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Comparative assessment of original, reproduced, and innovative mudbrick formulations for the conservation of earthen structures at Sheikh Al-Arab Hammam Citadel (18th Century), Qena, Egypt

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Abstract

The 18th-century Sheikh Al-Arab Hammam citadel which is located at Farshut, Qena about 566 km the south of Cairo has a historical and architectural value where it represents military and civilian barracks reflecting the strategic plans and military systems implemented in the Egyptian regions as well as mudbrick material manufacturing and using in such type of military buildings This citadel exhibits significant deterioration, characterized by the complete or partial loss of several remaining walls. Addressing these challenges necessitates a range of restoration interventions, including stitching, reconstruction, and reinforcement. This research investigates the composition and physical-mechanical properties of the original mud bricks, aiming to compare them with four proposed mixtures to figure out the most suitable formulation for restoration applications. The study compares: (1) fractured samples of the original composition, (2) reconstituted bricks using fresh materials in original proportions, and (3) two innovative modified formulations. Each mixture is evaluated in terms of its physical and mechanical characteristics to find the best approach for conservation efforts. To achieve this objective, samples of the original bricks were collected and subjected to chemical and mineralogical analysis, building upon previous studies that employed X-ray diffraction (XRD), color assessment using the Munsell chart, surface texture examination via BAUSH & LOMB stereomicroscope, and measurements of density, porosity, water absorption, compressive strength, and shrinkage. Considering certain limitations, including the potential alteration of material properties over time due to aging. The findings indicate that the primary mudbrick composition (70/30 sand: soil), when reconstituted with new materials with 1.7 MPa strength and water absorption (13.5%), is viable for applications requiring structural load-bearing capacity, while alternative formulation (sand/ soil + 1% straw by weight with length 1-1.5 cm) may be employed for non-load-bearing applications needing crack resistance. It also confirmed the Utilization of fragments of original materials for repairs where authenticity is paramount.

Keywords

Comparative Assessment; Mudbrick; Sheikh Al-Arab Hammam; Restoration Interventions; Innovative Formulations.

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التقييم المقارن لخلطات الطوب اللبن الأصلية، والمعاد انتاجها، والمبتكرة لترميم المنشآت الطينية بقلعة شيخ العرب همام (القرن الثامن عشر)، قنا، مصر

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الملخص

تتمتع قلعة حمام شيخ العرب التي تعود للقرن الثامن عشر وتقع في فرشوط بمحافظة قنا على بعد حوالي ٥٦٦ كم جنوب القاهرة بقيمة تاريخية ومعمارية حيث تمثل ثكنات عسكرية ومدنية تعكس الخطط الاستراتيجية والنظم العسكرية المطبقة في المناطق المصرية وكذلك توظيف مادة الطوب اللبن في هذا النوع من المباني العسكرية. تعاني قلعة الشيخ العرب همام، التي تعود إلى القرن الثامن عشر الميلادي، من تدهور كبير يتمثل في الفقدان الكلي أو الجزئي لعدد من الجدران الباقية. يتطلب التعامل مع هذه التحديات مجموعة من تدخلا الترميم، بما في ذلك عملية التزرير، وإعادة البناء، والتدعيم. تبحث هذه الدراسة في تركيب الطوب الطيني الأصلي وخصائصه الفيزيائية والميكانيكية، بهدف مقارنته بعدة خلطات مقترحة لتحديد التركيبة الأكثر ملاءمة لأغراض الترميم. تتضمن التحليل المقارن إعادة استخدام وتوظيف الخلطة الأصلية من قطع الطوب المتناثرة، وإعادة إنتاج نفس الخليط بمواد جديدة بالنسب ذاتها، واقتراح تركيبتين معدلتين. يتم تقييم كل خليط من حيث خصائصه الفيزيائية والميكانيكية لتحديد النهج الأمثل لجهود الحفظ. ولتحقيق هذا الهدف، تم جمع عينات من الطوب الأصلي وإخضاعها للتحليل الكيميائي والمعدني، استنادًا إلى دراسات سابقة استخدمت حيود الأشعة السينية (XRD)، وتقييم اللون باستخدام مخطط مونسل، وفحص نسيج السطح عبر المجهر المجسم BAUSH & LOMB، بالإضافة إلى قياسات الكثافة، والمسامية، وامتصاص الماء، ومقاومة الضغط، والانكماش. تشير النتائج إلى أن تركيبة الطوب الطيني الأساسية التى تتكون من (٧٠% رمل: ٣٠ % تربة)، عند إعادة إنتاجها بمواد جديدة، صالحة للتطبيقات التي تتطلب قدرة تحمل هيكلية، بينما يمكن توظيف التركيبات البديلة (٧٠% رمل: ٣٠ % تربة + ١% من ألياف القش) للتطبيقات التى لا تتحمل الأحمال والتي تحتاج إلى مقاومة التشققات، مع التأكيد على إمكانية إعادة استخدام المواد الأصلية المتناثرة في عمليات الإصلاح التي تستدعي الحفاظ على أصالة المواد.

