potential settlement in later periods. The Early Holocene was characterised by high levels of flood water and increased lake ranges, which favoured the formation of lake sediments. Such lake reservoir existed in the vicinity of the plateau, on which the fortress was later constructed [29]. The next period is characterised by low flood levels, which lasted till the beginnings of the Second Intermediate Period, when a Hyksos settlement began to function near the plateau. High flood levels and increased lake ranges have been noted from that time till the end of the Ramesses II fortress. Therefore, a catastrophe caused by these factors must have occurred during the construction of "Wall 1", which caused the instability of its structure. Extensions were added to both sides of the wall to protect it against damage [25]. The wall structure, composed of a core and two extensions (innner and outer), has not been explained yet (Fig. 8).

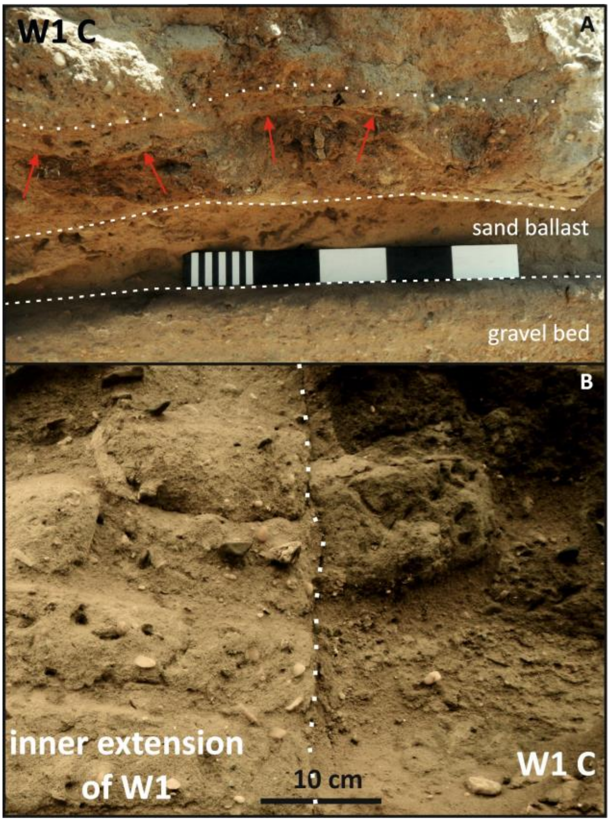

Fig. 8. Deformation visible in "Wall 1". A – plastic deformations of the bottom mud brick layer (marked with arrows and a dotted line), B – deformed structure in W1 C (poorly visible brick pattern) and non-deformed structure in W1 inner extension (well-visible brick pattern). Symbol of object as in Figure 2B.

Field observations performed on the wall and its basement have shown that its lowermost parts contain very deformed bricks. Such deformations were caused by severe soaking of the lowermost parts of the structure. Intense floods must have occurred during "Wall 1" construction or directly after its raising; they caused rise of groundwater level and its rise to the lower parts of the wall, which resulted in the instability of the entire construction. The only rescue for the building endangered by destruction was adding extensions to the wall to stabilize its construction from both sides. A factor that favoured flooding at that time was the close distance to watering channels in the vicinity of the fortress. Such location of the channels must have promoted flooding of the fortress during high water levels of the Nile. Another factor which could have resulted in flooding of the area around the fortress was the occurrence of low ground to the north of the fortress. Geological investigations in the Tell el-Retaba site have indicated the presence of lake deposits in this region [16, 17]. It may be assumed that this region was periodically flooded during high water levels, as confirmed by sediments drilled around the fortress.

Mud brick properties and their changes caused by deterioration processes

Brick structure plays a significant role in the material disintegration process. The brick structure was observed in macro scale during field investigations. The process of mass brick production caused that the mud brick material was not sufficiently homogenized and contained numerous loosenings, large pores and disconformities as admixtures of various minerals or unmixed fragments (clasts) of the source material (Fig. 9A). Such anisotropy of internal structure of the mud bricks influenced their initial parameters, and additionally enhanced the intensification of deterioration processes. In turn, the structure of the brick material reconstructed in laboratory conditions is different. In macro scale it is characterised by a larger uniformity than the original mud bricks (Fig. 9B and C).

