Conservation Strategy for Monumental Limestone in Egypt

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1 Introduction

The study of the ancient technology of buildings highlights how various kinds of stones have been used in erecting ancient buildings all over the world and through the ages, but limestone of different physiochemical and mechanical properties was the principal stones widely used for these purposes, especially in Egypt.

The ancient records show that the exploitation of stones for different purposes in Egypt can be tracked back as early as 40,000 BP when the middle Paleolithic inhabitants of middle Egypt were quarrying and working cobbles of chert along the limestone terraces on either side of the Nile Valley.

The excavations reveal that the first tombs from the Early Dynastic cemeteries in Lower Egypt had been built of mud brick and limestone and granite blocks (3000-2649 B.C.) and from the end of this period until the 18th dynasty limestone played a major role in building the pharaonic tombs, pyramids, and temples, especially in the Old and Middle Kingdoms. The most important buildings are the Zoser pyramid, the Giza pyramids, and the other tombs in Saqqara and Giza.

Lehner (1985) calculates that more than 9 million tons of limestone were used for building the pyramids at Dahshur and Giza. The limestone blocks had a uniform coloration of a mainly white color, a fine texture, and were of moderate hardness.

2 Limestone Quarries

Limestone Quarries occupy the two sides of Nile Valley from Esna in Lower Egypt to Alexandria at the North. There are about 88 limestone quarries which have been identified and huge amounts of limestone and temples. The most famous quarries from the north to the south.

2.1 Max Quarry (Pleistocene)

Most of Greco-Roman Tombs and the Roman Theater at Alexandria had been cut in this quarry and the limestone blocks taken from this quarry are widely used in the historical buildings in this area.

The limestone from these quarries is oolitic limestone, which is highly porous, sparsely fossiliferous stone.

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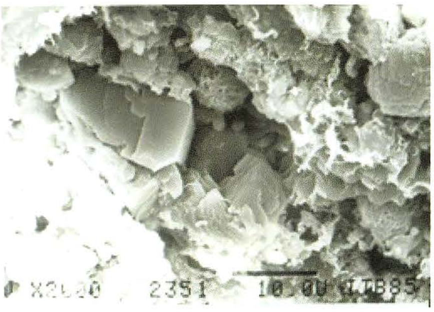
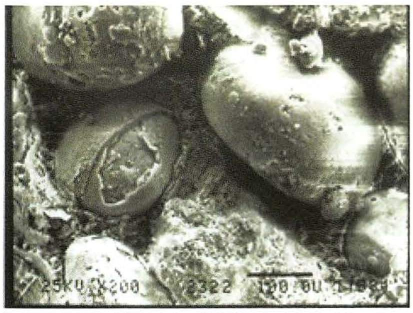


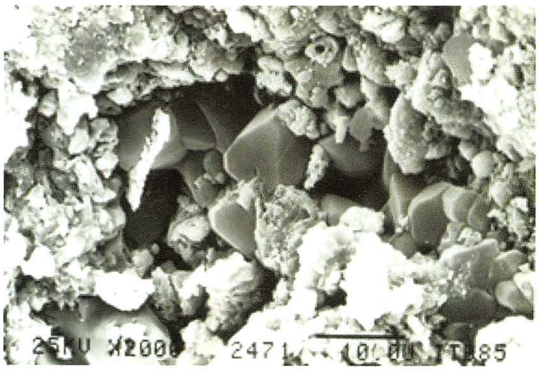


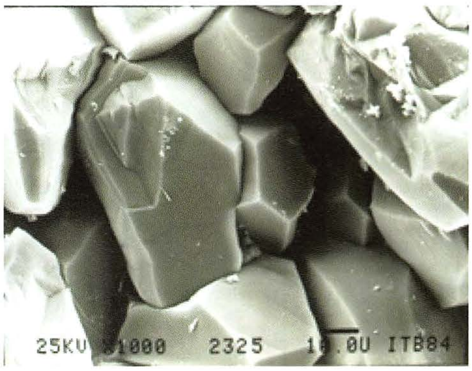
2.2 Giza Plateau (Upper Eocene)

The Giza plateau was the main source for the limestone blocks employed for building the Giza pyramids during the 4th dynasty (Old Kingdom). On the other hand, the great statue which is called the Giza Sphinx had been cut in the plateau.

Also during the 4th dynasty, millions of limestone blocks taken from this quarry were used for building the temples and the tombs in this area.

Giza plateau limestone is dolomitic, fine-grained, fossil, and ferrous. Some parts of the plateau are silty, sandy and clay. Limestone is highly porous limestone especially in the lower parts of the Sphinx.

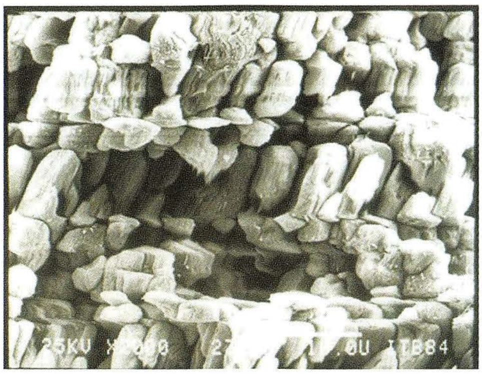




2.3 Saqqara Quarries (Upper Eocene)

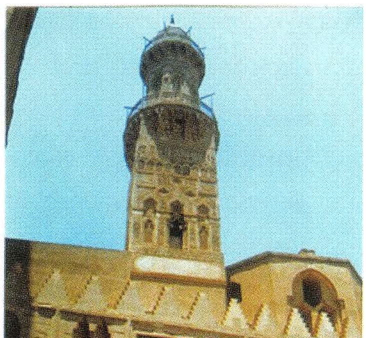
The Saqqara quarries are considered the oldest quarries used for building the Step Pyramid for King Zoser from the 3rd dynasty (Old Kingdom), which is considered the most famous and the oldest monument built completely of stone.

This type of limestone is slightly dolomitic, fine-grained, silty, sandy, friable, clay and highly porous stone.

