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Groundwater damages on the historic buildings of Cairo: the case of the medieval walls of Mokattam limestone.

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Abstract. The conservation of historical buildings in Cairo represents a complex matter, influenced by several key factors such as the cultural context, the intrinsic features of a vast and heterogeneous architectural heritage and the environmental conditions. An Italian-Egyptian research group is working on the peculiarities of the monument conservation in old Cairo, concerning the material decay in relation to the anthropic and climatic factors and the pollution levels. Monument vulnerability levels strongly need to be identified and systematized to delineate adequate programs of control, management and intervention. One of the main topics developed is the study of the deterioration mechanisms of stone materials in medieval walls, connected to the capillary damp rising from the ground, common in Egypt, always accentuated by the combination with other factors. The research examines some historic buildings in different areas (El-Gamaleya, El Darb El Ahmar, Al Qarafah). The variety of materials has led to limiting the first phases of the study to the masonry materials, with special attention to the limestone blocks. The intersection of data collected on the field with those relating to underground water and environmental factors has allowed us to focus on some aspects of the problem. Some syntheses have been proposed on the main mechanisms affecting the studied material *in situ* and the necessary directions for further investigation have been identified. Our first results highlight the relationship existing between the environmental thermo-hygrometric excursions and the capillary water rising from the ground, which affect the evaporation speed, the imbibition levels and the crystallization of salts inside and on the rock surface. The studied rocks display intense weathering (decohesion, dissolution) due to a number of chemical and physical phenomena, responsible for a generalized decay of the mechanical properties of the original material. The observed widespread phenomena of carbonate sulphation also suggest the atmospheric contribution of particulate matter and polluting compounds. The mineralogical and physical characterization of the limestone allowed us to estimate its resistance to the decay processes.

1. Introduction

In recent years, the close relationship between threats to the architectural heritage and environmental changes, induced by the increase in urban population and resource misuses, has been pointed out. Namely, a complex interaction relates monuments and the underground waters as hydrologic processes are able to accelerate the decay of historical buildings and sites. It becomes clear that the management of the waters and that of the built heritage are strictly interdependent. The accurate knowledge of the



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subsoil, especially in highly anthropized areas is claiming for increasing attention, to understand the present damages of the built heritage, and to properly define conservation strategies. The correct understanding of the subsoil, in turn, must account for the geological settings and the anthropic interventions. Accordingly, architectural and archaeological conservation studies have, recently, undergone an interdisciplinary and multi-scale approach.

During the last decades, Egypt experienced an abrupt growth of population, joined to a huge urban drift. These phenomena fully pose the country in this problem, and very critical conservation tasks are displayed throughout it. Here we report the preliminary results of a multidisciplinary investigation on the state of conservation of building materials of the Cairo medieval monuments, aimed to identify the dynamics of their deterioration. The study proceeds via the survey of representative case studies, in relation to water rising, and sets up criteria for the technological knowledge of the buildings in a conservation perspective. The proposed procedure provides, in a multi-scale approach, several kinds of information: from the urban to the building scale, then the masonry, the decorative elements and the individual stone blocks. Indeed, a set of desk-based and on-field investigations has been applied to significant buildings, selected for their historical and architectural relevance, and for the enhanced level of degradation. The investigation has proceeded through architectural survey, identification of building materials and their alteration processes. Then, a selection of samples collected from detached blocks of limestone was made available for laboratory characterization. These latter were carried out to establish on a more quantitative level the decay processes attributable to soluble salts, polluted water and air.

2. The groundwater rising in Egypt

Several scientific evidence of environmental concerns in the underground waters of the Nile basin was recently provided. Namely, numerous studies report of a widespread seasonal rising of the water table, the lowering of the river level, the salinization of soils in many places of the valley and delta [1]. Climatic changes and environmental consequences of anthropization are identified as major players of this degenerative process. The realisation of the Aswan dam in 1968 induced several changes in the hydrogeological asset of the valley: the drainage of the groundwater exerted by the Nile has been altered, as well as the progressive salinization of soils (nitrates and phosphates due to the major need of fertilisers), is registered southward along the river, where, moreover, the traditional irrigation, carried out by flooding the fields, contributes to the over-hydration of soils [2]. Combined to the rise in population, new fields at the boundary with the desertic regions are progressively involved in this process. The increasing of salinity has been also detected in the Nile Delta Aquifer (NDA), in combination with different sources (marine water intrusion and deep groundwaters) [3]. In Delta region, the anthropic effects also contribute to the water consumption by industrial activities and the waste management in the urban areas.

