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ASSESSMENT OF PHYSICAL AND MECHANICAL CHARACTERISTICS OF MASONRY BUILDING MATERIALS IN HISTORIC MILITARY TOWERS IN ALEXANDRIA-EGYPT: A CASE STUDY

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Abstract

Historic masonry structures must have a full characterization of its building materials before starting in any rehabilitation procedures. As the same in medicine field, where, any treatment procedures must be preceded by a correct diagnosis. Mechanical and physical properties assessment gives important information about the current situation and a full characterization of building materials used in historical masonry structures. Limestone and lime or gypsum mortar is the most common masonry types used in construction of historic military structures in Alexandria, Egypt. The paper is concerned with assessment of building materials used in historical military towers in Alexandria - Egypt, which over the years its building materials suffered a lot of damage phenomena due to various causes (internal and external factors). The methodology, calibrated on historic tower No. 3 located in Alexandria –Egypt dating back to19th century. The methodology followed in the paper to assessment of masonry used in military structures allowed not only to assessment and record their properties but also to define and record the relation between building materials properties, surrounding environmental conditions and deterioration phenomena they present.

Keywords: *Masonry; Military towers; Building materials; Damage; Deterioration phenomena; Sampling; Petrographic properties*

Introduction

Throughout the history masonry or natural stones have been widely used as a building material in most of historical buildings. Over the years, all masonry building materials have been affected by several deterioration factors (internal and external factors). So the interaction between the building materials properties and deterioration factors controls the type and extent of decay or deterioration phenomena [1]. Thus the continuous changes of the environmental actions play an important role in historic masonry buildings deterioration [2].

Mechanical and physical properties assessment is aimed at assessing the current situation of an existing structure building materials. In the same time architectural heritage, by its nature, rarity and history, present a number of challenges and difficulties in diagnosis or rational methods of analysis and restoration due to many causes for example, the rare of modern legal codes and building standards [3-5].

In fact, when neither the real state of damage phenomena nor the mechanics of deterioration is known, the effectiveness of any proposed intervention is certainly unknown.

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Restoration can be successfully accomplished only if diagnosis of building materials properties and the state of damage has been carefully carried out. Laboratory tests can give useful information not only to assessment the current situation but also for the choice of the appropriate material for substitution [5-7]. However, we can say that the investigation or building materials assessment methodology should be performed to check the reliability of hypothesis on damage causes and evolution, control the building materials before and during the restoration processes, expect the behavior of building materials after the intervention, and to control the effectiveness of the repair and strengthening.

Description of the building

Historic military structures are among the most ubiquitous of historic building types in Egypt. They are not only represent the history of wares in Egypt, but also represent a part of Egyptian architectural history, it simply constructed by using local resources (building materials, techniques and skills of constructions).

Military Towers are deemed to be a witness to an important era in Egyptian history with its victories and failures. They had an important role in protecting Egypt maritime coast or borders. During history rulers and kings were interested to immunization Egypt borders, especially, those overlooking the Mediterranean Sea from Abu Qir to Port Said, thus they established many fortresses, castles and fences see figure 1. Military Towers are among these fortresses. The Mediterranean Sea borders in Egypt have 21 ancient Military Towers.

Fig. 1. Typical military architectures in Alexandria

Military Tower No. 3 is one of military structures located in Abu Qir in Alexandria governorate. Dating bake to Mohamed Ali reign (early 19^{th} century). The building is considered to represent the structural and architectural trends prevailing in military towers structures in Alexandria this period (Fig. 2). The in-plan geometry of the Tower has a cylinder shape. The Tower walls were built with semi-chiseled or chiseled limestone, bound together with mortar. Limestone, Lime-gypsum mortar and Lime-gypsum plaster are the building materials used in the construction of the tower No. 3.