الكلمات الدالة

التقييم المقارن؛ الطوب اللبن؛ شيخ العرب همام؛ تدخلات الترميم؛ الخلطات المبتكرة

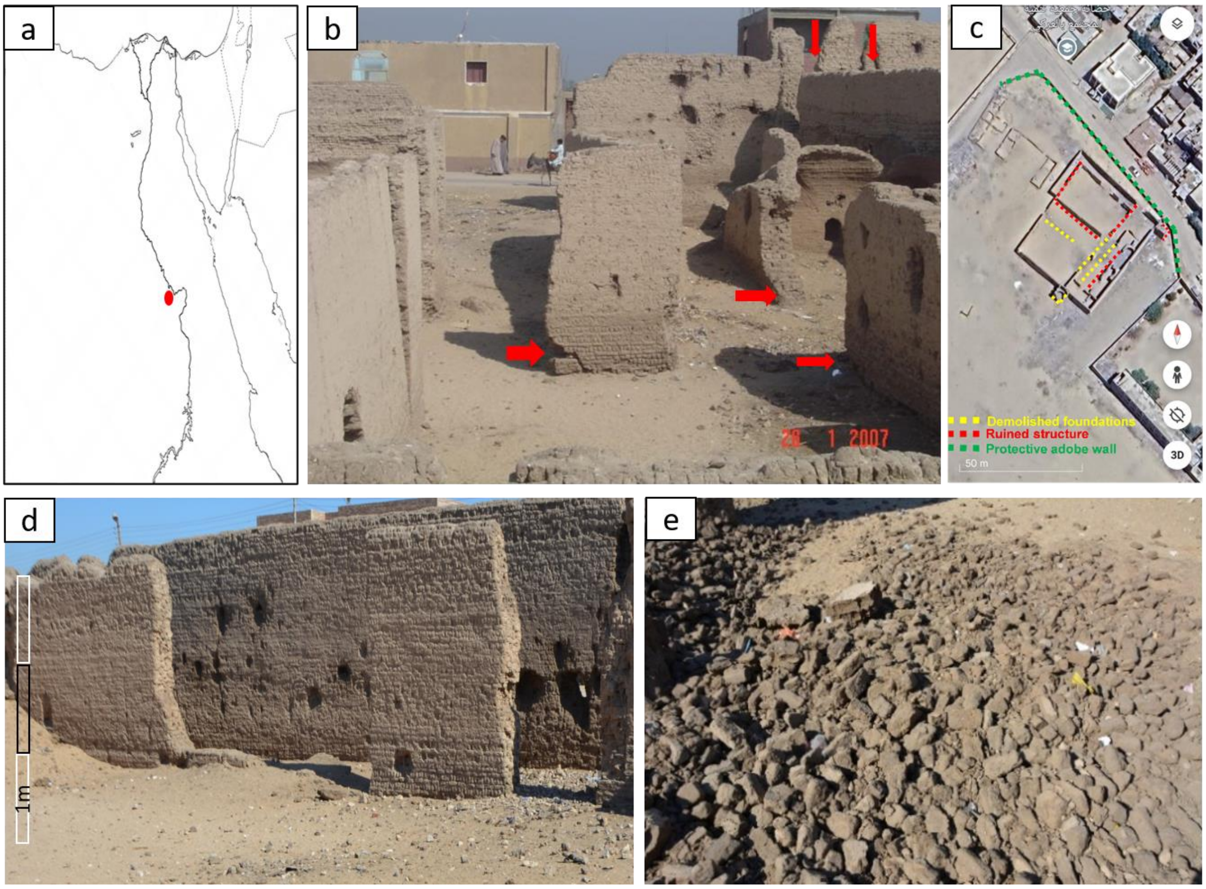
1. Introduction.

Historical and archaeological earthen architecture constructed of mudbricks is susceptible to various external and internal factors that can lead to degradation [1]. These factors cause a loss of strength and cohesion, resulting in weakening, erosion, and disintegration of the earthen structures. Numerous studies in materials science, geology, and other fields have combined efforts to devise solutions that ensure the preservation of these earthen cultural heritages and their preservation for as long as possible [2].

This work deals with the Sheikh Al Arab Hammam Citadel, dating back to the eighteenth century, which is in the village of Al-Araki and its surrounding areas (Farshut – Qena), where remnants of military and civilian barracks. These structures hold considerable historical, architectural, military, political, and social significance, reflecting the late 18th-century developments in Upper Egypt. Furthermore, this period represents a crucial phase that illustrates the strategic planning and military systems employed across Egyptian regions [3]. Constructed primarily of mudbricks, the citadel stands as an example of earthen architecture that has suffered progressive deterioration over time. It exhibits multiple forms of damage including tilting and bending of walls, horizontal and vertical cracks, basal erosion, and partial collapses in figure (1-b, d, and e).

These earlier issues need a prioritized intervention plan to address urgent and emergency repairs. This study focuses on the collapsed parts of its walls which could threaten the longevity of this citadel and its continued existence for successive generations, which necessitates intervention to support and reconstruct the collapsed areas. Considering the recent interest in this citadel, attempts have begun to preserve and explore it through recent excavation works [4,5,6,7]as shown in figure (1-c). Based on a prior assessment confirming the structural integrity of the original mudbricks as a workable building material, the fallen bricks can be reutilized [8]. The reuse of original mud brick materials aligns with sustainable conservation practices by preserving authenticity and minimizing waste. Additionally, repurposing collapsed materials presents an environmentally responsible approach to heritage preservation [9].