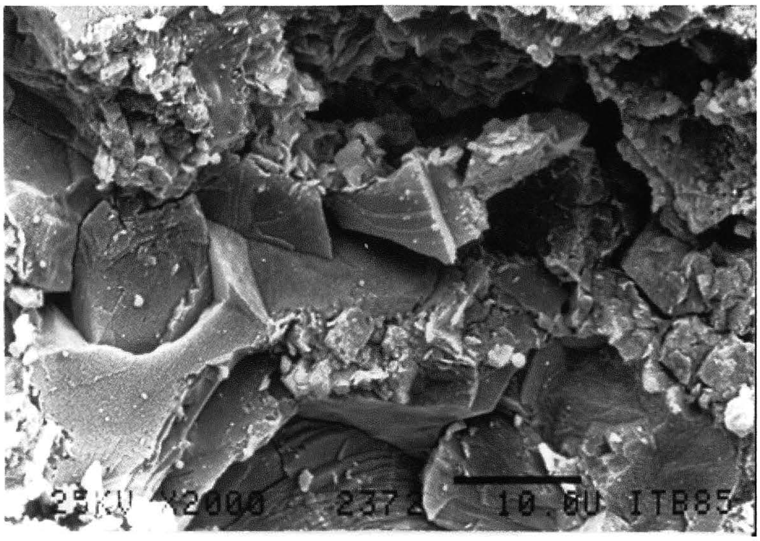


2.4 Mokattam Quarries (Middle Eocene)

The Mokattam quarries played a key role in building the Coptic and Islamic buildings in Cairo.



The limestone of these quarries is different in its physiochemical properties of the limestone in the other quarries and is highly dolomitic, fine-grained, fossiliferous, and made from low porous stone.



3 Petrographic Characteristics of Egyptian Limestone

Geological studies show that Egyptian limestone varied greatly in its petrographic characteristics from one quarry to another. The limestone of the Max quarry contains high amounts of crystalline salts (chlorides and sulphate) because it was originally formed in the marine environment, whereas the limestone of the Giza plateau, Saqqara, and Mokattam quarries contains high percentages of clay minerals, calcium sulphate, silt and sand. Generally, this rock contains different kinds of fossils and some different minerals such as dolomite, hematite, and goethite.

This rock is relatively soft and easy to work with, prepared for construction and artistic works and generally highly porous (its porosity ranges from 6.7% to 12.4%). For this reason, moisture can easily find its way into the limestone blocks of the historical buildings in Egypt.

Theophrastus recorded in his treatise the characteristics that made building stones valuable; a) Stones occupy large areas and consist of layers of different thickness, b) Stones can be quarried in suitable blocks, and c) Stones have a pleasant appearance and other aesthetic values such as smoothness and reasonable hardness.

The availability of limestone quarries in the northern part of the Nile Valley enabled the ancient Egyptian architects to build unique buildings which served different purposes and were decorated with different decorative elements. The ancient Egyptians did not leave any part of these buildings without decorative touches. Herz wrote that the limestone blocks were used to lighten the buildings' superstructures.

4 Mechanism of Deterioration

The natural building materials (stones, mortars, etc.) used in the historical buildings are always exposed to deterioration due to the severe effects of physiochemical mechanical and biological factors. The ability of these materials to resist these effects depends on their physiochemical and mechanical properties as well as on the degree of their homogeneity and on the specific surface area exposed to the factors previously mentioned. In addition to these factors, the traditional quarrying methods used in the past for extracting the blocks of stones can sometimes be considered a cause of damage with passing time because the mechanical bush-hammering will result in superficial microcracks on the surfaces of stones. Technical studies show that the porosity of these stones is influenced by the hammering techniques.

In this case the total porosity of soft stones is almost twice that of sound stones.

The most common deterioration mechanisms of monumental stones can be classified as follows:

1. Atmospheric mechanisms
   a. Variations of air temperature and relative humidity and condensation
   b. Wind erosion
   c. Acidic rain water
   d. Solar radiation
   e. Air pollution
   f. Groundwater penetration
2. Biological mechanism (mainly microorganisms and higher plants)

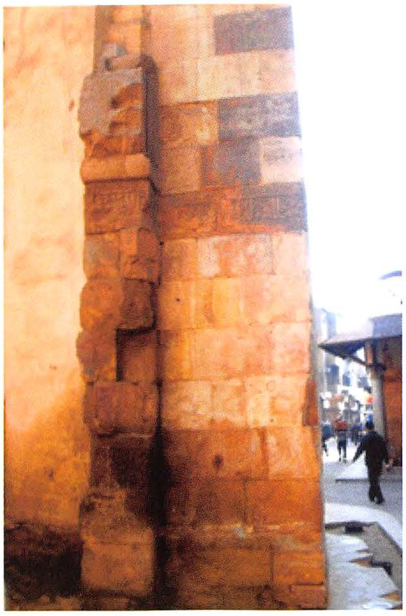
In addition to these deterioration mechanisms, there are also natural disasters (earthquakes, volcanos, floods, etc.), and man-made deterioration, which is not the subject of this scientific work.

Due to the diurnal and seasonal variables of air temperature in the surroundings of the historical buildings built of limestone, severe differential expansion and contraction of mineral constituents are created which result in exfoliation and fracture of stone. The stone's mineral constituents will then lose their cohesion and these mineral constituents will be exposed to chemical damage in these cases because most chemical reactions proceed more rapidly as the air temperature increases. Under these natural conditions most of the limestone blocks of the historical buildings in the Egyptian deserts (Giza pyramids) are seriously affected. Scaling, flaking and crumbling are also considered common deterioration phenomena on the surfaces of these stones.

4.1 Relative Humidity Variations

The relative humidity changes diurnally, and seasonally in the surrounding areas, and are considered to be one of the main sources of moisture, which plays a key role in promoting the fracturing and weathering of monumental limestone. Water penetrates into the porous limestone through pores and micro cracks and causes serious mechanical stresses either by hydration or subsequent crystallization of soluble salts.