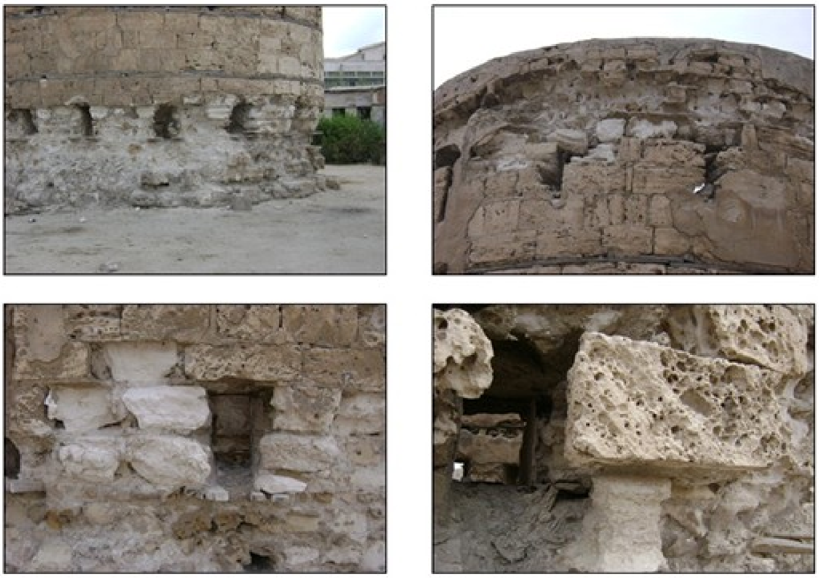

Fig. 2. Examples of deterioration phenomena in the military tower

Methodology

The assessment of the physical and mechanical characteristics of the masonry building materials used in historical military towers in Alexandria is based on visual observation, sampling of the construction materials, laboratory testing of the samples and results discussion. The work is concerned with the assessment of physical and mechanical properties of limestone, mortar, and render used in historical military tower No. 3 in Alexandria, Egypt which over the years suffered a lot of damage phenomena due to various causes.

Methods of characterization and laboratory tests

The assessment of the physical and mechanical characteristics of the masonry materials used in heritage buildings usually aim to identify the mechanical (strength, deformability, etc.), physical (porosity, etc.) and chemical (composition, etc.) characteristics of the materials and the presence of any discontinuities within the structure. The assessment methodology of the physical and mechanical characteristics of the masonry materials is based on (**a**) Visual observation and sampling of the construction materials, (**b**) Laboratory testing of the samples (X-Ray Diffraction (XRD), polarizing microscope and uniaxial compression test [8, 9], (**c**) The deterioration mechanism (the mutual relationship between masonry properties and environmental factors and (**d**) Obtained results discussion and concluding remarks. The tested or targeted tower is named as tower No. 3 and the building beside it (Fig. 2).

Sampling

The main materials used for the building construction in the case study tower are limestone, lime-gypsum mortar and poor coating render. The sampling included many samples of limestone, mortar and render from different parts of the tower. The sampling processes were effected either by carefully removing relatively small stones through the use of chisel or small fragments of stone were removed from the underside of the tower or by collecting the isolated or fall stones. Scratched mortar and render samples were taken for chemical and mineralogical qualitatively analysis as shown in figure 3.

Fig. 3. different sampling processes (stone, mortar and render sampling

Testing

Samples were taken and appropriately prepared for the chemical and mineralogical characterization. The mineralogical characteristics of building materials were established through X-ray diffraction (XRD) analysis and polarizing microscope applications, while mechanical properties were determined by uniaxial compression tests.

The collected samples are shown in table 1. On the other hand figure 3 shows the locations of sampling. It must be noted that from the in-situ sampling the mortar was found very weak and friable due to the effect of groundwater and other deterioration factors.