Given the limited availability of collapsed mudbricks to support the necessary restoration processes, this study aims to reproduce compatible mudbricks that are suitable for various reinforcement tasks needed to restore the Sheikh Al-Arab Hammam citadel. In an earlier study, the first step focused on assessing the deterioration of the earthen architecture of the citadel, showing the most vulnerable areas prone to collapse and statement the corresponding intervention processes. Subsequently, the archaeological material was analyzed to understand its composition, helping the production of mudbricks with similar or closely matched specifications [10-11]. Consequently, the goal of this work is to produce mudbrick units that are compatible as much as possible with the original, ensuring no damage is inflicted. By determining the chemical composition and physical properties of the original building material, the desired compatibility can be achieved [12]. Replicating the historical mixture ensures harmony with the existing structure, preventing issues related to differing material properties. Furthermore, employing a replicated historical mixture preserves the architectural integrity and historical accuracy of the structure, contributing to the longevity and stability of the citadel's architecture. Therefore, this work aims to evaluate the physical properties of original mudbrick, reproduced mudbricks, and innovative mixtures close to original composition for conservation purposes.



Figure—1 a) Location of the Citadel at Farshut, Nag Hammadi, Qena Governorate, b) An overview of an internal part of the citadel highlighting missing elements that pose a risk to the structural stability of the walls. (After Mahmoud Abdelwahab, 2007) c) Satellite view of the ruins of unearthed ruins of the citadel shows the current state of its structures (captured on 28.12.2024), d) ruins of standing walls in the inner courtyard of the citadel, and e) full collapsed walls of the citadel.

2. Materials and methods.

To achieve the aim of this research, two stages have been conducted on both the archaeological mudbrick of the citadel and the proposed mixtures for restoration purposes, respectively. Firstly, samples of the original fallen mudbricks used in the construction of Sheikh Al-Arab Hammam citadel were taken and characterized in terms of mineralogical, chemical composition and physical properties to obtain a reference base. That allows for proposing, and comparing the original material to the reused, reproduced, and innovative mixtures in the second stage. Then, comparable evaluation can facilitate recommendation of the most proper mixture for manufacturing mudbrick [13].

As for archaeological mudbricks, the dimensions were initially measured using a ruler and then sectioned into cubes measuring 5 cm × 5 cm × 5 cm with the aid of a professional cutting device, the Elektra Beckum Mitre Saw KGS 300 Professional. Surface morphology and texture were analyzed using a BAUSH & LOMB stereomicroscope, supplemented by illumination from a Jenalux 20 device [14]. The samples underwent a drying process in an incubator set to 60°C for 24 hours, followed by cooling within a desiccator containing silica gel. This procedure was repeated until a stable weight was obtained [15]. To determine the clay mineralogical composition, the original mudbrick sample was subjected to three preparatory treatments (bulk, glycolation, and heating to 550°C) before analysis using a Buker D 5000 diffractometer, operating at 36 mA and 36 kV with CuKα radiation. [16-17]. The identification of various mineralogical phases, encompassing both major and minor minerals, was conducted utilizing PANalytical X'Pert HighScore Plus software. A petrograph examination was also conducted. The imaging used a Zeiss Axiolab Opton polarizing microscope, equipped with a Canon Powershot G2 digital camera connected via an eyepiece adapter [18]. To the percentage of sand, clay, silt, and gravel [19], particle size distribution analysis was performed on the original mudbrick using a Mastersizer 2000 laser diffractometer [20]. Additionally, the physical properties, including color (assessed via the Munsell chart) [21,22,23] bulk density, water absorption [24], and porosity (measured via gas psychometry) were measured [25]. In addition, the mechanical behavior of original mudbrick in terms of shrinkage and compression strength tests after drying were measured by a digital caliper and a 150-ton hydraulic press machine (Tinius Olsen, Willow Grove, PA, USA) respectively [26-27].

Then, the second stage took place including preparation, mixing, and formulating of four mixtures including the reused original mixture, reproduced original mixture with fresh constituents and two other proposed mixtures close in their proportions to the original composition where sand and mud represent the main matrix. The first proposed composition consists of sand and soil in a 60:40 ratio (approximately 1.5:1), with a slight increase in the silt proportion up to 40%. This adjustment is intended to mitigate the effects of low clay content, which compromises structural integrity when exposed to minimal moisture levels [28]. The other is composed of Sand/ Soil 70/30 ≈ 2.5:1 ratio + 1% straw by wight with length 1-1.5 cm. It has the same composition as the original with a slight percentage of straw due to rare, detected fibers in the petrographic analysis. The used soil was sourced from surrounding local location due to its suitability and availability near the site [29] approximately 295 meters away, where it is believed the original material might have been extracted due to (Medany 2010). 1 month after the air-drying process, six cubes of each mixture 5cm * 5cm* 5cm were assessed for the same physical and mechanical properties. Finally, the results of original (reference standards), reused, reproduced mudbricks, and proposed mixtures were evaluated to identify the most suitable mixture for large-scale production for conservation purposes based on comparative physical and mechanical evaluation.

3. Results.

3.1. Examination and analysis of original mudbrick.

3.1.1. The visual examination results of original mudbrick units from various locations in the citadel revealed that the average dimensions of original mudbricks is 20 *10* 6 cm (volume ≈ 1200 cm^3). The stereo microscopic analysis of the adobe bricks revealed a surface characterized by rough texture and the presence of loose sand grains. Additionally, surface pores and gaps were observed. Furthermore, color examination of the mud brick samples, conducted using the Munsell soil color chart, figured out that the samples from various locations from the citadel walls are within the 7.5YR 5/4 range indicating brown color (Figure 2).

