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Original article

ASSESSMENT OF DECAY CAUSES OF VENUS MARBLE STATUE IN MERIT AMOUN PARK –AKHMIM, EGYPT

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Abstract:
This paper discusses the environmental conditions affecting archaeological statues in Egypt, highlighting the decaying factors, mechanisms, and forms identified through documentation and analytical methods. Akhmim, one of the oldest Egyptian cities in Sohag, Upper Egypt, is home to several statues that suffer from decay due to two primary causes: environmental factors and harmful cultural practices. This study presents the results of scientific analysis conducted on one of the most significant decay factors impacting the Roman marble statue of (Venus) at the Ramses II Temple in Akhmim. The goal is to understand how a densely populated environment contributed to the material's degradation. Documentation methods including weathering mapping and the use of the 3D zephyr 6.009 program, as well as Close Inspection and Complimentary Survey (CICS), utilizing both manual and electronic measurement tools to identify evidence of different past human activity in the study area. Furthermore, samples taken from the statue and a nearby well were analyzed using various techniques, including, digital and petrographic microscopy, Scanning Electron microscope coupled with Energy Dispersive X-ray spectroscopy (SEM-EDX), X-ray diffraction (XRD) and Atomic Absorption spectroscopy (AAS). Results revealed that the statue is primarily composed of calcite as an essential component of marble and minor amounts of dolomite. The main deterioration products were identified as halite salt and clay minerals, which result from numerous decaying factors and relevant mechanisms attributed to human activities, air pollution, and the aggressive impact of groundwater and domestic wastewater. Additionally, alternative cycles of drying and wetting were found to play an essential role in the ongoing deterioration.

1. Introduction

Upper Egypt is renowned for its famous pharaonic stone monuments, which reflect the unique creative achievements of humankind in ancient times [1]. These monuments are significant for both the cultural identity and economic situation of Egypt [2,3]. However, they have suffered weathering and damage over time [4,5]. The case study examined here is a headless marble Greco-Roman female statue located in the archaeological park of Akhmim, one of the eleven main cities of Sohag Governorate. This governorate lies in the middle part of the Nile Valley, approximately 460 km south of Cairo, between latitudes 26º 6` 54`` and 27º 9` 26`` N and longitudes 31º 13` 18`` and 32º 36` 50`` E, fig. (1-a) covering a total area of about 11022 km^2 [6,7]. The study area itself (*Akhmim district*) is located east of the River Nile in Sohag Governorate between longitudes 31º 35` and 31º 55` E and latitudes 26º 30` and 26º 38` N. [8,9], fig. (1-b). It spans an area of approximately 11 km^2. The length of the River Nile within the study area reaches 125 km, and the width of the valley ranges between 16 and 20 km [10]. The Roman female statue under investigation, fig. (1-c), was excavated in 1984-1985 near its current location [11]. It was selected as a case study due to the following reasons: *) *Remarkable sculptural features, including clearly defined folds in the drapery*. *) *Type of marble used*, *) The depiction of *loose –fitted garments, which are characteristic of the Greco-Roman sculptural style*. Due to its beauty and refined craftsmanship, the statue was called "Aphrodite" or "Venus" after the Roman goddess associated with love and beauty [12]. The statue is carved from white marble and stands 2.2 m tall. It is a headless marble statue, located within the Akhmim archaeological park, positioned approximately 20 m west of the Merit-Amon statue and 20 m east of the main well. The statue is mounted on a limestone pedestal, measuring 116 cm in width and 70 cm in height.

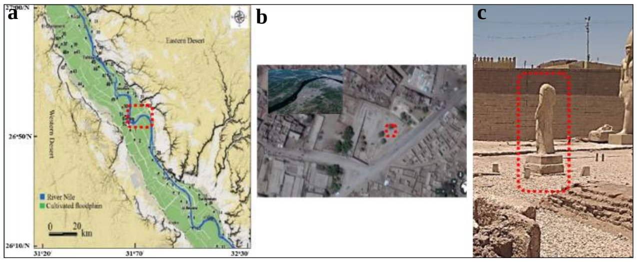

Figure (1) **a.** map of the study area (*After: Elkordy, et al., 2019*) [8], **b.** Google map of the study area (*within red circle*), **c.** the Roman statue within *Merit-Amoun* archaeological park.

2. Condition Assessment of the Study Area

2.1. *Environmental situation*

2.1.1. Topographical features

The topography of the study area refers to the slope variability of the land surface; the degree of this slope determines the extent of runoff, where topographical changes have an impact on the onset of runoff [13]. The spatial distribution of surface topography and infiltration characteristics impacts both surface runoff and hydrological connectivity in response to single rainfall events [14]. Topography can significantly impact the dispersion and diffusion of air pollutants by altering meteorological conditions [15]. Pollution levels tend to be higher in valleys than in areas of higher ground due to interactions between airflow (winds) and the Earth's surface which limit pollutant dispersion [16]. In the study area, the topographical features, fig. (2), range in elevation from a minimum of 51 m to a maximum of 418 m, with an average of 141 m [17]. Moreover, the archaeological city lies beneath the modern city of Akhmim [18]. According to Rawlinson [19], the statue under study was part of a single temple complex, featuring a stone and mud brick enclosure, two colossal statues, and other artifacts, including a Roman statue that was once considered one of the wonders of the ancient world [20].