Table 1. Type of samples and location of sampling

Specimen	Material type	Specimen type	Sampling location
B3-s-1	Limestone	fragments	Tower base - Fig. 3
B2-s-1	Limestone	fragments	Tower body - Fig. 3
H3-s-2	Limestone	fragments	Building wall - Fig. 3
B3-Mo-1	Mortar	Scratched	Tower base - Fig. 3
H3-Mo-1	Mortar	fragments	Building wall - Fig. 3
H3-PL-1	Render	fragments	Tower body - Fig. 3
H3-PL-2	Render	Scratched	Building wall - Fig. 3

Limestone

The methodology followed in the paper for analysis of the mechanical the physical, the microstructure and the chemical properties of limestone are in the following steps

X-ray diffraction (XRD), method usually used in mineralogy and petrology of limestone that makes possible identification of the minerals that compose the investigated sample. X-ray diffraction spectra of patterns of limestone samples B3-s-1, B2-s-1 and H3-s-2 are presented in figure 4. For X-ray diffraction pattern presented in figure 4, one can observed the presence of the *Calcite* ($CaCO_3$), the main composite of limestone, *Quartz* (SiO_2), traces of *Dolomite* ($CaMg(CO_3)_2$) and *Halite* (NaCl) in addition to some minor elements which are showing by the peaks of lower intensities (Fig. 4).

Otherwise X-ray diffraction pattern presented also in figure 4, show the presence of the *Calcite*, *Quartz*, in addition to minor of *Dolomite* and *Halite*. On the other hand the same results were obtained for X-ray diffraction pattern presented to the third specimen (H3-S-2 specimen) where the main elements are *Calcite*, *Quartz* and minor of *Dolomite* and *Halite*.

Following to XRD analysis, appropriate specimens were prepared for polarizing microscopy examination. Four samples were taken from different locations of the tower and the room beside it. The samples have been determined by using the polarizing microscope, and based on the Petrographic classification of *J.R. Dunham* [10]. The study deals with the petrographical characteristics of 4 different samples which are identified as carbonates and salts with carbonate fragments (Fig. 5)

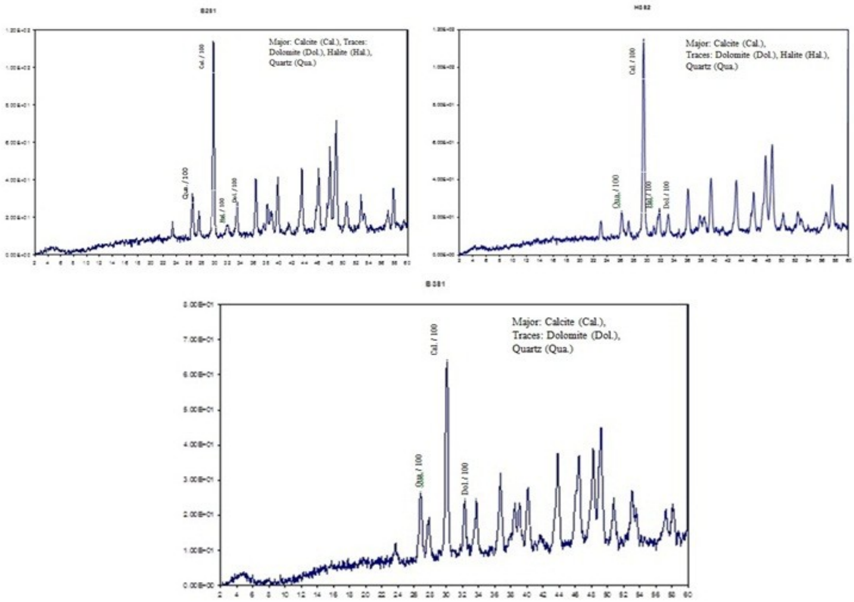

Fig. 4. XRD patterns of B3-S-1, B2-S-1 and H3-S-2 specimens

Where samples B3-S-1 and H3-S-2 indicate and show that the rock is dark yellow highly fossiliferous hard limestone. Microscopically the rock is larg foraminiferal (Oolitic). It is composed of skeletal allochems of different sized and shapes, and some scatted quartz grains embedded in fine grained micrtic or pseudo spar which is partially dolomitized matrix as shown in figure 5.