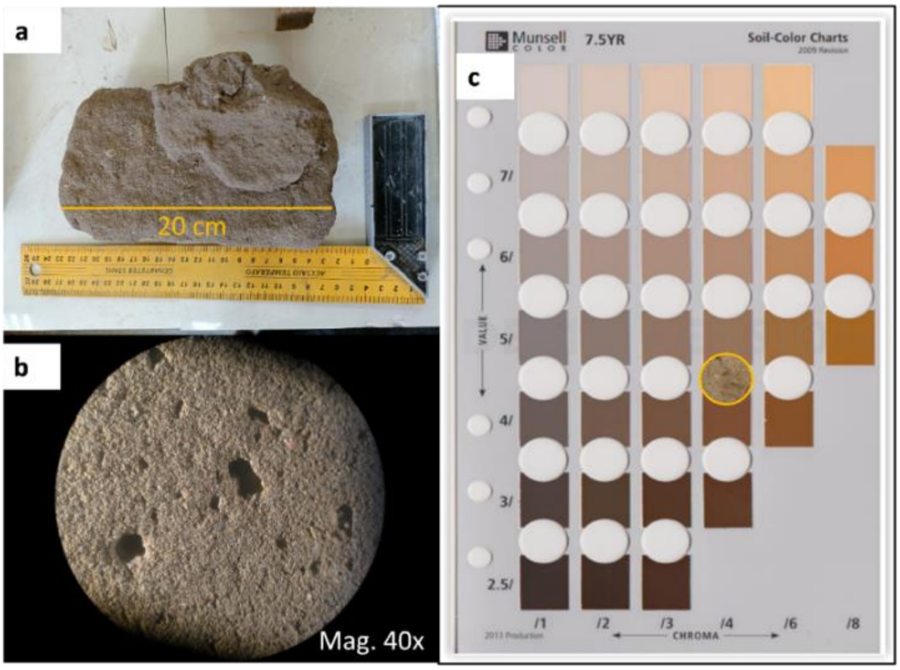


Figure 2 – a) Deteriorated original mudbrick from the citadel, b) Macrophotograph of the surface texture of the mudbrick at 40X, c) shows the placement of the mudbrick color range as determined by the Munsell chart.

3.1.2. Petrographic analysis.

The results of the thin section revealed quartz as a main constituent of the filler, with augite, calcite, and feldspar identified as accessory minerals. Abundant fine quartz grains were seen embedded within a clay matrix. The grains displayed rounded to sub-angular shapes with marked scarcity of organic fibers. In addition, it revealed fine pores, where the largest pore diameter observed was approximately 0.5 cm as shown in Figure- 3.

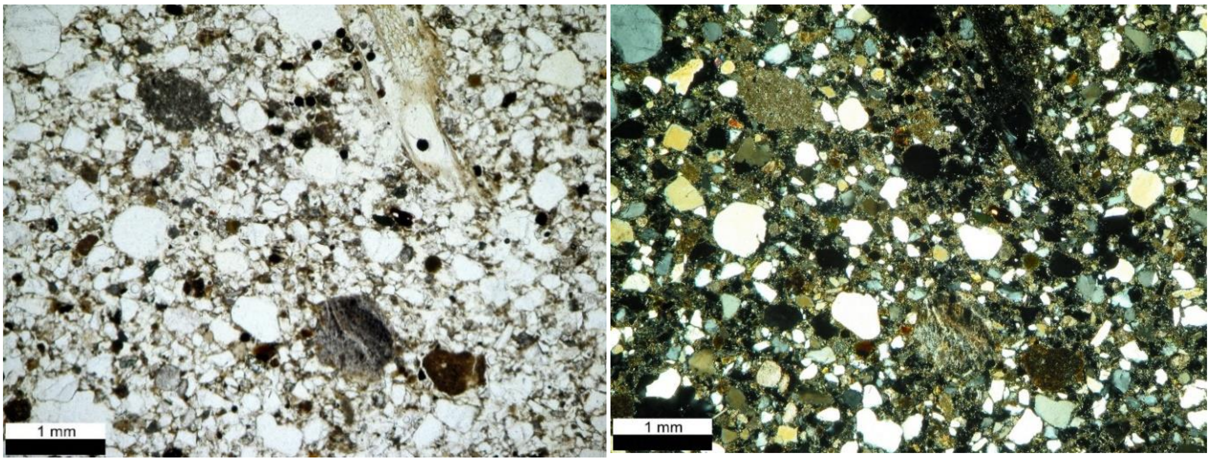


Figure 3- Microphotographs of thin section composition of original intact mudbrick under plane polarized (left) & cross polarized (right): Field of view is ca. 6 mm mud brick, shows dominant presence of quartz and rare organic fibers.

3.1.3. Grain size distribution.

The grain size distribution revealed the sand content reaching approximately 70.09%. Most sand particles were in the 0.250 to 0.5 mm range, accounting for 19% of the sample. Additionally, the samples contained silt (26.87%), clay (1.91%), and gravel (1.11%) as shown in table 1.

Table 1. Granulometric analysis of the original mud-brick sample of Sheikh Al-Arab Hammam citadel (reference baseline).