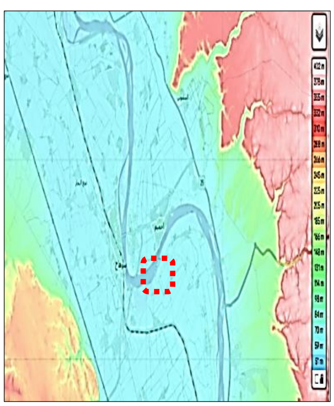

Figure (2) topographical map of Sohag area (*After: https://en-gb.topographic-map.com/map-f9st3l/Sohag/*).

2.1.2. Geological framework and hydrogeological setting

Sohag governorate, located in Upper Egypt, spans approx. 125 km along the Nile Valley, with an average width ranging between 16 to 20 km. It is bordered by the Red Sea Governorate and Eastern Desert, to the east and by the New Valley Governorate and Western Desert to the west [21]. Geologically, according to Said [22]; Elbeih, et al. [23], the geological formations of Akhmim consist of rock ranging from Lower Eocene to *Thebes*, *Muneiha*, *Issawia*, *Qena* and *Dandara formations*, in addition to *flood plain sediments*, fig. (3-a). Hydrogeologically, the availability of groundwater sources include the multiple water sources that feed and affect the level of the aquifer, fig. (3-b). They include *rainwater*, *Nile water*, and *man-made sources*, such as domestic wastewater and agricultural drainage [24,25]. These sources depend on water interactions with rocks and other waste in ambient areas [26]. A critical concern in this context is the adverse effects of groundwater, which moves horizontally between the Nile and adjacent grounds, driven by elevation differences from higher to lower levels [27]. According to Ahmed & Ali [28] and Gedamy [29], this groundwater is increasingly threatened by pollution from urbanization, agricultural chemicals, and reuse of wastewater for irrigation. These factors can significantly affect the preservation of artifacts within the Akhmim Archaeological Site. The seasonal fluctuations of the Nile- from the flood season (July-Dec.) to the dry season (Dec.-Jan.)- lead to elevated groundwater levels because of post-irrigation drainage, causing more decaying features [30]. In addition, the aquifer levels increase with the low slope in the surrounding areas, depending on some variables, such as expanding faults, cracks, and gaps in the surrounding and bedrock that ultimately increase wastewater absorption [31]. According to D′ossat [32]; El-Gohary [33], metrological conditions are among the most significant external factors contributing to the deterioration of stone buildings, particularly depending on their geographical location. In our study, the main climatic parameters affecting the site, tab. (1), include temperature (*T*), relative humidity (*RH*), windblown particles (*WB*), and rainfall (*RF*), all of which can contribute to material decay over time.

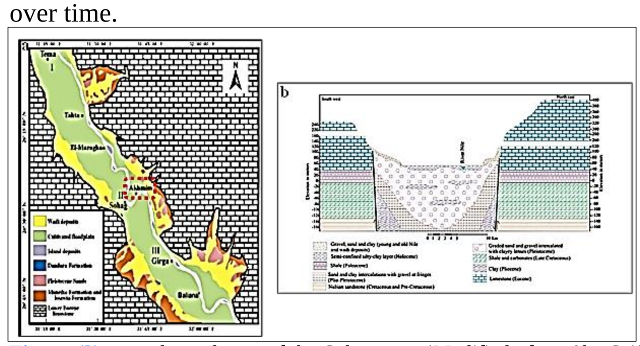

Figure (3) **a.** geological map of the Sohag area (*Modified after: Abu Seif & El-Shater, 2010*), **b.** groundwater Metrological conditions

Table (1) rates of metrological elements through 30 years in Akhmim (*After: Egyptian Metrological Authority*).

Elements	Years	Winter	Spring	Summer	Autumn
Temperature °C	1991-1998	15.37	25.29	37.31	25.64
	1999-2009	16.82	25.05	36.97	24.83
	2010-2019	16.2	25.35	37.36	25.45
Relative Humidity %	1991-1998	56.27	36.27	38	47.18
	1999-2009	58.3	38.8	38.4	49.6
	2010-2019	55.7	34.8	37.4	48.3
Rain Fall mm	1991-1998	0.06	0.13	0	0.03
	1999-2009	0.07	0.05	0	0.02
	2010-2019	0.05	0.05	0	0.02
Windblown Knots	1991-1998	3.97	4.3	4.33	3.57
	1999-2009	3.72	4.19	3.96	3.32
	2010-2019	4.21	4.63	4.03	3.52

2.2. *Dominant decaying factors*

2.2.1. Pollution and pollutants (AP)

Air pollution involves change in the chemical, physical or biological characteristics of the environment [34,35]. In our case, the main effects of *AP are* attributed to dry depositions [36], including gases (SOx and NOx), dust, and surface crusts. In the same context, the presence of gases is owed to the effects of sulfur oxides (SO_x) originating essentially from various industrial activities and nitrogen oxides (NO_x) that are emitted by vehicular traffic, tab. (2-a & b). These deposits and air-borne particles accelerate chemical reactions on marble surface, contributing to material deterioration through acid formation and crust buildup, as argued by Charola [37].