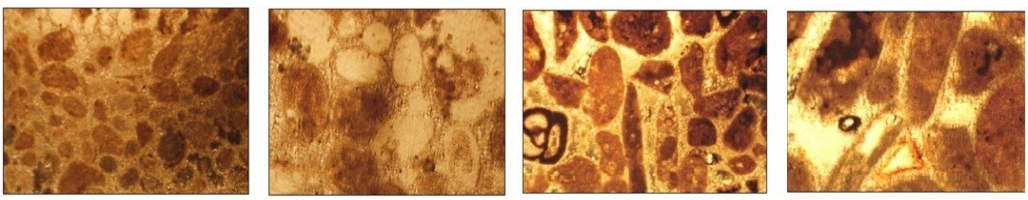

Fig. 5. Samples B3-S-1 and H3-S-2 under the Polarizing Microscope (under the two horizontal polarizing 64)

Several samples taken from different locations of the tower have been examined to assessment and determine the physical properties (porosity, Density and Water adsorption) of limestone used in the construction of the building. The void ratio N (%) is calculated by hydrostatic weighing method that is based on the Archimeds method, and immersed in distilled water. The test is repeated three times on the samples for each specimen.

The empirical following formula was applied for calculate the porosity ratio [%]. $N = 100 \cdot [(M_{sat} - Ms)/(M_{sat} - M_{hyd})]$, where: M_s = Mass of the dry rock, M_{sat} = Saturated mass, M_{hyd} = Hydrostatic mass. Tables 2 and 3 presented the results of limestone physical and chemical properties tests.

The mechanical characteristics of the samples were established from uniaxial compression tests. The following tables (Table 4) indicated to the values of compressive strength of limestone samples.

Table 2. Shows the physical properties of limestone of the tower

Sample ID	Dimension	Density	Volume	porosity	Coefficient of Water adsorption
H3 S2/1	5x5x5	1.89	125	22.1	11.71
H3 S2/2	5x5x5	1.98	125	20.7	10.43
H 3S2/3	5x5x5	1.97	125	20.4	10.31

Table 3. Shows the chemical composition of limestone of the tower and the building beside

Sample	CaO	SiO_2	MgO	Fe_2O_3	Cl	Na_2O	SO_3	L.O.I.
B3– MO – 1	34.5	26.7	1.19	2.19	2.28	1.55	2,43	13,19
H3 – MO – 1	39.1	26	0.18	0,22	2.35	1.8	2.52	46,61

Table 4. Shows the Compressive strength values of stone specimens (tower)

Sample ID	Dimensions (cm)	Surface area (cm²)	Compressive strength (kg/cm²)
H3 S2/1	5x5x5	25	97
H3 S2/1	5x5x5	25	112
H3 S2/2	5x5x5	25	110

Mortar joints

From the samples chiseled out at the locations of the lower and higher parts of the building, samples were taken and prepared for the chemical analyses. Otherwise from in-situ sampling the mortar was found very weak and friable due to the effect of groundwater and other deterioration factors. Table 5 presented the results of the chemical analysis of the mortar used in the construction of the targeted building.

Table 5. Show the physical properties of mortar samples

Sample ID	Dimension	Volume	porosity	Density	Coefficient of Water adsorption
B3S3/1	5x5x5	125	21.48	2.03	10.58
B3S3/2	5.2x5.2x5.2	125	18.59	2.03	9.15
B3S3/3	4.3x4.3x4.3	79.51	23.81	1.90	12.5

X-ray diffraction patterns of mortar layers used in between limestone units are presented in sample B3-Mo-1 and H3-Mo-1. Where Figure 6 presents the XRD results of mortar specimen B3-Mo-1 and also presents the XRD results of mortar specimen H3-Mo-1.

Render/plaster coating

Render or plaster coating used in the tower construction and the room adjacent the tower is currently in a bad situation due to the effect of environmental surrounding factors. One of the most observed deterioration phenomena in the tower No. 3 and the room beside is the fragmentation of masonry mortar joints between the limestone course and the extensive detachment and loss of wall render/plaster.

Chemical and mineralogical characterization to plaster coating was established to assessment the composition and the deterioration composition elements in plaster coating used.

Table 6 presented the results of the chemical analysis of the two render samples tested (H3-PL-1 and H3-PL-2).