Granulometric Analysis				
Sieve Size (mm)	Phi Units	Equivalent Diameter (mm)	Fraction Content (% by weight)	Fraction Type
256,0	-8,0	>256,0	0,00	Stone 0%
128,0	-7,0	128,0-256,0	0,00	
64,0	-6,0	64,0-128,0	0,00	
40,0	-5,3	40,0-64,0	0,00	
32,0	-5,0	32,0-40,0	0,00	Gravel 0%
16,0	-4,0	16,0-32,0	0,00	
8,00	-3,0	8,00-16,0	0,00	
4,00	-2,0	4,0-8,0	0,00	
2,00	-1,0	2,00-4,00	1,11	
1,00	0,0	1,00-2,00	2,13	Sand 70,09%
0,500	1,0	0,500-1,00	15,78	
0,250	2,0	0,250-0,500	19,25	
0,125	3,0	0,125-0,250	17,35	
0,0625	4,0	0,0625-0,125	11,44	
0,0500	4.3	0,050-0,0625	4,14	
0,0312	5,0	0,312-0,050	6,72	Silt 28,87%
0,0156	6,0	0,0156-0,312	8,45	
0,0078	7,0	0,0078-0,0156	5,33	
0,0039	8,0	0,0039-0,0,0078	4,02	
0,00200	9,0	0,002-0,0039	2,35	
0,000975	10,0	0,000975-0,002	1,92	Clay 1,91%
0,000488	11,0	0,000488-0,000975	0,00	
0,000244	12,0	0,000244-0,000488	0,00	

3.1.4. Clay Mineralogy.

The XRD analysis of the historical mudbrick sample, conducted under three treatment conditions (oriented, glycolated, and heated to 550°C), revealed the following mineralogical phases. The oriented sample of the original mud brick revealed distinct peak positions indicative of specific minerals. Notably, Quartz (SiO_2) was identified, where dominant peaks confirmed their prevalence as the primary crystalline phase. Minor peaks confirmed Calcite presence. As for clay minerals, Kaolinite was identified by characteristic peaks at 12.4° and 24.8° 2θ, Illite detected with peaks at 8.8° and 26.8° 2θ, and Montmorillonite, with a peak around 19°. When the sample is glycolated, peak positions are still consistent with those in the oriented sample, albeit with minor shifts attributed to glycolation. The identified minerals include Kaolinite and Illite with enhanced peaks, a prominent presence of Quartz, and a more discernible Montmorillonite following glycolation. Upon heating the sample to 550°C, the peaks for Quartz become more defined and intense, while Kaolinite and Illite persist, and Montmorillonite shows evidence of dehydration or transformation. Additionally, no harmful salts were detected. The results of mineralogical phases are shown in Figure 4.

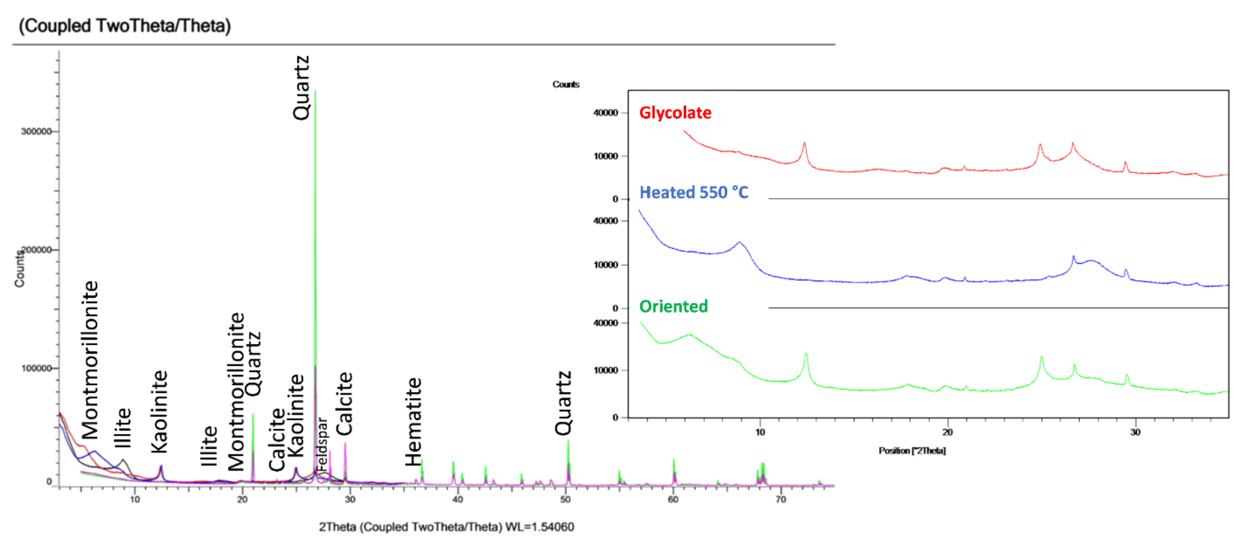


Figure- 4. The X-ray diffraction (XRD) chart illustrates the three treatments of the mudbrick sample: oriented, glycolated, and thermally treated at 550°C.

3.2. Physical and mechanical properties of original and proposed mixtures:

The results of measured physical properties revealed that the original mudbrick exhibits a density of 1.68 g/cm³, with porosity at 29.6% and a water absorption rate of 18.5%, indicating a moderately porous structure. The compressive strength was measured at 0.79 MPa. Shrinkage measurements were not recorded for this formulation. The original mud brick serves as the baseline reference for comparison.