Table (2-a) concentration average of gases and dust (*After: Samir, 2017*).

Types of concentration Rate	SO_2 (µg/m$^{3)}$	NO_2 (µg /m$^{3)}$	TSP (µg /m$^{3)}$	Dust fall (g/m^2/month)
Highest monthly	73.33	66.68	192.70	92.25
Lowest monthly	4.18	9.85	41.60	23.86
Highest quarterly	49.04	37.11	113.95	67.27

Table (2-b) analysis of the chemical components of dust fall (*After: Samir, 2017*).

Components	**SO_4**	**Cl**	**NO_3**	**NH_4**	**NO_2**
Percentage	14.21%	4.72%	1.93%	0.57%	0.050%

2.2.2. Salt weathering (SW)

Salt weathering is one of the most severe threats to preserving cultural heritage built from porous materials [38]. The growth of salt crystals within confined stone pores generates internal forces that damage the building's material due to crystallization pressure [39]. In our case, the statue is affected through an aggressive mechanism caused by saline water transported via the porous limestone pedestal, which then rises to the statue through capillary action. This water is characterized by the presence of some common salts found in Egyptian soils, such as sodium sulphate (Na_2SO_4), sodium chloride (NaCl), potassium nitrate (KNO_3), and potassium chloride (KCl) [40,36]. The degradation process resulting from salt decay occurs directly through complex mechanisms that depend on other factors, especially alternative wetting/drying cycles, as well as heating/cooling cycles [41].

2.2.3. Human damages (HD)

According to some specialists [42-45], human activities or anthropogenic activities, while capable of creating masterpieces, can destroy landmarks simultaneously. These defects are not only complex but also have long-lasting consequences. These are typically triggered by the side effects of industrialization, urban sprawl, and the resulting population growth. In this case, the archaeological site is located within a densely populated urban cluster, where harmful habits such as graffiti, ritualistic blood maculation, and littering have directly contributed to the statue's deterioration.

3. Materials and Methods

3.1. *Field study*

Architecture elements and sculptures made of marble are susceptible to various weathering processes, as argued by Amoroso and Fassina [46] and Fassina, et al. [47]. According to Kühlenthal [48] and Kühlenthal and Fischer [49], close inspection and complimentary survey (CICS) with manual and electronic measurements techniques, are essential for identifying evidence of different past activities in the study area. These methods are particularly useful for studying the entire landscape [33], and for assessing immovable structures through three critical stages identification, evaluation, and documentation of past treatments.

3.2. *Samples*

Samples were collected from different parts of the statue, with detailed information regarding type, dimensions, altitudes, and orientation), as listed in tab. (3) and fig. (4)

Table (3) detailed description of different samples collected from the statue under study

Samples	Kind	Measure (cm)	Altitudes (cm)	Orientation	Purpose
1	Fragment	2×2	10	N	EDX XRD PLM SEM.
2		2×1	30	N	
3		5×1.5	10	E	
4		4.5×2.5	100	W	
5		3.5×2	200	S	
6	Solution	1 liter	3 m. from the well inside the study area		AAS

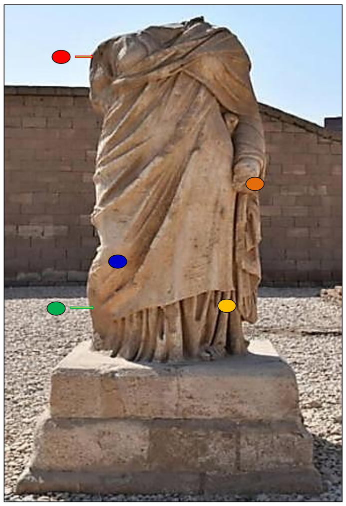

Figure (4) sampling locations ● (S-1 N), ● (S-2 N), ● (S-3 E), ● (S-4 W) and ● (S-5 S),

3.3. *Investigations*

According to El-Gohary [33], the samples were investigated by several techniques. A *Roshs 1600X 2MP zoom microscope 8 LED digital microscopy* (*DM*) was used to determine the visual change on the surface of marble samples, such as variations in color and texture. Petrographical microscope examination (*PM*) was adapted using a BEL photonics microscope model 220 V/50Hz ser. no. 563810, connected to canon power shot camera model A650 IS IMAGE stabilizer to identify the petrological characteristics of the samples. Furthermore, a *Quanta FEG250 scanning electronic microscope coupled with an energy-dispersive X-ray spectrometer (SEM-EDS)* was utilized to investigate the morphological features of damaged layers. In the same context, the samples were analyzed to define their chemical composition using a *Bruker D8 X-ray diffraction* (*XRD*), equipped with a copper line focus X-ray tube, producing Kα radiation, which was used to assess the mineralogical composition of the marble samples. Finally, a Perkin Elmer AAS Analyst 400 - "Unico-1200" atomic absorption spectrometer (*AAS*), located in the Geology dept., Faculty of Science, Sohag Univ., was employed according to El-Gohary and Redwan [50] to define the water quality (hydrochemical characteristics), as well as the types and concentrations of salt content present in the rock samples, by testing extracted water solutions prepared from the collected rock samples.