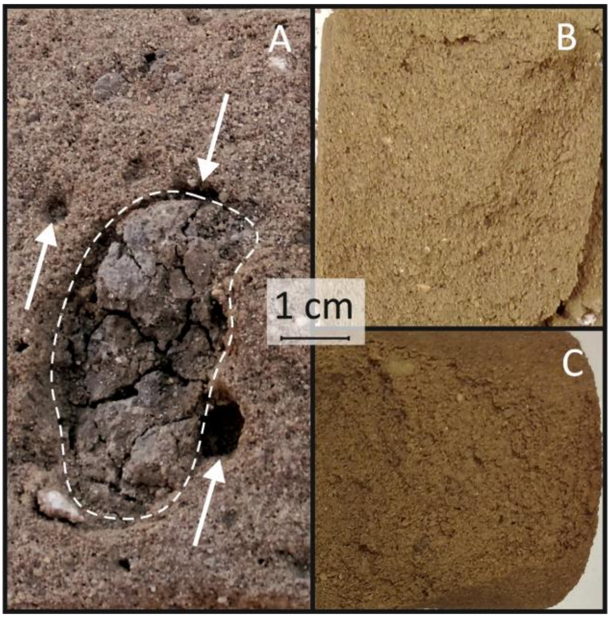

Fig. 9. Brick material structure from Building 834 in macro scale (see text for details): A – heterogeneous structure of mud brick, note large clay clast with desiccation cracks (surrounded by dashed line) and large pores (arrowed), B and C – reconstructed homogeneous structure of mud brick material.

Results of the analysis of basic physical and mechanical properties of the original mud bricks and the reconstructed brick material for selected objects have been presented in Table 2 and compared in Figure 10.

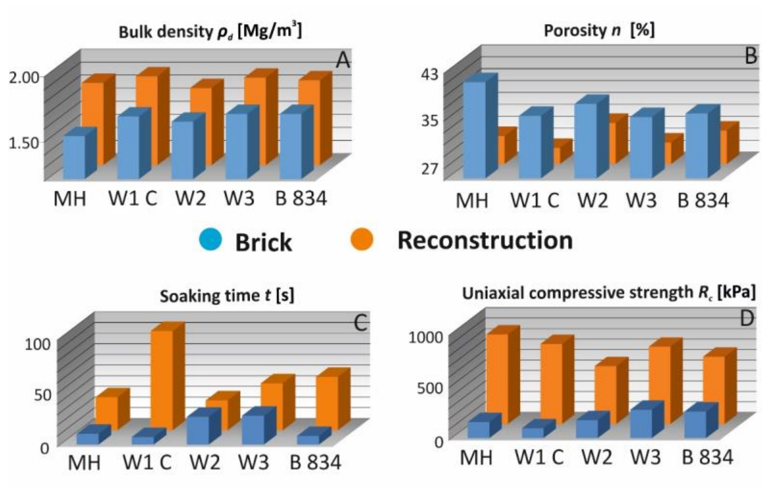

Fig. 10. Comparison of physical and mechanical properties of mud bricks and reconstructed brick material (see text for details): A – bulk density, B – porosity, C – soaking, D – uniaxial compressive strength. Symbols of objects as in Figure 2B.

Table 2. Physical and mechanical properties of mud bricks (B) and reconstructed brick material (R). Symbols of objects as in Figure 2B. * - value without considering soaking of clay clasts (compare with *M. Zaremba et al* [16]. Values in italics and in parentheses correspond to the number of performed tests.

Sample collection site		Specific gravity ρ_s (Mg/m^3)	Bulk density ρ_d (Mg/m^3)		Porosity *n* (%)		Void ratio *e* (-)		Soaking time *t* (s)		Uniaxial compressive strength *Rc* (kPa)	
		B R	B	R	B	R	B	R	B	R	B	R
18th Dynasty	MH	2.61 *(1)*	1.53 *(11)*	1.83 *(6)*	41.2	29.7	0.70	0.42	10 *(6)*	31 *(3)*	161 *(7)*	856 *(6)*
19th Dynasty	W1 C	2.60 *(1)*	1.68 *(8)*	1.88 *(6)*	35.5	27.7	0.56	0.38	7 *(4)*	93 *(3)*	92 *(8)*	765 *(6)*
20th Dynasty	W2	2.63 *(1)*	1.64 *(15)*	1.79 *(6)*	37.5	31.9	0.60	0.47	26 *(3)*	28* *(3)*	175 *(9)*	553 *(6)*
	W3	2.62 *(1)*	1.70 *(14)*	1.87 *(6)*	35.3	28.6	0.55	0.40	27 *(4)*	44 *(3)*	245 *(8)*	738 *(6)*
	B 834	2.66 *(1)*	1.70 *(10)*	1.85 *(6)*	35.9	30.6	0.53	0.44	8 *(6)*	50 *(3)*	265 *(7)*	642 *(6)*