2.1. The impact on the architectural heritage in Cairo. Effects on the architectural heritage linked to the rising of the water table and to pollution of the groundwaters have been described in Egypt for decades. From Abu Mena to Thebes, no Egyptian site can be considered free from the threat of the groundwater rising, due to the cultivation of arid areas. By the evaporation from the surfaces of soils and buildings, shallow waters, with their content in salts, can rise up through the alluvial levels. The cyclic stages of dissolution and crystallisation of salts lead to the progressive rock disintegration (Figure 1).

In Cairo, this process is widespread, with the astonishing decay of the architectural heritage, as claimed since the UNESCO report of 1980 [4]. Today the problem is still unsolved and cycles of groundwater rising and evaporation are destroying the lower parts of many historical buildings [5]. It should be considered that in Cairo annual rainfall sums to less than 40 mm, humidity occurs in the range 45-84 % and daily evaporation ranges between 2.5 and 15 mm [6].

The geological setting of the old town consists of intercalation of alluvial sediments, and relics of former settlements, in a layer up to 15 m thick. Below, formations of clay, for a thickness up to 4 m, and

sands, up to 100 m in depth, occur. Each formation hosts a proper water layer, supplied by different processes: clays catch waters from rain, irrigation, leaks from pipelines and reservoirs, and waste fluids whereas sands from river and groundwater. Events, like the recent urbanisation of the Mokattam Hills in the North East, increase this supply [4]. The two levels are connected, and the rising of the lower water table, due to both geological and anthropic causes, can influence the saturation of the upper table.

The rise of population in Cairo (from 14 to 20 million, +44 % rate in the last 17 years) has highly influenced the changes in the depth and contamination of the water table [7]. The poor knowledge of the subsoil and the scarce control on the pipelines contribute to increase the criticality level of the system [8]. The worst situation appears in the Quaternary water layer of the North East of Cairo, where contamination down to 40 m depth (then it reduces and disappears in the next 20 m) has been described [6]. This layer tends to feed areas characterised by the intensive water pumping used for agricultural and industrial purposes. A wide range of Total Dissolved Solids, as well as intense contamination levels by nitrates, sulphates, Al, Mn, have been described in relation to anthropic activities (e.g. agriculture) or wastewater management [9]. Recent studies claimed a role by abandoned reservoirs or pipelines, as concentration steps in the groundwater circulation, with adverse effects on the adjacent buildings.



Figure 1. Common evidence of limestone decay in Medieval buildings in Cairo.

3. The historical Mokattam limestone and its deterioration

Except for the reused stone blocks coming from the southern archaeological areas, almost all limestone used in the historic building of Cairo, since pre-Dynastic times, comes from the Mokattam Formation (Middle Eocene), which mainly outcrops on Jebel Mokattam, and from Giza Plateau to the hills in East Cairo [10]. The most valuable material (compact and hard) came from the ancient quarries of Tura-Masara. A less compact limestone (from shallow marine waters) was quarried from the outcrops of the Giza plateau. A successive formation, the Maadi Unit (Late and Middle Eocene), contains a marly, porous limestone [11]. Nowadays, active quarries, which also provide material for restoration works in this region, are located at Helwan.

The overall set of building materials known as Mokattam stone, results, from this brief survey, to be characterised by wide variability in composition and texture. The different textural characteristics of the Mokattam limestone from the various quarried outcrops can be responsible for the observed different decay processes and their extent [12]. The processes include dissolution, mainly due to rainfall acidified with CO_2 , and sulphation in which the atmospheric moisture, acidified with sulphur, react with CaCO_3 ,

forming gypsum and possibly black crusts. In the case of Egypt, where a strong thermal variation between day and night is registered, the surface of limestone exposed to intense sunlight can often reach values of 60-80°C [13]. This thermal variation leads internal stress, mainly along grain boundaries [14,15]. As a consequence, the stone undergoes granular disintegration with increasing of porosity [16,17]. The presence of moisture on and in stones and the salt crystallization inside the pore network may represent a significant environmental factor contributing to stone decay [16,18,19]. Temperature can play a relevant role on the imbibition/evaporation steps during salt crystallisation.

4. The on-field investigation. Cases study

The area in the boundaries of the Medieval town, with special attention to El-Mosky, El-Gamaleyya, El-Darb El-Ahmar, Al-Qarafah districts (Figure 2) was selected for the on-field survey; this, based on the previously available information, was aimed to assess a general level of decay of the buildings and the peculiar damage caused by water rising.