4. Results

4.1. *CICS decaying map*

Based on the results of CICS, it could be asserted that the statue (case study) has been exposed to many severe decaying factors. These are caused by synergistic chemical and physical mechanisms that have led to many decaying symptoms, such as *fading* or *discoloration*, *edge loss*, *bird scratches* and *droppings*, *surface crusts*, *detachments*, *cracks*, *granular disintegration*, *dust accumulation*, *soiling*, *salt efflorescence*, as well as *pitting* and *human induced damage*, as shown in fig. (5).

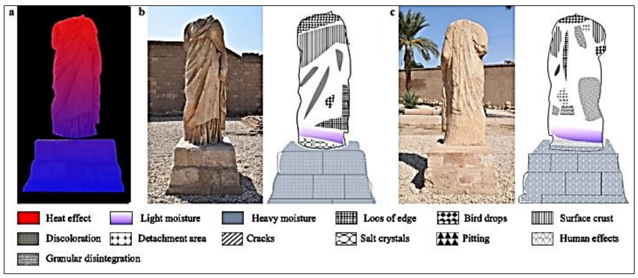

Figure (5) weathering map of the statue **a.** general effect of *temperature* & *moisture*, **b.** the front-side decay symptoms, **c.** the back-side decay symptoms.

4.2. *Digital microscope*

The results of the digital microscope revealed several surface alterations in the examined samples. These include disintegrated *calcite grains*, *color change* from the original white to a white tinged with pale brown hue (decayed color), *salts*, *discoloration* and the presence of *hard crusts. These crusts are* composed mainly of precipitated grains mixed with gaseous pollutants and airborne ash from hydrocarbon materials characterizing the study area. Additional observations include *grain disintegration*, *dust accumulation*, and general surface *soiling*, affecting the marble, fig. (6).

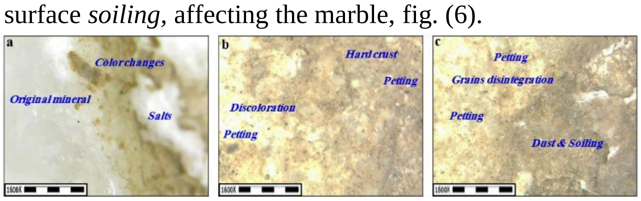

Figure (6) marble samples under digital microscope.

4.3. *Petrographical investigation*

Petrographic investigation confirmed that the marble samples were composed essentially of calcite, and low concentrations of dolomite (according to the analytical results mentioned in section 4.4). Significant to moderate amounts of quartz and orthoclase were also observed. Despite the presence of some variables and anisotropic features in the texture features of the grains, all sections showed a well-developed grain alignment of the grain shapes in all investigated samples. Additionally, the samples surface' showed a massive structural appearance, and increased porosity index and micro-cracks likely caused by degradation due to saline groundwater infiltration, fig. (7).

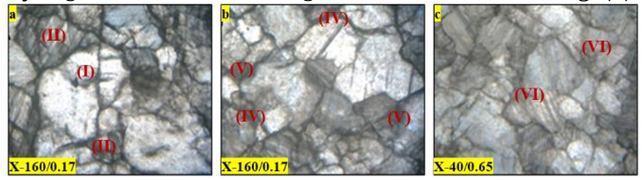

Figure (7) the examination of marble samples under polarizing microscope; **a.** cracks (I) and micro cracks and (II), **b.** clay minerals in quartz grains (III) resulted by the effects of chemical withering process (*confirmed by elemental analysis by EDX*), **c.** fine grains of calcite with low proportions of dolomite (IV), with presence of some cavities (V), and two sets of cleavage (VI).

4.4. *SEM-EDX*

SEM-EDX results illustrated the rise in the main component of marble, i.e., calcium, with an increase in minerals due to its penetration into the sample (*The main elements of calcite and clay, particularly Al, Si, and Fe, were detected by EDX*). Salt deposits on the marble surface, contributed to various structural alterations, including cracks, macro pores, and halite salt as large prismatic crystals, fig. (8). SEM–EDX analysis revealed an elevated calcium content, consistent with the primary component of marble. Additional elements such as Al, Si, and Fe, indicative of clay minerals, were also detected.