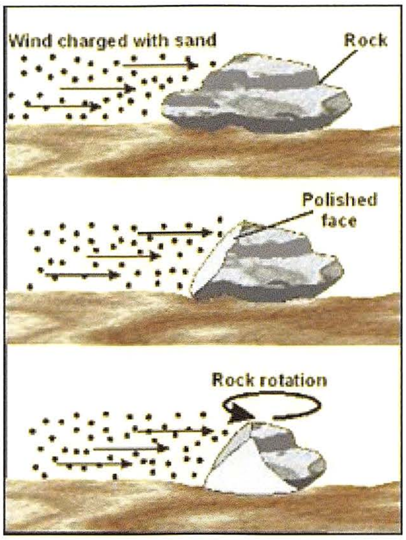
During the humid seasons (summer and winter) in Egypt many biological species grow extensively on the wet limestone blocks of the historical buildings in lower and Upper Egypt. In addition, periodical heavy crystallization of salts was also noticed on the surfaces of this type of stone, and porosity of the monumental stones affect salt weathering because salts commonly crystallize in larger pores first for thermodynamic reasons. Sodium chloride and calcium sulphate, are hydrates that dehydrate relatively easily in the response to changes in temperature and humidity.



4.2 Wind Erosion

Wind erosion is a very common deterioration phenomenon in the monumental stones of the historical buildings located in the desert area, which are exposed directly to wind direction.

Sand particles, which are harder than the mineral constituents of monumental limestone, cause disfigurement and pitting of the stones, which lose big amounts of their minerals especially in the windy seasons in Egypt (from April to July).



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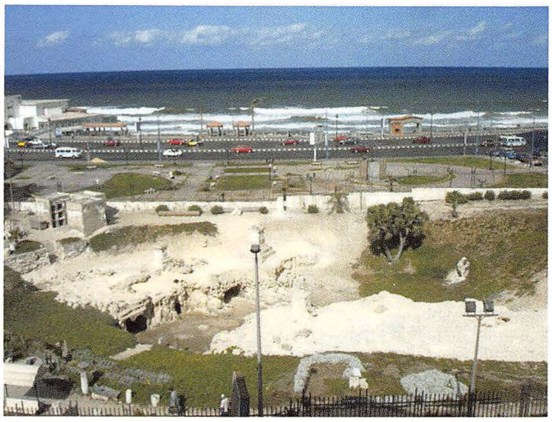
The Giza Sphinx is full of grooves, cracks and is seriously exfoliated in its western part due to the action of the Khamaseen wind which commonly bring with it huge amounts of sand and dust from the western desert.

Wind as a transport factor for other forms of deterioration plays an active role in the deterioration of monumental limestone. The northern wind in Egypt is responsible for transporting the sea spray of the Mediterranean Sea to the Greco-Roman tombs and the other historical buildings in Alexandria. The stones of these buildings seriously deteriorated due to the action of soluble salts (mainly chlorides).

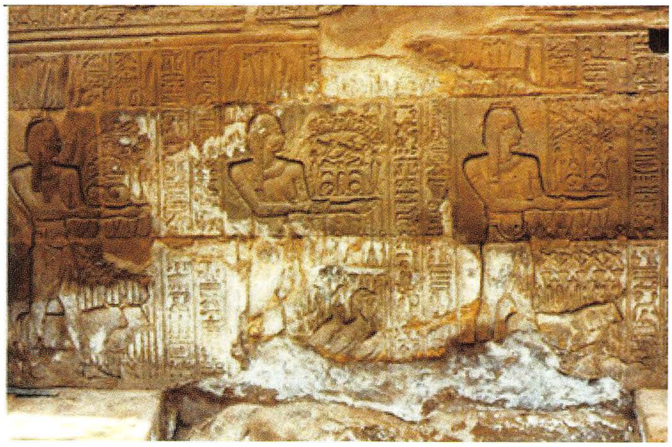
Wind coming from industrial and crowded cities such as Cairo where there are many cars and trucks, which is responsible for the deterioration of the historical buildings in this city. Air pollutants (gaseous, solid and liquid) cause the unpleasant grey and black layered appearance of the stones of these buildings. Moreover, the acids of gaseous pollutants cause serious damage to the mineral constituents of these stones.



4.3 Acidic Rain Water

Acidic rain water is one of the atmospheric parameters which cause severe damage to the carbonaceous building materials of the historical buildings, especially those located in coastal regions.

This kind of water is commonly acidic and corrosive because it contains soluble acids of natural and industrial gases (carbon dioxide, sulphur dioxide, etc.). Carbonate rocks are attacked and show the formation of whitish, hard, crystalline salts which scatter on the surfaces of these rocks.



On the other hand, rain water penetrating into the monumental limestone causes the dissolution of its mineral constituents, and transports the mineral constituents to the surfaces of these stones to develop a hard crust of these minerals mixed with salts that readily produce a very common deterioration phenomenon which is called "honey comb" weathering.

4.4 Solar Radiation

Solar radiation affects the monumental stones in the desert regions especially during the summer season. Radioactive heating and cooling the surfaces of these stones will result in micro cracks and the movement of soluble salts onto these surfaces or under them.

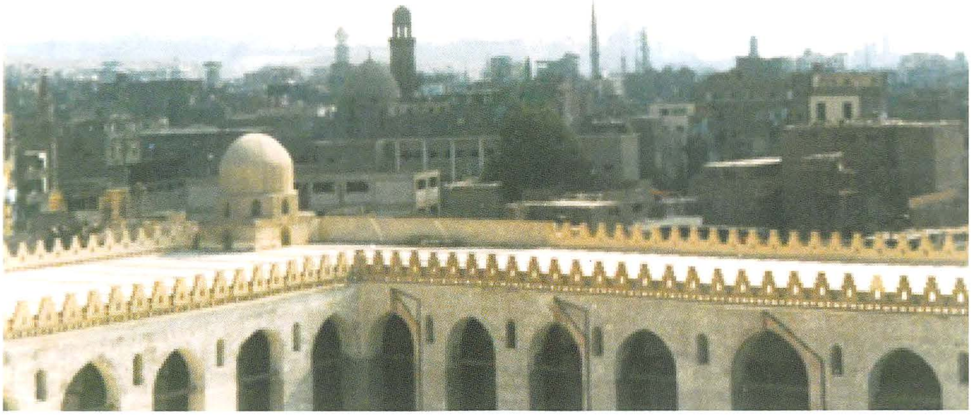
The ultra-violet light in solar radiation causes the change of color in the painting layers in some pharaonic tombs at Luxor in Upper Egypt.