The specific gravity ρ_s of the reconstructed material is the same as the brick material for all five objects and is from 2.60Mg/m^3 for the core of "Wall 1" (W1 C) to 2.66Mg/m^3 for building 834 (B 834). Despite the high content of the sand fraction, mainly quartz grains, the specific gravity of the bricks, apart from that of object B 834, is lower than 2.65Mg/m^3, i.e. the gravity density of quartz. This is probably caused by the admixture of organic matter in the clay fraction, which decreases the value of this parameter. Small amounts of organic matter were added to the mud bricks in form of straw chaff as a substance reinforcing the material. With time, due to erosion processes, it was completely decomposed.

The lowest value of the bulk density ρ_d was observed for bricks from Mustafa's House (MH) – 1.53Mg/m^3. Values of this parameter for bricks from the remaining objects are similar and reach from 1.64Mg/m^3 for W1 C to 1.70Mg/m^3 for "Wall 3" (W3) and B 834. The reconstructed brick material shows much higher values of bulk density than the mud bricks, with the exception of material from "Wall 2" (W2), for which the bulk density rose to a lesser degree and reached 1.79Mg/m^3. The highest increase of this parameter took place in the case of material from MH, from 1.53Mg/m^3 for original mud bricks to 1.83Mg/m^3 for the reconstructed material. Differences of this parameter in the reconstructed material result from the production technology, i.e. raw material, water content and material compaction. In turn, differences of this parameter in the mud bricks result from the overlapping of deterioration processes on differences in the initial mud brick properties, which are determined by the production technology.

Porosity *n* for bricks in all objects exceeded 35%. The highest values were observed for bricks from MH – 41.2% and W2 – 37.5%. Bricks from the other objects are characterised by similar values of this parameter – about 35.5%. Values of porosity for the reconstructed material are much lower and vary from 27.7% (W1 C) to 31.9% (W2). The largest difference in the values of this parameter between the original bricks and the reconstructed material was observed for MH (11.5%), and the smallest for B 834 (5.3%) and W2 (5.6%). Similarly, as in the case of porosity, the values of the porosity index *e* are highest for bricks from MH – 0.70 and W2 – 0.60. Approximate values of this parameter around 0.55 have bricks from objects W1 C, W3 and B 834. Values of the index for the reconstructed brick material for all objects are lower in comparison to the original bricks and vary from 0.38 (W1 C) to 0.47 (W2), and the differences between particular objects are not as significant. A significant decrease in the values of this parameter for MH from 0.70 for bricks to 0.42 for reconstructed material indicates that the clay and silt fractions infilled the pore space between larger grains in the sand fraction, which is of more even dimensions and high uniformity. A similar case may be observed in the case of brick material from W2. However, decrease of the values is not as significant and reaches merely 0.13. This is caused by an almost three times lower content of the clay and silt fractions in comparison to the contents of these fractions in bricks from MH, as indicated by *M. Zaremba et al* [16].

Porosity, void ratio and bulk density are parameters characterising the internal structure of the mud brick material. Large differences in the values of these parameters between the reconstructed brick material and the mud bricks point to significant loosening of their structure resulting from deterioration processes, including organic matter decomposition visible as empty voids.

The soaking time *t* of bricks from MH, core of W1 and B 834 is below 10sec soaking of bricks from W3 and W2 is slightly longer, at about 27sec. The soaking time for reconstructed material in comparison to bricks is much longer. The largest increase, almost 13 times, was observed for material from W1 C (from 7 to 93sec). The smallest differences were noted for W3 – from 27 for original bricks to 44sec for reconstructed material. In the case of bricks and reconstructed material for W2, characterised by large uniformity, the soaking time is similar.

Values of uniaxial compression strength *Rc* for bricks are from 92kPa (W1 C) through 160kPa (MH and W2) to over 240kPa (W3 and B 834). The reconstructed material is characterised by much higher values of this parameter than the mud bricks. The highest increase of its values was observed in the case of material from W1 C – from 92 to 765kPa (over 8 times) and from MH – from 161 to 856kPa (over 5 times). For the remaining objects the values of this parameter rose by three times. Comparison of the damage style shows that both original bricks and the reconstructed material behaved similarly. Destruction surfaces with a similar dip angle and with a characteristic shear fan have been observed (Fig. 11).