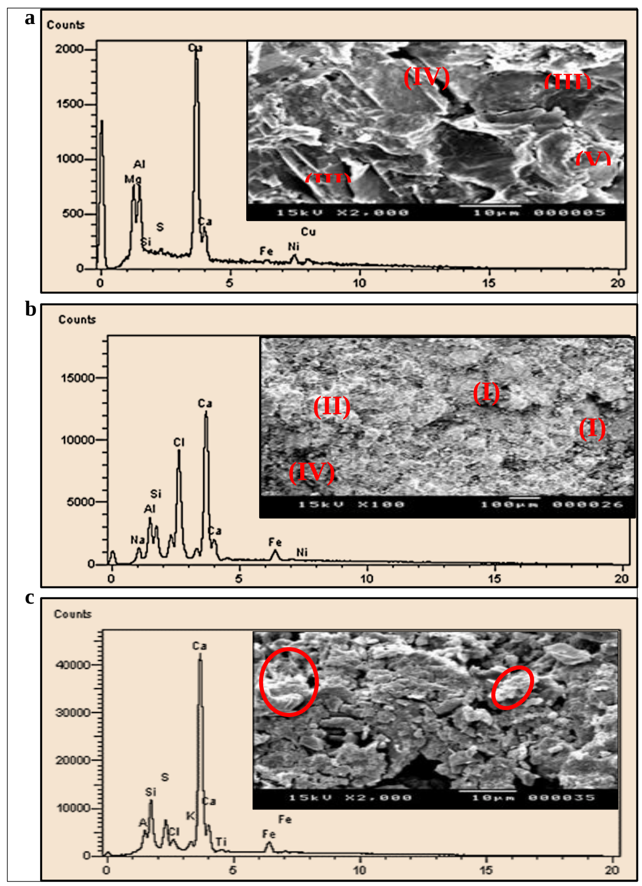

Figure (8) **a.** & **b.** EDX patterns & SEM photomicrograph of deteriorated samples from roman statue with some deteriorated features such as: clay minerals (I), salt deposits (II), cracks (III), macro-pores (IV) and halite crystals (V). EDX patterns; **a.** spot point from a single particle on sample, **b.** from full frame of sample, **c.** proportion of gypsum salt as a deterioration product.

4.5. *XRD*

XRD results illustrated consistent mineralogical compositions across all analyzed samples. For example, the sample taken from the lower part of the statue (***foot*** *sample no. 1 in tab. 3 taken 10 cm from the top pedestal*) contained calcite ($CaCO_3$), as a major component, and dolomite ($CaMg(CO_3)_2$), quartz (SiO_2), gypsum ($CaSO_4.2H_2O$), and halite (NaCl) as minor components, fig. (9-a). The second sample taken from the upper part (***shoulder*** *no. 5 in tab. 3, 200 cm from the top of the pedestal*) showed the same results but with slightly lower concentrations of gypsum and halite, fig. (9-b).

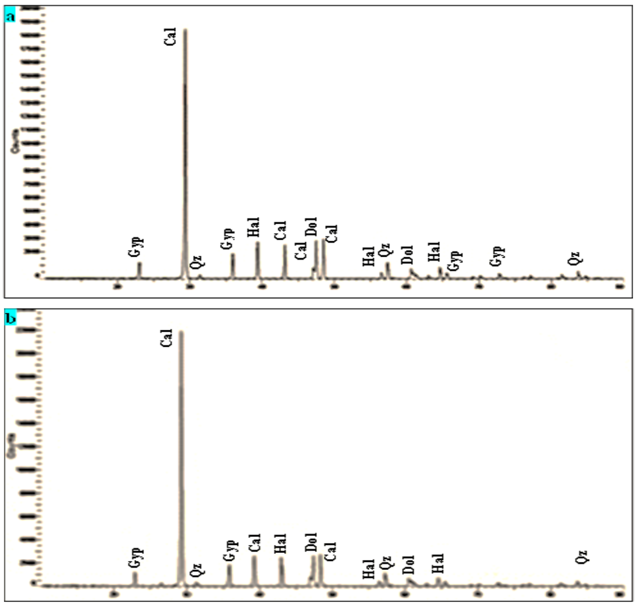

Figure (9) XRD patterns of the **a.** 1st sample taken far away from 10 cm from the top pedestal, **b.** 2nd sample taken far away 200 cm from the top of pedestal

4.6. *AAS*

The analysis confirmed that the chemical constituents were notably varied due to the multi-synergetic effects resulting from the combination of dominating salts in the study area. Furthermore, a very high TDS value (880 mg/l), was detected, mainly attributed to various water sources such as the *River Nile and domestic wastewater from surrounding houses*), tab. (4).

Table (4) analytical results by using AAS and titration analytical methods

Variables	Elements/salts	ppm	Water Origin	
			Salt	***%***
	Ca	104.7	$Ca(HCO_3)_2$	41.53
Cations	**Mg**	41.2	$Mg(HCO_3)_2$	10.92
	Na	101.6	$MgCl_2$	5.77
	K	3.7	NaCl	26.22
	HCO_3	325.4	Na_2SO_4	13.58
Anions	**Cl**	198.5	$NaNO_3$	0.50
	SO_4	84.3	KNO_3	1.46
	NO_3	12.2		
Other Properties		**Total dissolved solids (TDS)** 880		**pH** 9.4

5. Discussion

The Roman Venus marble statue shows extensive deterioration, necessitating a tailored restoration plan. The results indicate that various decay mechanisms affected the monument resulting from a combination of environmental, anthropogenic, and material-specific factors. It is of utmost importance to find the root causes of its decay and evaluate and address them systematically.