For all the surveyed buildings (about 20 monuments) a field form was compiled, reporting observations on the architectural and technological aspects, the urban contextualisation, the building materials and the conservation tasks. Digital mapping of selected walls was then operated. After this step, a schematic mapping of the visible effects attributable to water rising in the considered district has been attempted. The digital relief of selected parts of buildings allowed to document both the construction and technological details, and the qualitative determination of the erosive processes involving the limestones as a function of the appreciable water rising. The comparison of the available photographic documentation of the same sites along the last decades, permitted to assess a rough esteem of the incremental step in decay.

All the investigated monuments display relevant levels of decay in the lower parts of the limestone. Several forms of decay were detected for the Mokattam limestone blocks, such as deposits, crusts, honeycomb and abrasive weathering, mechanical damage due to several chemical and physical phenomena (Figure 1); stone appears largely affected by erosive phenomena, mainly correlated to crystallization of soluble salts, and by sulphation coverages. Our survey points out evidence that are in a clear relationship to the Fitzner et al. [5] results and correlate with the presence of water rising and pollution. According to the on-field evidence, and on the literature data, a detailed study aimed to a deep knowledge of the physical, chemical, mineralogical and petrographical properties of the Mokattam stones is mandatory to exploit efficient conservation activities.

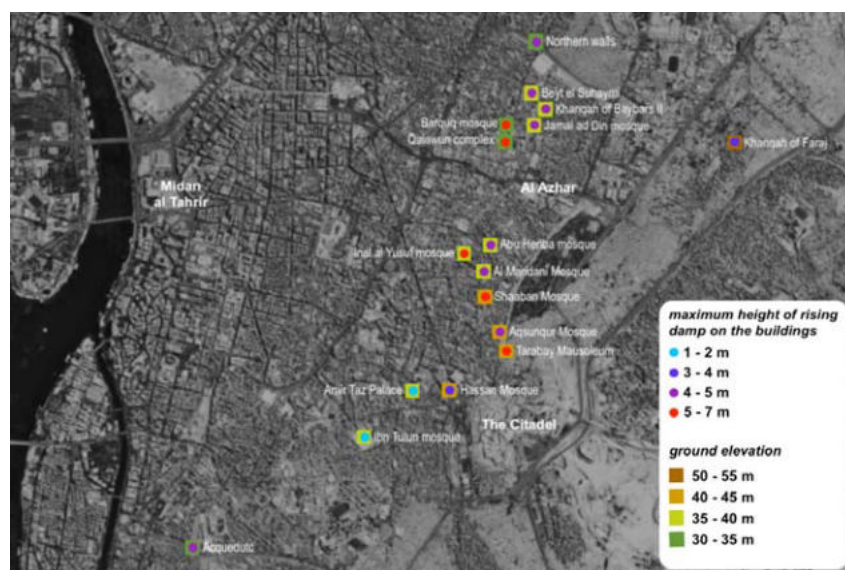


Figure 2. Map of the water rising height and ground elevation of investigated buildings.

Our on-field survey of the Medieval town remarks that the height of rising fronts increases while moving toward North East and lowers in the southern districts. Exemplar cases are the Mosques of the main streets in El Gamaleyya, where rising fronts are more than 6 m high. Evident damaged surfaces mainly concern calcareous stones, with specificities arising from water fluxes, composition and evaporation characteristics. Different *facies* can be related to stratifications of past and actual phenomena alternated for years on the considered walls. Disintegration due to the action of the dissolved salts in the rising water levels is alarming and it results in a retraction of the actual surfaces for the original outline of the walls (Figure 3).

If a general accordance between stone porosity and degradation level can be inferred, in certain cases also less porous stones present conspicuous phenomena. It is thus suggested that the evaporation can drive the process of soluble salt rising and crystallisation before their exit to the stone surface. This process could be the cause of internal stress that solicits the block and results in the detachment of the surface layers. To this general trend, effects ascribable to the general air pollution are also visible. Widespread sulphation phenomena of carbonate surfaces are observed and black crusts can be evidenced. In general, these dark/black sulphated surfaces are located immediately above the level of the main detached area and thus are somehow connected to the water rising, too. The continuous erosion and detachment of the altered stone let fresh surfaces to be exposed and the process to be renewed. Accordingly, the overall degradation of the wall proceeds at a very high speed. In agreement with this description, one can cite the constant presence of white microcrystalline particulate at the ground of the degraded walls.