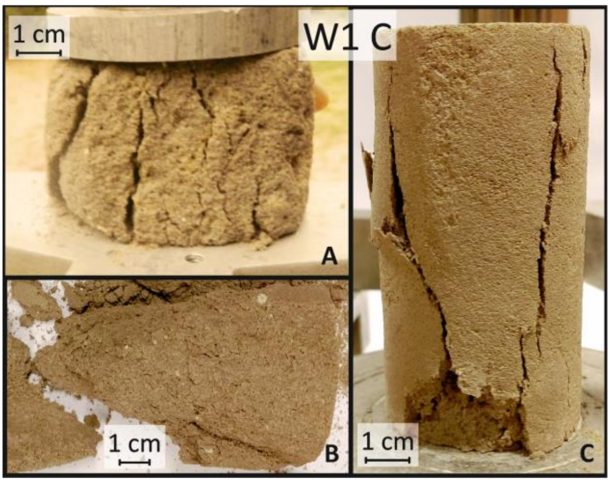

Fig. 11. Type of sample destruction after uniaxial compression test of W1 C (see text for details): A – mud brick, B and C – reconstructed mud brick material. Symbol of object as in Figure 2B.

Higher bulk density and lower porosity, thus better compaction of the mud brick material influences slower soaking and higher mud brick strength. As indicated by *M. Zaremba et al* [16], the clay fraction content was of large influence on these parameters. The fine particles of the clay fraction hardened the contacts between the grains of the coarser fractions. The clay fraction could contain significant amounts of decomposed organic matter, which is characterised by strong hydrophilic properties and may decrease the mud brick strength. Very high values of porosity for bricks from objects MH and W2 and low values of strength result from the grain size composition of the source material, in which the sand fraction is characterised by high uniformity of the grain size as indicated by *M. Zaremba* [27]. In turn, studies of the reconstructed material indicate that in the case of MH, a very resistant building material was obtained. Most probably, this was caused by a well-matched content of the added fine-grained material, which contained a sufficient contribution of the silt and clay fractions that tightly infilled the pore space between grains of the sand fraction.

The values of parameters of the reconstructed brick material and their comparison with the parameters of original bricks indicate that sun-dried mud bricks were characterised by good primary properties. The differences in the grain size and mineral composition of the material used for their production and the structure of the produced bricks influenced not only the rate of deterioration processes but also the prevailing type of the process.

Decrease of bulk density values and increase of porosity are observed with increasing brick age (Tables 2 and 3, Fig. 10). In turn, values of these parameters for the reconstructed brick material do not show such relationships. The observed trend indicated worsening of brick parameter with longer impact of the deterioration factors. i.e. with brick age. Only in the case of the reconstructed brick material from W2, a decreased bulk density value and higher porosity were observed in comparison to the remaining objects. Bricks from object W2, in which the contribution of the sand fraction with uniform grain size reaches almost 90 %, and the finest fractions, thanks to which the bricks were cohesive, achieve only 10 % [16], from the beginning had lower density and higher porosity compared to other objects from the site. This suggests that the material was used to produce bricks that had poorer parameters. It would seem that after being subject to deterioration processes, these bricks should proportionally lose in quality and possess much lower values of the parameters. In turn, comparison of brick parameters from W2 with bricks from other objects shows that values of their parameters changed insignificantly due to weathering processes. This may result not only from the applied raw matrials but also from the untypical form of “Wall 2”, which was a wide, low platform, ca. 2m high [23]. Such construction did not undergo intense deterioration process, contrary to the high wall.

Table 3. Influence of deterioration processes on the changes of physical and mechanical properties of mud bricks. Symbols of objects as in Figure 2B. ↓ - value decrease, ↑ - value increase, * - value without considering soaking of clay clasts (compare with *M. Zaremba et al* [16]

Sample collection site		**Mud bricks colour**	**Changes of the physical and mechanical properties [%]**				
			Bulk density ρ_d (Mg/m^3)	**Porosity *n* (%)**	**Void ratio *e* (-)**	**Soaking time *t* (s)**	**Uniaxial compressive strength *Rc* (kPa)**
18th Dynasty	MH	light grey	↓ 16	↑ 39	↑ 67	↓ 68	↓ 81
19th Dynasty	W1 C	grey-brown	↓ 11	↑ 28	↑ 47	↓ 92	↓ 88
20th Dynasty	W2	light grey	↓ 8	↑ 18	↑ 28	↓ 8*	↓ 68
	W3	brown	↓ 9	↑ 23	↑ 38	↓ 39	↓ 67
	B 834	dark brown	↓ 8	↑ 17	↑ 20	↓ 84	↓ 59