Thermal cracking is observed in these tombs due to the sharp variations in air temperature (day and night) in summer.

4.5 Air Pollution

Air pollution is considered the most severe factor causing serious damage to the carbonaceous building materials used in the historical buildings. Winkler noticed that the deterioration rates seriously increased in these buildings due to the air pollution in the last 60 years.

Both wet and dry pollutants cause significant damage to the limestone blocks used in the Coptic and Islamic buildings in Cairo, which is considered a highly polluted city because it is crowded with cars and industrial sources.



The highest concentration of air pollutants commonly occur at night in some cases and in some cases during the day time.

Although dry pollutants are slower in destructive action than wet pollutants, they have more continuous effects than wet pollutants. On the other hand, the dry pollutants (dust, soot, solid particles, and black carbon) play a dominant role in the oxidation of gaseous pollutants and they also cover the surfaces of stones with black layers that are usually mixed with crystalline salts.

The rate of deposition of Solid pollutants depends on:

1. Porosity and roughness of the stone's surface
2. Motion of solid pollutants towards the surface
3. Evaporation and condensation of water vapor

The precipitation of pollutants on the stone surface will be of big quantities on the coolest parts of this surface than on the warm parts, and the condensation on this surface will increase these quantities. In this case these pollutants will have a better chance of adhering and soluble trace gasses will be more readily captured.

The gaseous pollutants which are produced from various industrial activities and traffic are more harmful than other pollutants on carbonaceous materials (mainly limestone and marble) because these pollutants are transformed in aqueous phases into acids.

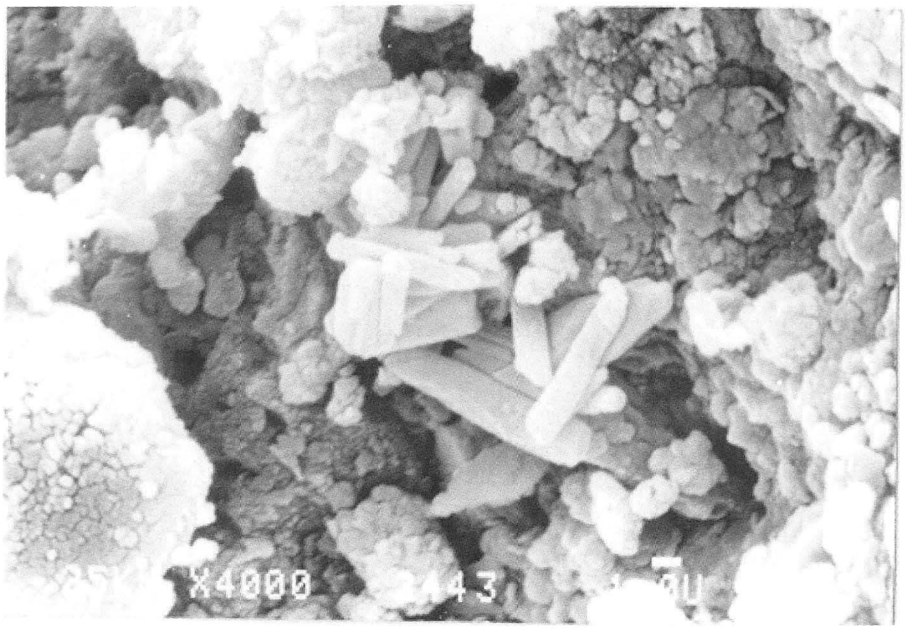
Scientific studies have shown that SO_2 is the primary pollutant involved in the sulphation of carbonaceous building materials:

$$CaCO_3 + SO_2 \xrightarrow{H_2O} CaSO_4 . 1/2\ H_2O \quad CaSO_4 . 2H_2O + CO_2$$

In the pH range of atmospheric droplets between pH 3 and 6, SO_2 is 90% dissolved and the formation of sulphuric acid increases the acidity of the droplets and stops at pH values below 2. This strong acid plays an active role in the deterioration of the limestone blocks of the historical buildings in Cairo because as a result to the reaction between this acid and calcium carbonate, the principal mineral of limestone calcium sulphate is formed.

The major crystalline salt presenting on or below the surfaces of limestone blocks.

The SEM micrograph show that the mineral constituents are seriously deteriorated due to the sulphuric acid.



4.6 Groundwater Effect

Groundwater combined with the salts weathering are considered very harmful deterioration factors to the monumental limestone.

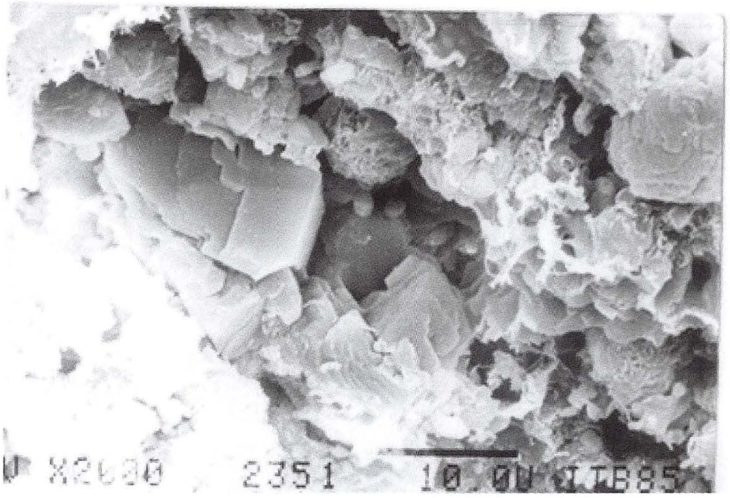
The chemical composition of ground moisture is highly variable because this kind of water is considerably rich in ingredients from sources such soils, rain, water, microorganisms, acid of gaseous pollutants, and salts from different sources, etc.

Ground water moves from the soil on which the historical buildings were built upward into the walls of these buildings by capillarity action. The height of this water in the walls of these buildings is governed by the atmospheric conditions in the surrounding air temperature as well as the porosity of the building material, and often this height ranges from a few meters to 10 meters or so.

The soluble salts are carried by ground moisture and tend to recrystallize on or below the surfaces of the building materials after the evaporation of moisture. A wet salty line can develop, which is often associated with a white rim of efflorescence and crypto florescence beneath these surfaces.