5.1. *Decaying mechanisms*

5.1.1. Decay causes due to geographical location (*GL*)

Based on tab. (1), the primary causes affecting the study area are attributed to four main environmental factors: The 1st factor is attributed to temperature fluctuations in this region, characterized by an extreme desert climate. Temperature fluctuations are more significant than in the northern parts of Egypt. In winter, the min. recorded temperature was 14 ºC in the winter of 1998 and 2014, while the summer temperatures often exceed 39 ºC at midday, with such extremes recorded c in 1996, 2000, 2002, 2005, 2016, and 2020 [51]. The 2nd factor is relative humidity *RH* fluctuation in the air, which in the study area is generally below 61 %, with the highest values recorded in winter 2009. In contrast, summer RH levels often drop to 35 % or lower. Such fluctuations cause both light and heavy moisture accumulation on the front and back surfaces of the statue as a physical form, fig. (5-b & c), promoting the development of cracks and internal fissures within the statue due to salt crystallization cycles caused by expansion and contraction [42]. According to Ṡtα̃stnẏ [52], efflorescence is a direct symptom caused by moisture migration and RH variation, due to a clear correlation between stone decay, water, and salt effects. The 3rd is wind blows (*WB)*, maximum wind speed records (WB_{knots}) reached 5 knots in winter 2013, spring 2015, summer 2017, and both summer and autumn 2018. On the other hand, minimum values of 3 knots were recorded in autumn 1995, 2001, 3003 and 2015, and winter 2003. The 4th factor is rainfall (*RF)*. The study area receives extremely low rainfall. The max annual average was 0.04 mm. recorded in winter 1997, whereas the min. annual average rainfall was 0.0 mm. in most other months.

5.1.2. Decay causes due to pollution and pollutants (*AP*)

Table (2-a) presents the types and concentrations of pollutants with air-borne particles and aerosols (gases and dust) that affected the study area. These pollutants contributed to the formation of a surface encrustation or hard crust, primarily composed of gases and air-borne particulates such as SO_2, NO_2, *total suspended particulates*, and *dust fall*. According to Abudlude, et al. [53], the concentration of these pollutants—alongside molecular diffusion and atmospheric turbulence — determines both the amount deposited, as well as the nature [54] and roughness and other properties of the stone in question [55]. In our case, other critical factors exacerbated the visible decaying symptoms, such as stone wetness due to ground moisture, *relative humidity (RH) levels*, condensation, and transpiration accumulating on the statue's surface throughout the day. Such conditions facilitate the reaction between the pollutants and marble [37]. In the same context, the chemical analysis of the dominant dust fall components in the ambient air of the study area, tab. (2-b), revealed the presence of certain gases such as SO_4, Cl, NO_3, NH_4 & NO_2. These sub-stances caused both chemical and physical damage through processes of deposition and absorption, which in turn led to typical acid attacks, especially in the presence of water sources as attested previously by El-Gohary [35] in a similar case.

5.1.3. Decay due to salt weathering (*SW*)

Despite the minor detection of salts shown by XRD results, fig. (9-a & b), salt weathering is considered one of the primary damage processes affecting the marble statue. This is largely due to the aggressive behavior of some salt types dominating the groundwater in and around the study area, tab. (4). According to El-Gohary [56]; Hagag, et al. [57]; Nagy [58], the local groundwater is characterized by the presence of some salts, especially *halite*, *thenardite*, *sylvite*, and *niter* that originated from synergetic water sources dominating the area including *domestic wastewater* and *irrigation runoff*. The degradation mechanism was attributed essentially to the aggressive chemical attack of the stone body that occurred directly through complex mechanisms depending on some factors, such as **a)** the mineralogical composition of the building materials; **b)** major decaying factors responsible for the natural verity in stone reactivity; **c)** adsorption abilities of some salt ions, e.g., Cl and SO_4, in addition to the dominated environmental conditions [59]. Many site visits revealed that, on the one hand, the dominant sources of salts in the area could be attributed to **1**) the original mineral composition of local rocks, **2**) bird droppings, **3**) residues from previous restoration processes, **4**) airborne pollutants, and **5)** microorganisms. On the other hand, the dominant factors of salt crystallization were **a)** Temperature fluctuations (T), **b)** stone's type and porosity index, **c)** salt type, **d)** conditions of evaporation, and **e)** height of the statues [41]. The detection of gypsum salt in XRD results could be attributed essentially to the effects of the chemical weathering process on the limestone pedestal and alternative drying and wetting cycles in the study area [37,60].

5.1.4. Decay due to human damage (*HD*)

In the study area, human-induced damage is clearly evident. (**1)** The movement of vehicles passing by the location emits large amounts of gas pollutants and dust, which accumulate on the monuments' surfaces [35]. This accumulation distorts the outer appearance and initiates chemical processes that contribute to surface deterioration. **2)** The weekly market is held in close proximity to the statue's location; separated only by a low wall less than two meters in height. **3)** Urban sprawl and heavy vehicles passing by cause vibrations [7]. **4)** Certain harmful social practices- such as vandalism and disregard for cultural heritage- have erased some features of the monument and activated biological and microbiological decaying factors [61]. All these human-related activities contribute to several symptoms of deterioration, particularly expansion and contraction [62], wind erosion [63], and physical fading [50]. In addition, chemical weathering, salt hydration [40], and pitting due to acid rain led to hydration and crystallization cycles [38] as well as wetting and drying cycles. These are considered among the most critical decay mechanisms contributing to the deterioration of marble artifacts, especially in open areas.