Formulation (**Mix 1)** that stands for original material washed and re-compacted revealed density of 1.73 g/cm³, it exhibits a reduced porosity of 26.75%, leading to a lower water absorption rate of 15.7% compared to the original. This improvement is reflected in an increased compressive strength of 1.1 MPa, suggesting enhanced cohesion and stability. Shrinkage was recorded at 1.3%, demonstrating minimal contraction upon drying.

Formulation (**Mix 2)** that represents reproduced mixture with fresh Constituents (Sand/Silt+ Clay at 70/30 ≈ 2.5:1 Ratio) where the introduction of fresh materials with precise constituent ratios yields a density of 1.75 g/cm³, the highest among the tested formulations. The porosity decreases significantly to 22.5%, contributing to a water absorption rate of 13.5%. The enhanced composition strengthens the material, achieving a compressive strength of 1.7 MPa, the highest recorded value in this study. Shrinkage increased slightly to 2%, suggesting structural adjustments during the curing phase.

Formulation (**Mix 3)** represents the proposed formulation 1 (Sand/Silt+ Clay at 60/40 ≈ 1.5:1 Ratio) adjusting the silt-clay ratio leads to a density of 1.69 g/cm³, closely resembling the original mud brick. The porosity is reduced to 20.2%, resulting in a water absorption rate of 16%, the lowest among all mixes. Despite these improvements, the compressive strength is measured at 1.5 MPa, slightly below Mix 2. Shrinkage increased to 2.8%, highlighting its sensitivity to drying-induced volumetric changes.

Formulation (**Mix 4)** represents the proposed formulation 2 (Sand/Silt+ Clay+ 1% Straw at 70/30 ≈ 2.5:1 Ratio). The addition of 1% straw aims to replicate historical compositions while enhancing workability and resilience. This mixture achieves a density of 1.74 g/cm³, keeping moderate compactness. The porosity is still at 26.8%, contributing to a water absorption rate of 14%, which is lower than the original mud brick but higher than the other modified formulations. However, the compressive strength measures 0.6 MPa, indicating a reduction in load-bearing capacity. Measured shrinkage (1.5%), reflecting moderate stability upon drying. The preparation process of formulated samples, along with the examination of their color and texture, is illustrated in Figure 5, while the physical and mechanical properties are detailed in Table 2 and Figure 6.

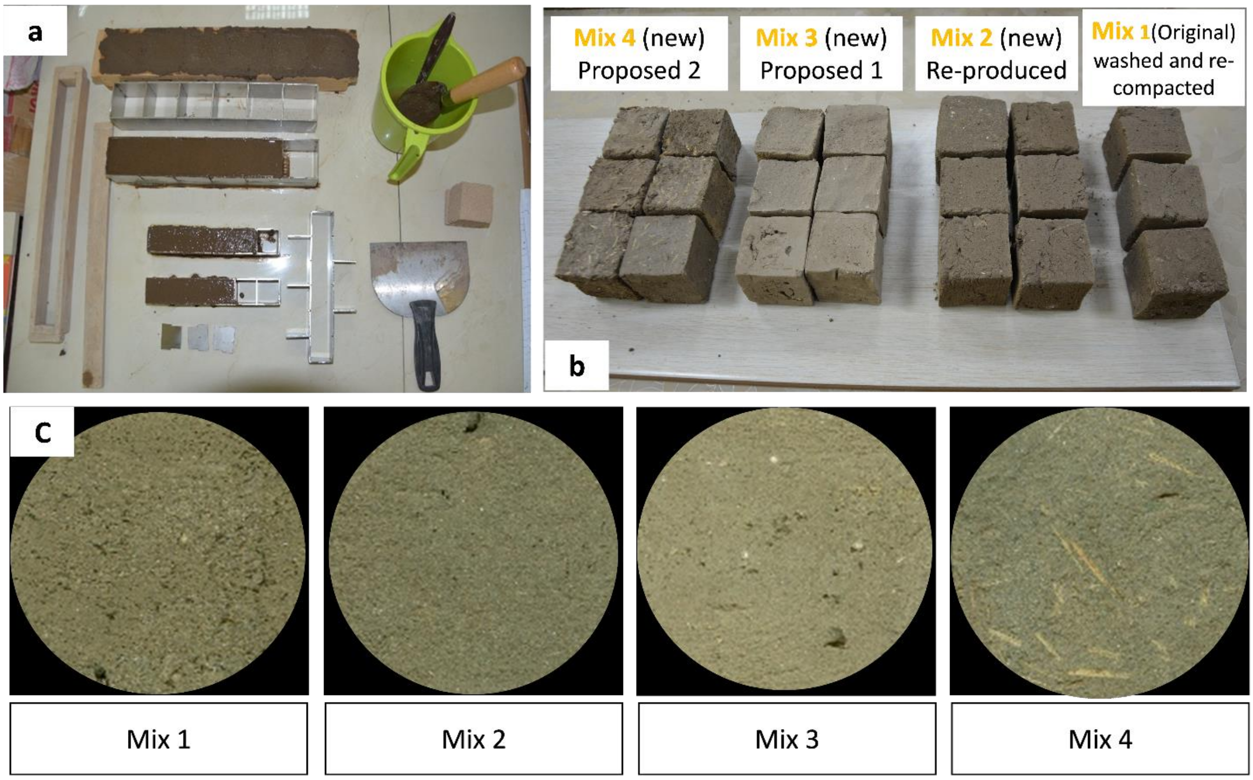


Figure 5. (a) Preparation of formulated samples using stainless steel bars for molding at the laboratory, (b) Formulated samples for mechanical and physical testing, and (c) Macro-photographs of the surface texture of various mixtures.