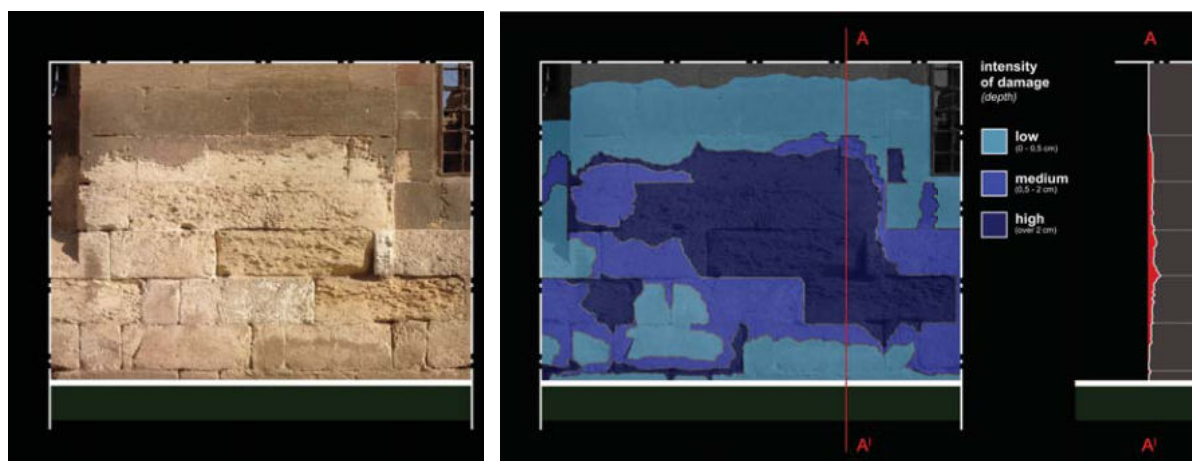


Figure 3 – On the left: rising water damage on the limestone blocks of Faraj ibn Barquq' Khanqah. On the right: the decay of the stone expressed as three levels of intensity, defined on the basis of the density of the alveolization and the depth of the loss of material.

5. Laboratory investigations. Mineralogical and petrographic characterization.

Rock samples, collected from Al-Maridani mosque, Al Aqsunqur mosque, Qalawun Complex and from the Khanqah of Faraj ibn Barquq, were analyzed.

Mineralogical and petrographic analyses were carried out using X-ray Diffraction (XRD) and a polarizing microscope, respectively. XRD analysis was conducted using a Philips PW 1050/37 powder diffractometer with radiation $\text{CuK}\alpha_1$ ($\lambda=1.545 \text{ \AA}$) and graphite monochromator, operating at 40 kV, 20 mA, investigated range $2\theta=5-70^\circ$, software X'PertPRO and High Score for data acquisition and data interpretation of the mineralogical composition; the textures of the marbles were studied on thin sections (30 microns thickness) using a Zeiss Axio Scope.A1 polarising microscope, equipped with a camera (resolution 5 megapixel).

The composition of the studied rocks consists of prevailing calcite (CaCO_3) with small amount of quartz; various other mineral phases, such as halite (NaCl), nitratine (NaNO_3), and the CaSO_4 minerals (gypsum, bassanite, anhydrite) are observed in the different samples (Table 1). For one of the studied samples, the observation in thin section, in polarized light, highlights a rock with carbonatic composition and micritic texture.

The porosity is low, with pores displaying irregular shape. Rare little cracks are present. Remains of microfossils, sometimes showing an evident calcitic recrystallization, are very abundant; calcite and detrital quartz crystals are rare as well as small agglomerates of iron oxides.

According to the Dunham classification [20], the rock could be defined as a mudstone having a quantity of grains $< 10\%$ and prevalent mud-sustained texture (Figure 4).

Sample	Provenance	Calcite	Quartz	Gypsum	Anhydrite	Halite	Bassanite	Nitratine
MB 30	Khanqah of Faraj ibn Barquq	XXX	Tr	X	Tr	-	-	-
AIM 1	Al Maridani Mosque	XXX	Tr	Tr	-	-	-	-
AIM 2	Al Maridani Mosque	XXX	Tr	X	-	Tr	Tr	Tr
MBL	Blue Mosque	XXX	Tr	-	-	Tr	-	-
QWA	Quallawun Mosque	XXX	Tr	X	-	X	-	-