5.2. Decaying symptoms

Fading or *discoloration* is primarily attributed to the effects of high temperature T and UV radiation, especially evident on the upper parts of the face of the statue, fig. (5-a). Furthermore, cyclical temperature variations cause the formation of salt crystals in powder form on the statue's surface. *Loss of the edge* is a type of weathering that occurs when angular corners of rock fragments are removed from a piece of stone due to abrasion mechanisms. The angular and sub-angular grains are changed into rounded and sub-rounded grains, fig. (10) [64]. Scientifically, this form is defined as a feature affected by a stone surface, which is not the result of a deliberate human intervention to modify its morphology, but rather an environmental macroscopic or microscopic feature.

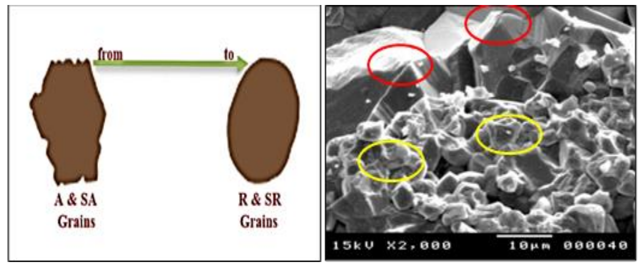

Figure (10) changing the particles from angular and sub-angular grains (●) into rounded and sub-rounded (●)

Bird scratching and droppings: The availability of many food sources in the vicinity has attracted several bird species [64], including *Sturnus vulgaris, Passer domesticus*, Columba *livia domestica*, and *Streptopelia senegalensis aegyptiaca*. The damage caused by bird droppings to historic buildings can be extensive through scratching of the stone fabric and the release of acids from their excrement, which significantly damage the stone surface, as reported by some authors [65-67]. **S**urface crusts form as an indirect result of temperature T fluctuations and air pollutants affecting the Roman statue [36]. They are especially manifested in the crusts and the loss of fine details such as the folds in draped garments because of the lack of pores in the marble. According to El-Gohary [33], these crusts are dark, firmly adhesive deposits on the statue's surface, formed through accumulations of gypsum (*salt crystals resulting from the crystallization process*) and calcite (*main body of the statue*) mixed with quartz grains (*resulting from the Western Mountain of Sohag*). In addition, pollutants such as car exhaust, fly ash, and certain hydrocarbons are incorporated into solid particles as a mobile source of air pollution, especially intensified by temperature fluctuations [35,37,68]. *A detached area* in contour scaling in the upper right side of the statue's back was another form of decay [36] attributed to the continuous chain of wetting and drying cycle of the monument, fig. (4-c), as attested by E-Gohary and Al-Shorman [62]. *Cracks* mainly result from the volumetric expansion of stone, due to alternating heating and cooling cycles. These thermal cycles cause a permanent volumetric expansion, especially when it returns to its ambient temperature [61,69,70]. From a specialized point of view, our statue was affected by this form of damage both in the *front upper part* and the *left back part*, fig. (6-b & c). It resulted from the alternative cycles of halite (*dominant salt in Egyptian land*) crystallization and hydration pressures within the stone pores, fig. (11). *Granular disintegration*, in our case means suffering of the mainly fine-grained marble of the statue of an increasing loss of stone material, the detachment of smaller stone elements from large-sized elements, flaking on the edges, and granular disintegration. This form appears as stone crystals or small fragments that can be easily removed by hand, and it is mostly observed all along the top, and phenocrysts form a relief [71]. Furthermore, it could be asserted that this symptom could be resulted as a direct influence of a degree of consensus that thermally induced micro fracturing [72], which, is the primary cause of granular disintegration in marble as argued by Koch & Siegesmund [73]; Goldie [74]; Viles [75]; Viles & Goudie [76] in similar cases.

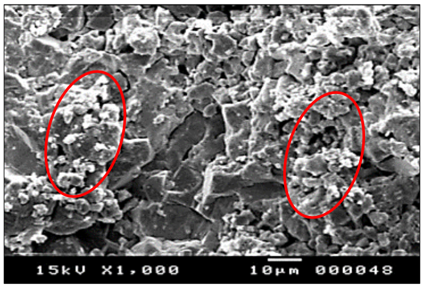

Figure (11) SEM micrographs of disintegrated grains within the statue body.