Table 2. Physical and mechanical properties of both the original and formulated mixtures

Mixtures	Average of measured physical properties						
	Weight (gm)	Volume (cm^3)	Density (gm/cm^3)	Porosity ≈ (%)	Water absorption ≈ (%)	Strength (MPa)	Shrinkage (%)
Original mudbrick	210	124.95	1.68	29.6	18.5	0.79	-
Mix 1 Original material washed and repoured. 70/30 ≈ 2.5/1 ratio	216.9	125.37	1.73	26.75	15.7	1.1	1.3
Mix 2 re-compacted with fresh constituents Sand/ soil 70/30 ≈ 2.5/1 ratio	217.9	124.51	1.75	22.5	13.5	1.7	2.1
Mix 3 Sand/ soil 60/40 ≈ 1.5:1 ratio	213.1	125.50	1.69	20.2	16	1.5	2.8
Mix 4 Sand/ soil + 1% by weight of straw with length 1-1.5 cm) 70/30 ≈ 2.5:1 ratio	218.5	125.55	1.٧	26.8	14	0.6	1.5

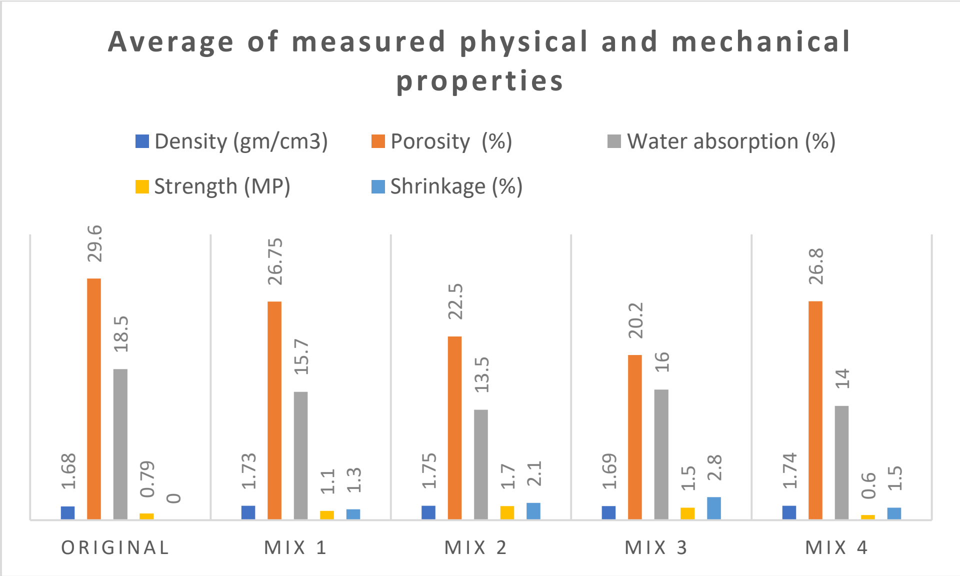


Figure 6. Average values of measured physical and mechanical properties.

4. Discussion.

As this work complements and follows on from a previous phase that included identifying the deterioration factors affecting the Sheikh al-Arab Hammam citadel, built of mud bricks, identifying the resulting deterioration patterns, and formulating recommendations for preserving the remaining ruins in light of relevant international conventions, the need arose to study the availability of mud-brick units that could be employed in various restoration operations, particularly those dealing with ruins that have been demolished or are about to partially or completely collapse.

This work focused in its first stage on characterizing samples of original mud bricks in terms of their chemical and mineralogical composition, the constituents included in the composition, their proportions and sizes, and their physical and mechanical properties, to establish a baseline and guide from which a comparison could be made of the best formulations from which to produce brick units for use in restoration and preservation work. At the second stage, four mixtures were evaluated in their properties to recommend the best for conservation works. **Mix 1** incorporates recycled mudbrick fragments, repurposing scattered remnants to restore material continuity; **Mix 2** keeps the original composition while integrating fresh constituents; and **Mix 3** & **Mix 4** are modified formulations, designed to improve mechanical performance while keeping historical authenticity.

The color analysis of the original mudbrick samples, as figured out using the Munsell Soil Color Chart, identified a hue of 7.5YR, a value of 5, and a chroma of 4, signifying a brownish coloration. This chromatic characteristic is attributable to the presence of ferrous minerals [30] within the soil from which the mudbrick was derived. Despite the Munsell Soil Color Chart is widely acknowledged as the standard reference for sediment color classification, ensuring consistent and precise comparisons, its reliability may be affected by several variables, including ambient lighting conditions, sample moisture levels, degree of preservation, and subjective perceptual variations among observers [31].