Most of these salts are hygroscopic salts which are able to absorb more moisture from the humid air in the surrounding areas where there is often 90% relative humidity. The masonry that contains 4% salt can retain 22% water.

As it was previously mentioned the lower parts of Giza Sphinx seriously deteriorated due to the infiltration of saline groundwater which causes the deformation of calcite crystals and the recrystallization of salts (mainly calcium sulphate and sodium chloride) leading to the collapse of the physical structure of limestone.



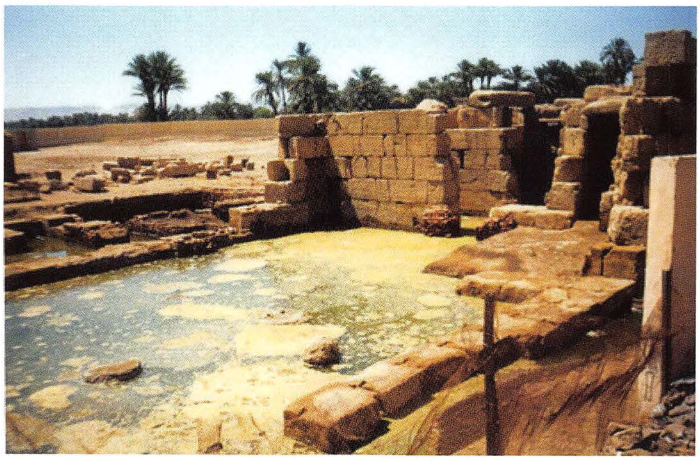
The pharaonic and Ptolemaic temples in Upper Egypt have become exposed to major problems especially in the distance from Luxor to Aswan after the high dam was built, which led to changes in the irrigation system in these regions and an increase in the height of the ground water table under the foundations and in the walls of these temples.

The absorbed water eventually evaporates from the stones leaving an efflorescence of hygroscopic nature scatterings on the surfaces of these stones.

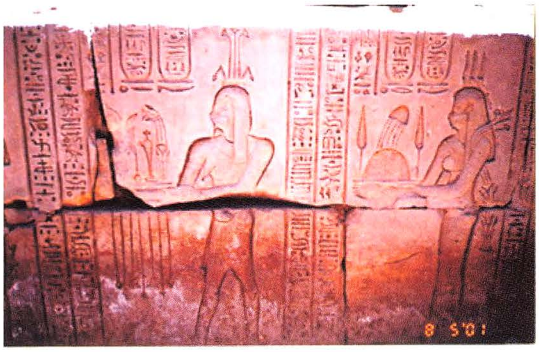
The deterioration of these stones develops in different ways as discussed by Berthelin as follows:

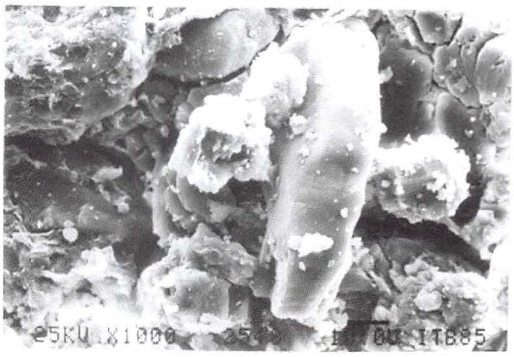
1. Organic and/or inorganic acids produced by the species
2. Chelating substances
3. Alkalis
4. Enzymes
5. Pigments

The lower parts of the historical buildings in the Nile Valley are continuously attacked by microorganisms due to the infiltration of ground water in these regions, which always keeps the surfaces wet. These wet surfaces are places for the growth of these microorganisms.



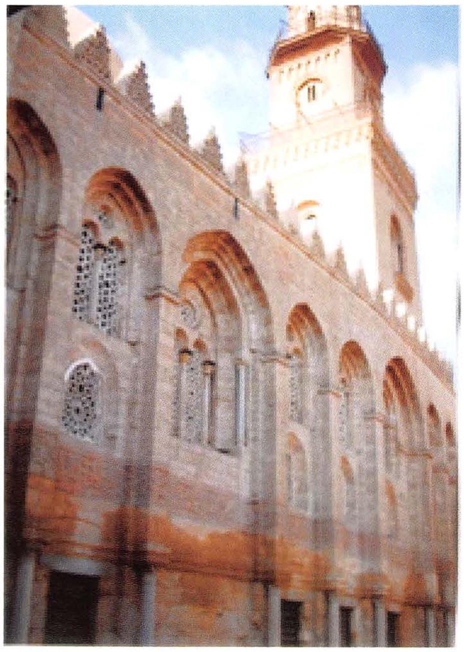
The colonies of various microorganisms (mainly algae and fungi) have been extensively scattered on the limestone blocks used for building the Cairo walls in 11th century. These microorganisms have contributed greatly to the deterioration of mineral constituents and the structure of these stones.

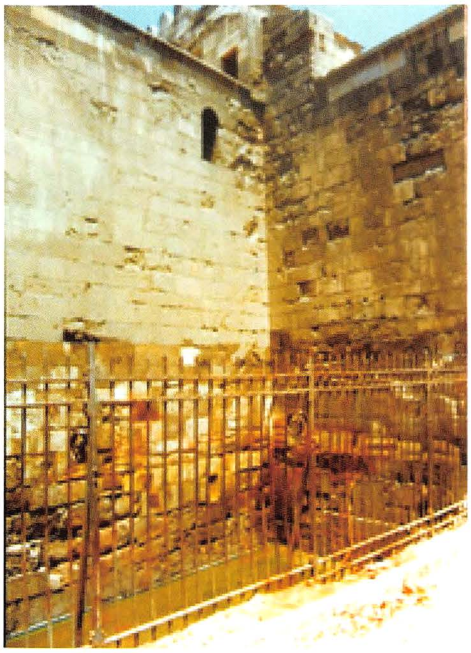




Extensive programs of restoration and treatment has been undertaken in recent years to minimize the water table under the foundations of these temples, which leads to the dryness of the walls.