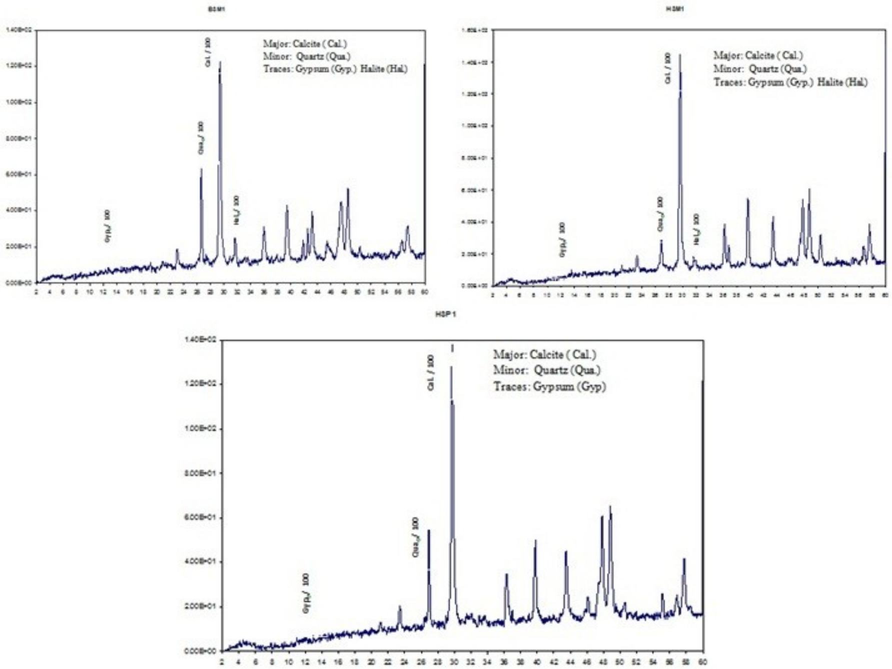

Fig. 6. XRD patterns of B3-Mo-1, H3-Mo-1 and H3-PL-2 specimens

Table 6. Results of chemical analysis (% w.w) of the mortar and render samples

Sample	CaO	SiO_2	MgO	Fe_2O_3	Cl	Na_2O	SO_3	L.O.I.
H3-PL-1	42.9	13	0.18	0.22	2.25	1.10	1,66	37.98
H3-PL-2	45.8	10.5	0.28	0,25	2.24	1.15	1.86	37,91

Two specimens were examined by X-ray diffraction analysis to determine the typology and the main elements used in plaster or render coatings in the building. As mentioned above plaster coating suffers significant deterioration phenomena and has detachment and lost from the majority of lower parts of the Tower No. 3 and the room beside.

X-ray diffraction spectra of patterns of render sample H3-PL-1and H3-PL-2 are presented in figure 6. The results refer to the use of lime-gypsum mortar with a huge amount of Quartz as a plaster coating in the tower and the room beside.

Discussions

For many centuries masonry building materials have arguably been the main building materials used in the construction of a wide range of historic structures in Egypt. Masonry is a nonhomogeneous material comprising blocks, natural (stones) or manufactured (bricks), and a series of mortar joints arranged either irregularly (in stone structures) or regularly (in brickwork) [11].

Egyptian Limestone are generally homogeneous in its chemical composition or characteristics, being dominated by *Calcite* or *Dolomite*, in contract it usually be highly variable in its physical characteristics such as porosity, capillarity, hardness, and fossil content.

Masonry deterioration processes can be more defined as the result of complex interactions between many different actions. These actions or factors act in the form of deterioration circle surrounding the building materials – for example, the act between the internal factors and external factors which have changed continually; many building stones have been exposed to changing process regimes over their lifetime.