XXX= abundant; X=low; Tr=traces

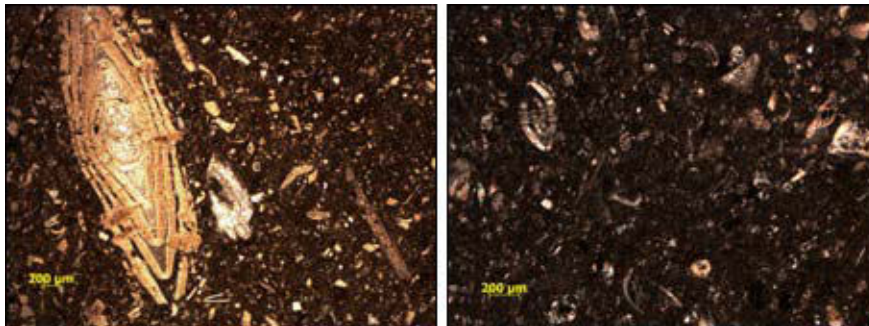


Figure 4 – Crossed polarized light images of the limestone from the Khanqah of Faraj ibn Barquq.

6. Discussion

The main evidence of the analytical results of the investigation carried out on the selected samples deals with both the rock constituents and their alteration layer. Concerning the rock composition, the present results (see Table 1) are in good agreement with the findings by Fitzner et al. [5], which carried out an extensive study (mainly performed through petrographic observations) of the different formation belonging to the so-called Mokattam stone. In particular, these authors evidenced the prevalent presence of calcite, whereas gypsum content varies between 0.5 and 4 wt%. Also, Fitzner et al. [5] reported notice from previous studies of the frequent association (in a very few amounts) of halite and gypsum. These authors, moreover, have already identified the same mineralogical phases as alteration products of the Mokattam stone surfaces. It has to be emphasized that also in the present study gypsum and halite were found in very low amount at the XRD. Under the adopted operating conditions, the mean detection limit (mdl) could be estimated in few wt% units (typically, 4%). Accordingly, we safely attribute the

identified phases to the alteration products, in a complete agreement with the visual inspection of the sampled surface and with the general relief of the sampled wall.

Having identified the most relevant crystalline alteration products of the sampled regions, the most relevant question to be addressed is the active mechanism of alteration: namely, if the chemical species necessary to allow the accumulation of both chlorides and sulphates in the alteration products are provided by the water uprising or by an atmospheric pollution. It is generally accepted that the urban atmosphere in Cairo can be rich enough of sulphate species (mainly due to anthropic activities) and also of sodium chloride, by both transport from the near desert regions (east and west of the urban agglomerate) and the seas (north and east of the urban agglomerate). However, since 2002, the Fitzner et al. [5] study has revealed how the weathering of the stone walls in nearly all the historical monuments follows an almost reproducible pattern, where at least four zones are discriminated: from bottom to top, i.e. 1) heavy weathered with stone detachment; 2) weathered with mainly halite as alteration product; 3) weathered with mainly gypsum and sulphates as alteration product; 4) unweathered original surface.

Our results confirm these observations; the multi-layered decay of the stone walls suggests that the clue of the weathering process has to be identified in the rising of the water table. According to the authors' opinion, the main (if not exclusive) weathering process is strongly related from the rising of the water table, which provides not only the wet environment able to catalyse the rock alteration and the consequent detachment, but also the formation of the salts necessary to the development of alteration processes (sodium chloride and sulphates). This weathering process, besides providing a loss of aesthetical effects, due to the surface alteration of the blocks, appears a more fundamental threat to the stability of the whole stone structure. The stone is exposed to weathering simultaneously at the surface and in its interior, with a progressive loss of physical coherence and mechanical properties [e.g. 5, 21-23]. Accordingly, we envisage the most serious risk to the conservation of the medieval Islamic buildings in Cairo in the rising of the water table.

7. Future perspectives

The main results of this first on-field survey agree with previous results of literature and mark alarming situations in numerous monuments of old Cairo. The reasons appear numerous and interrelated. Besides the cited natural and anthropic reasons, relevant tasks concerning the management policies are emerging [24]. The most recent trend focuses on the accurate knowledge provided by extensive and multidisciplinary scientific investigations.

The present study allowed to define the boundaries of a systematic program of investigation aimed at clarifying the different extent of degradation attributable to rising waters, and to organise a hierarchy of opportune intervention activities in Cairo Old Town. The comparison between present and past data on the subject will be highly desirable, to evidence systematic temporal trends. This holds true for satellite and aerial views and for the cartography. The monitoring of the rising of water through the monuments could be performed, with conservation purposes, by the cyclic survey of the surface weathering levels. Moreover, durability, and its parameterization, appears a very useful step, to be developed including combined effects of coefficients and porosity types. Finally, a detailed review of the geological settings of the region, including the specificity of the alluvial and surficial levels, in relation to the anthropic colonisation and use of the soil will be also necessary.

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