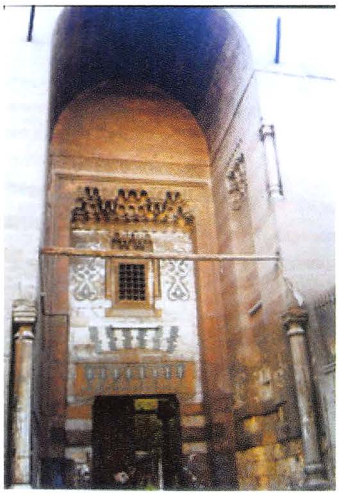
The historical buildings in Cairo were subjected to an attack of ground moisture before the performance of dewatering plans, which have been carried out in the last ten years. The water table was very high in the walls of these buildings due to the high porosity of limestone used in them.

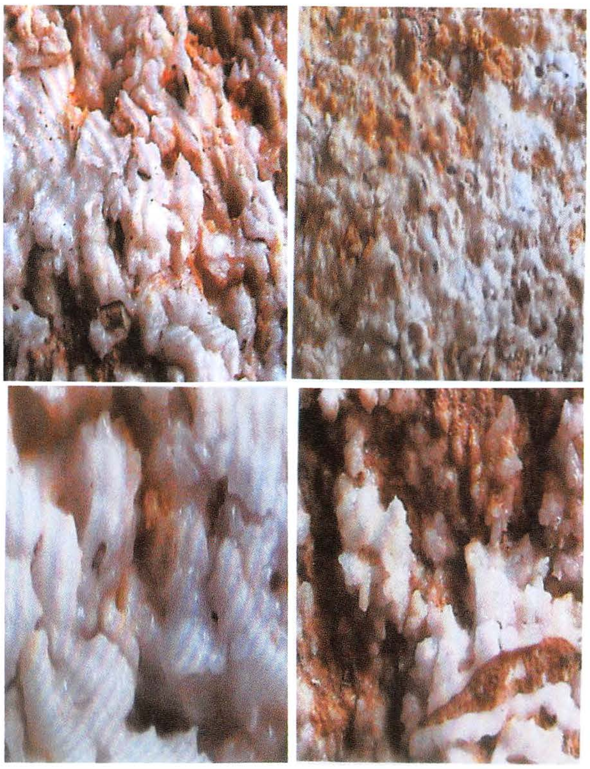




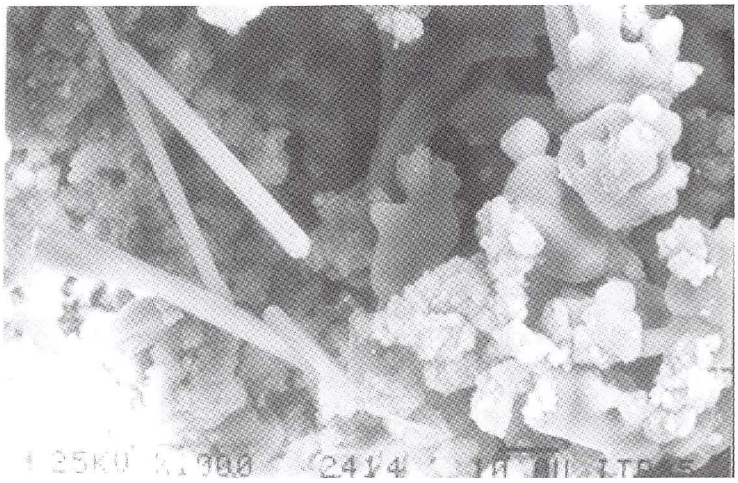
The absorbed saline solution is the main source of the crystalline salts, which form a thick hard crust on the walls of these buildings.

The most common crystalline salts are sodium chloride and calcium sulphate, which are responsible for the disintegration of the limestone blocks.





Due to the continuous crystallization and recrystallization of these hygroscopic salts inside the limestone blocks, these blocks have become seriously exfoliated, fragile, and incohesive.



4.7 Bio-Weathering

Bio-weathering causes severe damage to the carbonaceous building materials, and is as dangerous as other physiochemical weathering factors because microorganisms and organisms can cause not only aesthetic deterioration, but also a progressive loss of cohesion and transformation to the mineral constituents of these materials.

As discussed by Caneva and others, biodeterioration of natural materials is not considered as an isolated phenomenon but it always occurs with other physiochemical deterioration factors.

Microorganisms and organisms are affected by some natural and artificial parameters in their surroundings. High air temperature affects biological growth, which increases up to a certain level due to the acceleration chemical reactions.

High air temperature and relative humidity are considered active vehicles for the bio deterioration of natural materials. Light is the primary source of energy necessary for the growth of all photo synthetic organisms and even the non-phototrophic species can be affected in different ways by light as mentioned by Caneva and others.

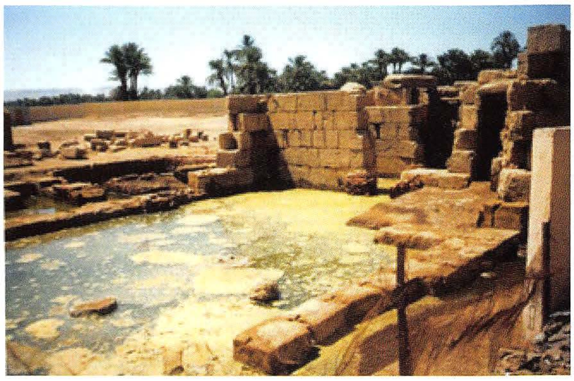
Air pollution affects the growth of organisms and micro-organisms. Some species, especially mosses and lichens, are used as pollution indicators and their numbers are good indicators for sulphur dioxide levels.

Organisms and microorganisms cause physiomechanical (disintegration) and chemical (decomposition) to the carbonaceous building stones.