Worth noting is comparison of parameters for mud bricks and the reconstructed material for objects W1 C and W2. Despite more favourable properties of the brick material from object W1 C, such as non-uniform grain size of the sand fraction, higher contribution of the clay and silt fractions, and lower porosity, it is characterised by lower uniaxial compression strength in comparison to bricks from W2, with differences exceeding 83kPa, which gives strength proportions of 0.53 (Table 2 and Fig. 10). In turn, analysis of the reconstructed brick material from both objects indicated an opposite relationship. Much higher strength was noted for the material from W1 C in comparison to W2, with the difference reaching 212kPa, which gives strength proportions of 1.38. The content of the clay fraction, responsible for the strength of such material, indicates low variability between the objects and varies from 5% for W1 C to 3% for W2. Therefore, the difference must be caused by the mineral composition of the fraction. This is confirmed by the fact that the brick material from W1 C is characterised by very high values of linear shrinkage LS, which exceeds 8%, whereas for the brick material from W2 it reaches only about 1% [27]. The reason for such large differences in shrinkage is hydrophilic clay minerals or the high content of decomposed of organic matter, which occur in the clay fraction of bricks from W1 C. The minerals with organic matter cause large shrinkage of the saturated material. After drying, the strength parameters became much higher. However, deterioration processes caused very unfavourable changes, owing to the fact that they acted longer, because the object is older by at least several tens of years. Long-term cycles of humidity change and the related shrinkage and swelling cycles resulted in loosening of the structure, and large decrease of strength and quality of the brick material from W1 C (Table 3).

An important role in mud brick degradation is played by time. The largest changes of the parameters between mud bricks and the reconstructed material are observed in the case of the oldest object studied, MH, and the smallest – in the case of the youngest object B 834 (Table 3, Fig. 10). A very large loss of strength is observed for all bricks, from 59% in B 834 up to 88% in W1 C, at an insignificant decrease of bulk density, from 8 % in W2 and B 834 to 11% in MH (Table 3). Large loss of strength is well expressed by correlation with a high correlation coefficient R^2 (Fig. 12).

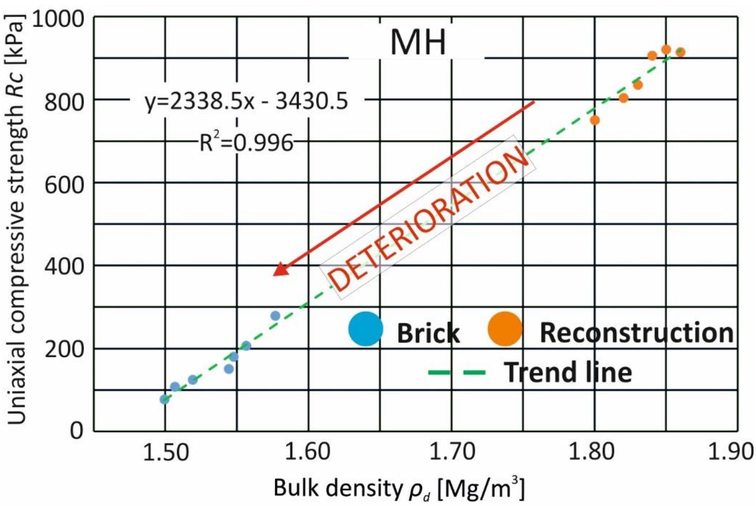

Fig. 12. Influence of deterioration processes on the mud bricks properties from Mustafa's House (MH). Correlation of uniaxial compressive strength with bulk density (see text for details).

The reason for such intense decrease of strength values at a small loss of bulk density values must be the lack of strong bonds at the boundaries between grains and particles, which during deterioration processes must have undergone strong weakening. In turn strong structural bonds in the reconstructed brick material result in high strength values. A more precise estimation of the type and influence of deterioration processes on the properties of mud bricks require further detailed studies.

Influence of deterioration on the preservation of mud brick architecture

Mud bricks from Tell el-Retaba produced over several centuries were characterised by variable properties, which caused significant differences in the values of their physical and mechanical parameters and variable resistance to deterioration. The impact of deterioration factors and the course of processes linked with them during object usage and after its abandonment resulted in continuous deterioration of mud brick properties and caused poor preservation of the monuments in Tell el-Retaba. Figure 13 presents a diagram of deterioration of mud brick monuments.