From the visual, chemical and mineralogical analysis it is clear that limestone used in construction of the military towers in Alexandria is porous *Oolitic limestone*. Otherwise the difference in its natural texture (grain size) in addition to the acts of dissolution and erosion phenomena, this does not prevent the growth of fossil and calcite in the pores or grains. Smith and Viles 2006 referred that, in particular, *Oolitic limestone* exhibit the greatest variability between all types/kinds of limestone commonly used in construction of historic structures. By definition *Oolitic limestone* consists primarily of small rounded grains coated with $CaCO_3$ and embedded in *Calcitic cement*, but their durability varies hugely in response to differences in characteristics such as porosity and bioclasts content [12].

X-ray diffraction patterns of limestone in figure 4 shows that the main chemical composite of limestone used in construction of military towers is *Calcite* and *Quartize*, in addition to some minor elements of *Dolomite* and *Halite*. Otherwise polarizing microscope examination shows that it has a lot of fossils and it is composed of skeletal allochems of different sized and shapes (Fig. 4). From the results obtained from XRD analysis and mechanical properties in tables 2, 3, 4 and 5 it appears that the stone is soft and porous, and has a considerable salt content. The results of the analysis listed in table 2 Indicate that it has high percentage of porosity (21%), and the highly porous content lead to adsorbed high content of moisture leading to dissolution and erosion phenomena.

Due to the effect of environmental or surrounding factors limestone in the tower and room beside has exposure to dissolution, bleeding and erosion phenomena as shown in figures 2 and 7. As a result of previous mentioned deterioration phenomena, the compressive strength values of limestone are insufficient manner (110 kg/cm²).

From physical and mineralogical test results limestone suffered a lot of deterioration phenomena such as salts crystallization, bleeding, dissolution and weekend internal content. On the other hand due to the high content of fossils with presence of high ratio of moisture and groundwater limestone losses permit high amount of its internal contents (fossils, *Calcite cement* and *Quartz* grains) as shown in figures 7 and 8.

However from in-situ observation to limestone in lower and higher parts of the tower we can notice the varying in forms and intensity of weathering processes, this because of differences in salt content and types, the major contents of fossils and because of the differing quality and weathering resistance of limestone used see figure 7.

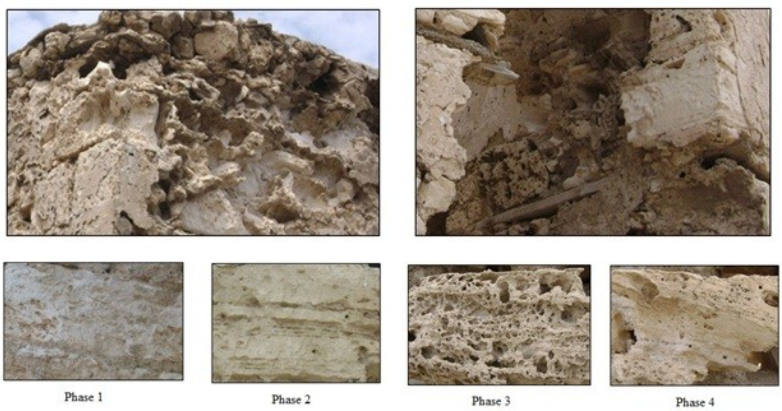

Fig. 7. Patterns of limestone surface weathering and dissolution

Fig. 8. Rapid decay to limestone blocks and collapse of whole sections of the wall

It is general susceptibility of *Oolitic limestone* found in marine atmosphere exposure to physical weathering, especially salt weathering that sets them apart from dense limestone and from the general preconceptions regarding the pre-eminence of solution loss. Because of this it is more common to see these limestone affected by patterns of surface dissolution decay [13].

Surface dissolution decay in limestone as shown in figures 7 and 8 may begin with limited and localized surface missing parts through granular disaggregation (honeycomb weathering). By the time and with the long-term of weathering acts the small hollows of limestone honeycombing can amalgamate to form larger cavernous hollows, distinctive bedding and multiple flaking. Invariably this is associated with the near-surface presence of salts crystalline crusts.

The result of such actions due to the salt weathering to Oolitic limestone used in the construction of historical military construction in Alexandria there is alarm visual evidence that individual blocks and ultimately, whole sections of the wall can become prone to rapid decay and, eventually, localized collapse (Fig 8).