The results of mineralogical analysis of the ancient brick composition by XRD confirmed its suitability for reuse, given the absence of expansive clay minerals or harmful soluble salts that could trigger internal deterioration [32-33]. This supports the continued utilization of the original soil source for conservation work. The presence of calcite is attributed to the carbonate content in the soil composition from which the original mud brick was produced, estimated to be approximately 8% [34]. Furthermore, the analysis of grain size distribution within the historical mud bricks yielded critical data for formulating new mixtures, enabling either precise replication of the original composition, strategic alterations (approximating or diverging from the source material), or incorporating targeted additives to improve specific properties. On the other hand, the second stage focused on physical and mechanical properties, which are fundamental for evaluating these mixtures and selecting the most proper formulations for practical application in restoration efforts. Considering the results obtained through physical and mechanical tests, it can be said that:

The evaluation of color and texture across the tested mud brick mixtures revealed a notable consistency between the original sample (baseline reference) and Mixes 1, 2, and 4, respectively. This similarity can be attributed to the comparable composition and proportional distribution of raw materials [35], ensuring a cohesive visual and tactile match with the original structure. In contrast, mix 3 showed slight deviations from this established range, indicating subtle variations in its material composition or the interactions of its constituents during processing. This observed phenomenon may be associated with the increased proportion of the silt/clay fraction, which consequently enhances the carbonate content, as evidenced by XRD analysis. The elevated carbonate concentration contributes to a noticeable lightening of the soil color [36-37]. Beyond color and texture, further investigation into physical and mechanical properties provides critical insight into the suitability of these mixtures for conservation applications. These parameters, including density, porosity, water absorption, compressive strength, and shrinkage, serve as essential criteria in figuring out the durability and structural compatibility of selected formulations. The following discussion focuses on these attributes, evaluating their impact on restoration strategies and material performance.

The original mud brick demonstrated inherently high porosity (29.6%) and water absorption capacity (18.5%); characteristics commonly associated with historic earthen materials referring to its structural integrity comparable with other sites in Egypt [38]. These properties are attributed to natural weathering processes, which induce micro-cracks’ formation and weaken structural bonds, leading to the gradual loss of clay cohesion [39]. Consequently, porosity increased slightly over time, while the material showed relatively low compressive strength (0.79 MPa). The washed and repoured original material (Mix 1) displayed improved density (1.73 g/cm³) and strength (1.1 MPa) reflecting aging vs. freshness and suggesting that re-compaction can enhance structural performance while keeping material compatibility - a crucial factor in conservation interventions [40-41]. Mix 2, formulated with fresh constituents matching the original 70:30 sand-to-silt/clay ratio, achieved best mechanical properties (1.7 MPa strength, 1.7 g/cm³ density) and the lowest water absorption (13.5%), supporting its use for structural repairs. This can be attributed to the sand-dominated mixtures which provide superior load-bearing capacity [42-43]. However, its high shrinkage (2.1%) compared to Mix 1 should be taken into consideration in large-scale applications. Mix 3 (60:40 sand/soil ratio) showed intermediate strength (1.5 MPa) but the highest shrinkage (2.8%), consistent with increased colloidal contraction from finer particles which increases water retention leading to greater drying shrinkage. In contrast, mix 4's incorporation of 1% straw fibers (1-1.5 cm length) effectively reduced shrinkage [44] to 1.5% while maintaining workable strength (0.6 MPa), demonstrating the well-documented role of fiber reinforcement in crack mitigation and increasing the elasticity of the mud brick [45-46]. However, when incorporating organic fibers into experimental and practical applications, careful consideration must be given to both the type and length of the plant fibers to ensure proper performance and material compatibility [47].

These results collectively suggest: Mix 2 can be recommended for structural elements requiring maximum strength, mix 4 for non-load-bearing applications needing crack resistance, and Mix 1 for repairs demanding strict material authenticity. As for Mix 3, adjustment of the constituent types and ratio can be suggested along with more testing of properties to mitigate of high value of shrinkage flaws. The findings support the Venice Charter's emphasis on using compatible materials in heritage conservation while demonstrating how controlled modifications can address specific performance requirements in earthen architecture preservation.

Figure- 7. Large-scale production of mudbricks based on the study's findings, with participation of students from the Conservation Department at Sohag University.

Conclusion.

The 18th-century Sheikh Al Arab Hammam Citadel exhibits significant deterioration aspects, characterized by the complete or partial loss of several remaining walls. Addressing these challenges needs a range of restoration interventions, including stitching, stabilization, structural completion, reconstruction, and reinforcement. Consequently, the choice of brick units with properties that ensure compatibility with the original materials is essential to preserve the integrity of the historic structure while preventing any adverse effects on its original fabric. Assessing the original mudbricks provides a benchmark for comparison, helping to understand the unique characteristics and properties of the historic material. The results from the original mudbricks serve as reference standards to ensure the reproduced and newly formulated mudbricks are close to the originals, to meet the desired specifications and to perform similarly to the original materials. Comparing the results of the produced mudbricks vs. the original mudbricks validated the replication process and pointed out the possibility of using Mix 2 re-compacted formulation with fresh constituents Sand/ (Silt+ Clay) 70/30 ≈ 2.5/1 ratio which can be suitable for structural elements requiring maximum strength and strict material authenticity. Additionally, mix 4 can be recommended for non-load-bearing applications needing crack resistance as well as its lower strength that will be less likely to exert excessive stress on the surrounding ancient material, preventing further damage. Despite the findings presented in this study, further experimental research with more tested samples is needed to address critical aspects of strength and weathering resistance, particularly in the context of global climate change. Future investigations should focus on assessing freeze-thaw durability cycles and abrasion resistance, as well as exploring experimental formulations incorporating diverse constituents and additives even with necessary adjustments formulations of this study for better performance. Furthermore, characterization of mud mortar used in laying mudbrick units in the citadel of Sheikh al-Arab Hammam is dispensable to be conducted for proper conservation works.

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