Traces of deterioration were observed on fragments of mud brick objects exposed in Tell el-Retaba and their reasons were identified. The deterioration factors which have particularly high impact on the objects include: 1) insolation and large diurnal amplitudes of temperature, 2) winds of different force and direction, 3) diurnal changes of atmospheric humidity, 4) short and intense rainfall, 5) oscillations of groundwater level, 6) climatic changes, 7) human activity, and 8) activity of organisms. The following traces related with deterioration processes were observed (Fig. 6): 1) exfoliation of mud brick surfaces as effects of cyclic warming of the exposed parts of the object, 2) mud brick deformations caused by water saturation during rainfall and/or high groundwater level (Figs. 6B and 8, 3) salt crystallisation of the surface and within the mud bricks as effects of cyclic humidity changes, 4) boring traces of organisms on the surface and within the mud bricks. Facts pointing to human reaction to the developing destruction have also been observed. Lack of stable protection and appropriate conservation after object abandonment must have increased the effects of deterioration.

Mud brick properties significantly changed due to deterioration processes (Tables 2 and 3, Fig. 10), particularly: 1) aggregation or disaggregation of the mineral grains, 2) increased hydrophyly of the material due to mineral weathering and decomposition of organic matter, 3) increase of shrinkage of material due to enrichment of the clay fraction with decomposed organic matter, 4) decrease of the degree of packing of the mineral grains, 5) decrease of bulk density and increase of porosity, 6) increased saturation of material and its soaking, 7) decreased strength due to decrease of intragranular cohesion and depletion of structural bonds, as well as 8) diminution of material structure.

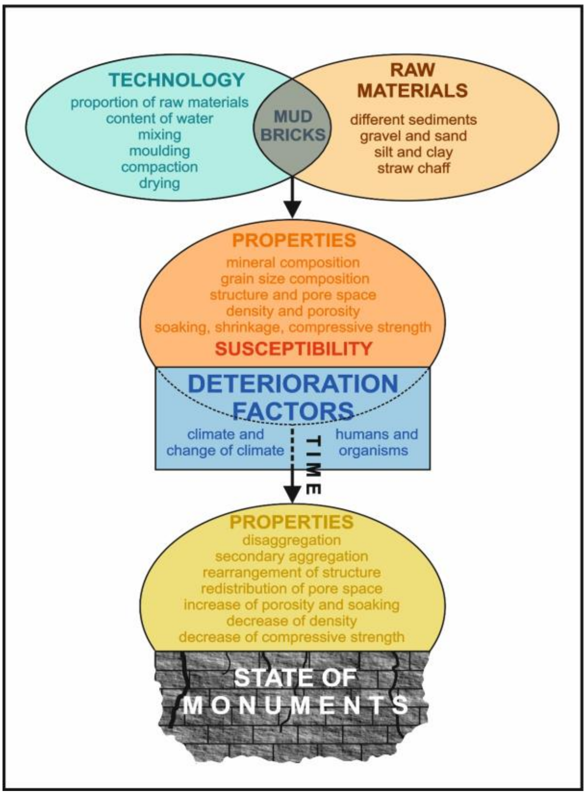

Fig. 13. Diagram showing the influence of deterioration processes on the preservation of mud brick architecture.

Conclusions

The raw materials and technology applied for the production of mud bricks in Tell el-Retaba determined the properties of the manufactured building material. The material was used to build defence and residential structures. Local raw materials, such as fluvial gravels and sands, eolian sands, and lacustrine silts and clays were used for mud brick production. Correctly matched proportions of the raw materials and water allowed for obtaining mixtures with optimal water content and consistency. Thanks to that, maximal compaction of material was achieved in cuboidal moulds used for mud brick production.

Parameters of the mud bricks produced in Tell el-Retaba could have slightly differed from those obtained for the brick material reconstructed in the laboratory. The reason for this was larger anisotropy of mud brick properties, resulting from the scale of their production (Table 2 and Fig. 9). Parameters of the reconstructed material are thus reliable for analysis and perfectly reflect the properties of mud bricks directly after their production, which is confirmed by the obtained correlations (Fig. 12).

Continuous deterioration processes influence the preservation conditions of the mud brick architecture. Analysis of the changes in the mud brick properties points to deterioration of their parameters with age and in consequence with the duration of the impact of the deterioration factors and processes. Good raw materials and more advanced technologies gave better initial parameters and lower susceptibility of the material, and in consequence – a lower impact of deterioration on the mud brick properties.

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