On the other hand mortar in historic structures, in general, consist of a cementations binder, fine aggregate, sand/filler materials and water. Depending on the state of the binder-based mortar layer, it can increase or decrease the friction stress between stone or brick units in masonry wall courses. Mortar also play a role in distribute compressive pressure between wall courses [14].

The mortar used in the construction of the tower and the adjacent room in the bad condition, it suffer significant damage phenomena due to some external and internal factors. From visual observation and survey the mortar is in bad current situation due to many cases (Fig. 9).

Fig. 9. Show decay of the mortar used

The harmful of deterioration surrounding factors and the poor composition of the mortar are the main factors lead to mortar loss and bleeding leaving stone courses without in-between mortar [15, 16].

XRD and chemical analysis were used in order to assist the physical and mineralogical characterization and to assume whether or not a lime-gypsum mortar was used for the masonry construction. XRD analysis was made to the passing fraction of the mortar and calcite, gypsum, *Quartz*, and *Halite* were the main detected mineralogical phases (Fig. 6). The mortar samples tested for lime, sand and loss of ignition ratio respectively is: 81%, 15% and 3%.

One the other hand construction defects play an important role in mortar decay as the builder used the marine or beach sand which contain in its composition shells and various shaped of gravels as shown in Fig 9. In the long-term with the weathering actions shells and gravels fall down. As sequences mortar began to bleeding and form larger hollows in it. And the result is fragmentation of masonry mortar and missing the binder-based mortar layer between limestone blocks courses leading to localized collapse in the building.

Conclusions

Masonry in historic structures in marine zones in Egypt suffers significant damage phenomena comparing with the other zones (Delta or Upper Egypt). The physical, chemical and mechanical properties of building materials play the main role with the surrounding factors in the essence of damage mechanism and deterioration phenomena they present. The general source of long-term decay performance of building materials, in particular sedimentary rock stones, may lie in structural and textural variations.

Limestone used in the construction of historic military buildings in Alexandria, Egypt has a typically non-uniform and largely surface decay dissolution appearance and characterized by marked temporal and spatial variability, not only within individual blocks or stones but also across complete structural or construction elements of the building leading to localized failure in wall.

from in-situ observation to limestone in lower and higher parts of the tower we can notice the varying in forms and intensity of weathering processes, this because of differences in salt content and types, the major contents of fossils and the differing quality and weathering resistance of limestone used. *Oolitic limestone* used in historic buildings in Egypt is frequently characterized by effective poor physical breakdown or failures which include the presence of initial surface roughening, leading to dissolution, pitting and honeycombing.

Depending on the long-term of weathering acts the small hollows of limestone honeycombing can amalgamate to form larger cavernous hollows, distinctive bedding and multiple flaking. Invariably this is associated with the near-surface presence of salts crystalline crusts. The result of such actions due to the salt weathering to *Oolitic limestone* used in the construction of historical military construction in Alexandria there is alarm visual evidence that individual blocks and, ultimately, whole sections of the wall can become prone to rapid decay and, eventually, localized collapse.

Structural defects play an important role in deterioration of historic military structures in Egypt. Structural defects include faults in the choice of building soil/site, irregular distribution of the structure‘s loads on the foundations, and faults in the choice of proper building materials. The use of improper sand in mortar compounds lead mortar to form larger hollows, distinctive bedding and missing the binding mortar between limestone blocks leading to localized collapse in the building.

Military towers constructed in marine zones in Egypt located in Abu Qir in Alexandria governorate which dating bake to Mohamed Ali reign (early 19th century) characterized by a lot of structural and construction defects comparing with those built before. Defects include faults in the choice of proper building materials as the use of Un-coursed random rubble limestone and improper mortar-based. The mortar which contains sea sand in its raw contents, without any filtration of its fossils and gravels content, lead to create weak bond between wall courses, the mortar in this case becomes the weak link and prevents a proper bond between stones. On the other hand render coating containing a large quantity of sand and a significantly smaller quantity of lime and *Gypsum*.

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