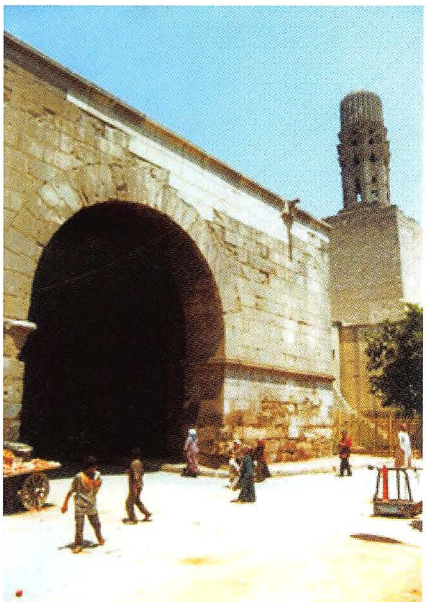
The deterioration of these stones develops in different ways (Berthelin):

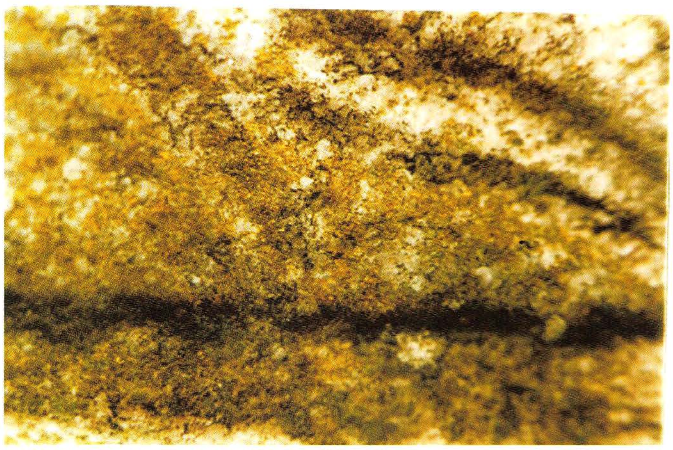
1. Organic and/or inorganic acids produced by the species
2. Chelating substances
3. Alkalis
4. Enzymes
5. Pigments

The lower parts of the historical buildings in the Nile Valley are continuously attacked by microorganisms due to the infiltration of ground water in these regions. The historical buildings have wet surfaces which are considered suitable places for the growth of these microorganisms.

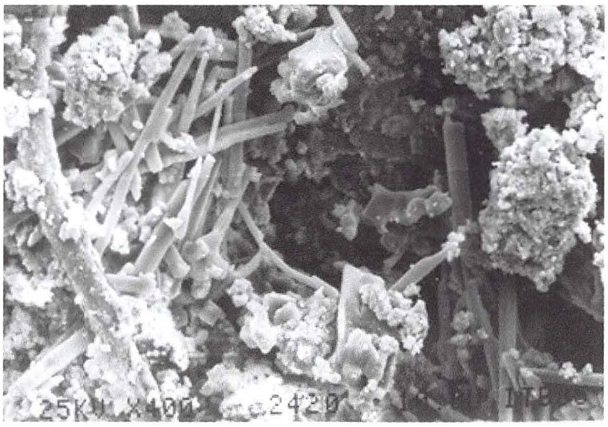


The colonies of various microorganisms (mainly algae and fungi) are extensively scattered on the limestone blocks used for building walls in Cairo in the 11th century.

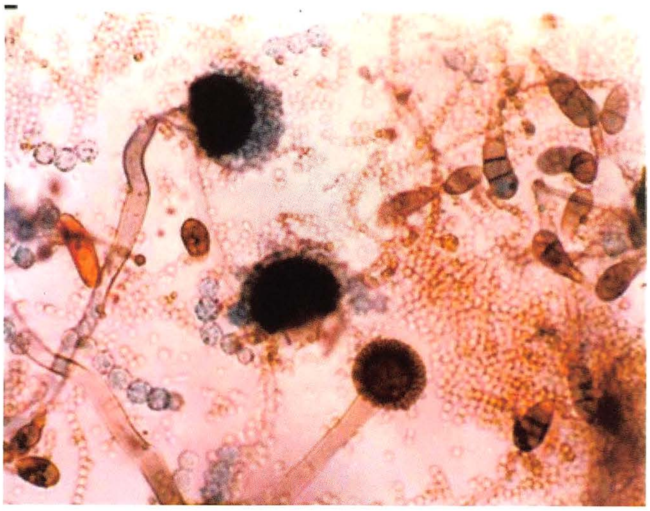




A SEM electron micrograph showed fungal species that had deeply penetrated into these blocks and caused serious damage to the mineral constituents and the physical structure of limestone.



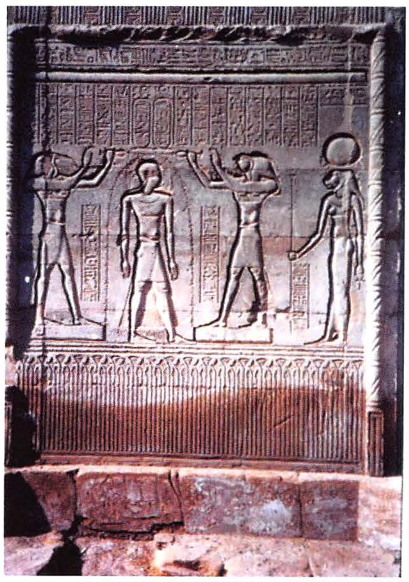
The light micrograph also showed the same effect in a sample of limestone.



Most of these species produce several acids such as carbonic and sulphuric acids which cause serious damage to the calcium carbonate of limestone, which is transformed into calcium bicarbonate due to the carbonic acid. Carbonic acid is then transformed into calcium sulphate due to the sulphuric acid.

The bacterial attack is always of chemical effect where it causes the formation of a black crust, a powdering, and exfoliation of carbonate materials.

Biological calcium sulphate (gypsum) is a very common salt on the surfaces of limestone of the historical buildings in Egypt due to sulphuric acid produced by various species of microorganisms.



5 Conservation

Conservation of monumental stones is considered a scientific strategy which gas developed greatly in recent years due to the continuous efforts of conservators and scholars all over the world.

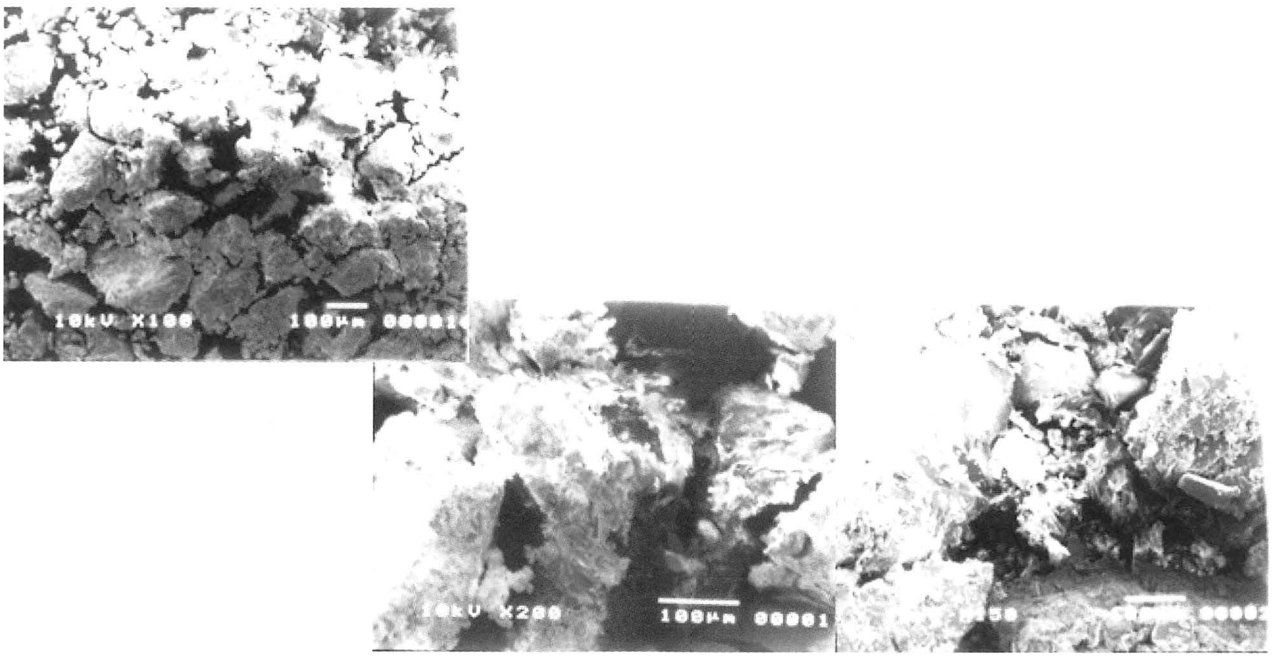
To conserve our cultural heritage it is essential to have a scientific community to elaborate innovative strategies, to exchange information and expertise, and to experiment with new techniques and materials which are effective and useful for conserving and preserving from sources of deterioration our human heritage.

For this reason we suggest that the European Union and the Union of the Mediterranean Basin should exploit any possible means to increase the exchange of visiting conservators and scientists between Europe and Middle Eastern countries. Technical support from the institutions of conservation and restoration of historical buildings and works of art in these countries is also needed.

As mentioned previously, the main target of the conservation processes is to prolong the life of archaeological materials by using effective and durable materials and methods of cleaning and the polymers which play a key role in the consolidation of the incohesive materials of buildings used in the historical buildings.

Treatment of monumental stones with polymers depends on the state of deterioration and the physiochemical characteristics of these stones. To do this various analyses from the samples collected from the deteriorated stones by means of SEM-EDS, OM, and other methods of investigation are necessary.

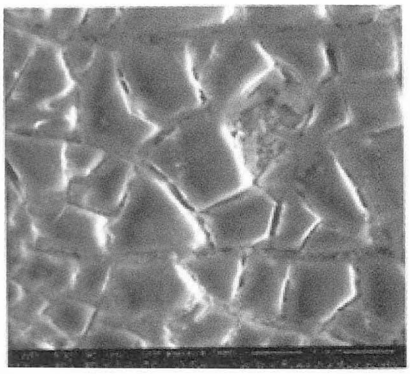
The SEM morphological examinations performed on some stone samples collected from some pharaonic buildings built of limestone showed that the physical structure of this type of stone has collapsed due to the severe effects of physiochemical deterioration factors and the crystalline salts, mainly hydrated calcium sulphate, which exist extensively in the matrix of the stones.

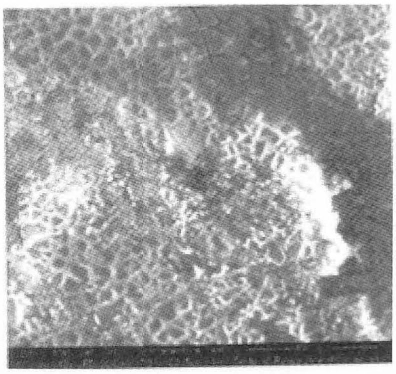


To consolidate the deteriorated samples, two types of polymers which are widely used in the consolidation of incohesive porous limestone and sandstone were used.

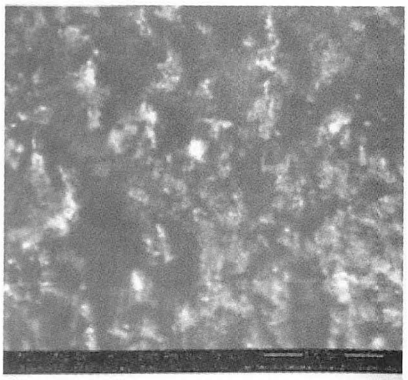
1. Paraloid B72, which is ethyl methacrylate, and methyl acrylate, were dissolved in acetone (from 3% to 5%).
2. Wacker OH 290, which is a Tetra-ethoxysilane, was also used.

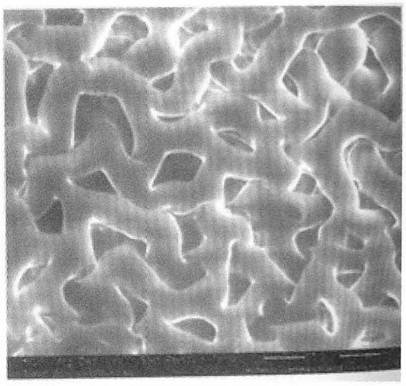
SEM morphological examination showed that Paraloid B72 solution deeply penetrated into the deteriorated samples forming net chains on the surfaces of these samples.





Wacker OH 290 was an effective polymer in consolidating the sandy limestone samples which homogenously penetrated into these samples forming net chains without causing any changes in the original color of these samples.





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