Dust and soiling: as shown in tab. (2-a & b) and fig. (5-c), both symptoms are considered among the main deterioration forms affecting the statue, especially during the spring season. According to Kuzmichev and Loboyko [77] and Menzelintseva, et al. [78], the sources of these dust deposits are mostly anthropogenic associated with the industry activities, agriculture, household emissions, and transportation. Samir [79] reported an average monthly dust fall of 61.127 g/m^2 in the study area. The analysis of the chemical components of the dust fall showed that they were composed of 14.21% SO_4, 4.72% Cl, 1.93% NO_3, 0.57% NH_4, and 0.050% NO_2. These materials contributed to severe forms of decay, such as **1)** accumulation leading to visual deterioration, **2)** compromised material integrity due to abrasive and chemical interactions, and **3)** initiation of surface discoloration process [80]. Furthermore, these materials cause mechanical erosion due to physical and/or mechanical abrasion of calcite during wind blowing, where, the hardness of calcite is (3) and quartz is (7) according to Mohs' scale [5]. *Salt efflorescence*: occurs as a result of moisture accumulation on the statue's surface and fluctuations in relative humidity (RH). These conditions are often generated by the reaction between adsorbed water with the statue surface. On a moistened surface, airborne particles have a better possibility to adhere, and water-soluble gases are more readily absorbed contributing to the formation of various salt families, fig. (8). According to the dominant gases and pollutants, the following chemical formulas are relevant: **(1)** $CaCO_3+CO_2+H_2O \rightleftharpoons Ca(HCO_3)_2$. CO_2 dissolves in water, but carbonic acid forms only 1% of the oxide, and the remaining CO_2 is in molecular form. In soft water (lacking dissolved ions), carbon dioxide is aggressive. The reaction of aggressive CO_2 produces bicarbonate $Ca(HCO_3)_2$. This reaction is reversible; under suitable conditions, $Ca(HCO_3)_2$ decomposes back to calcium carbonate $CaCO_3$, (the essential component of marble), and vice versa. When water is sufficiently present, it can leach this compound from the coating, decreasing the binder content in the coating and causing decay the coating in the final stage [27]. **(2)** $CaCO_3+2H^++SO_4^{2-}+H_2O \longrightarrow CaSO_4{\cdot}2H_2O+CO_2$. or $CO_2CaCO_3+SO_3+2H_2O \longrightarrow CaSO_4{\cdot}2H_2O+CO_2$. In the present study, air pollution rates were highest during winter, with a recorded SO_2 concentration of "49.04 µg/m^3", tab. (2-a) and "14.21%" in chemical components of dust fall", tab. (2-b). This oxide dissolves partly in water, forming sulfurous acid H_2SO_3 that is transformed by oxidation to sulfurous acid H_2SO_4. Both lead to the decomposition of calcium carbonate (the essential component of the statue), leading to the formation of gypsum salt ($CaSO_4{\cdot}2H_2O$), which is formed in large crystals characterized by a large molar volume under favorable humidity conditions. The main problem, in this case, is when the stone is exposed to rapid temperature changes, causing notable damage due to differential thermal expansion between the statue's main component (Cal. 0.15 mm) and the dominant salt (Gyp. 0.4-0.3 mm) [81]. The resulting stress leads to thermal cracking of the calcite and/or crystal grains, due to differences in thermal expansion coefficients along the (a) and (c) lattice directions, as attested by Winkler [82] and Marinoni, et al. [83], who suggested that the stress resulting from changes of air temperature beginning at about 40-60°C can impart micro fractures among mineral grains. This process ultimately leads to cracks along the grain boundaries of stone and micro-fissures, fig. (6) [84,85], especially when coupled with alternative cycles of hydration/crystallization processes [86]. In the same context, halite (NaCl) originating from saline ground water, a characteristic feature of Egyptian soil contributes to further deterioration. After drying, halite can accumulate within the cavities of the statue, appearing either as surface crusts due to evaporation and precipitation processes, or as crystals precipitated inside the pores and cracks underneath the superficial crystals, fig. (12) [71].

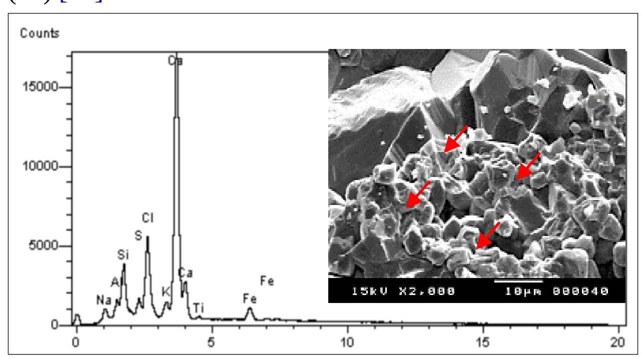

Figure (12) SEM micrographs of halite prismatic grains within the statue body.

According to the Encyclopedia Britannica [87], potassium nitrate (KNO_3), known as niter or saltpeter, is one of three naturally occurring nitrates: **1)** ordinary saltpetre (KNO_3), **2)** Chile saltpetre or nitratine, ($NaNO_3$), and **3)** lime or wall saltpetre ($Ca(NO_3)_2$) as shown in the following formula: $CaCO_3+2HNO_3 \longrightarrow Ca(NO_3)_2+CO_2+H_2O$. Potassium nitrate was observed in our case study as efflorescent white powder on the statue's surface. Its presence is attributed to the use of potassium-based K fertilizers in nearby agricultural lands or other anthropogenic activities around the study area. It is formed by a chemical reaction with the statue material [88], leading to efflorescence, fig. (13). Accordingly, it could be affirmed that crystallization salts caused significant damage to the statue, where the formed crystals exert crystallization pressures on their surroundings. If the pressure is higher than the marble's strength, failure occurs, especially with crystallization within the coating pores.

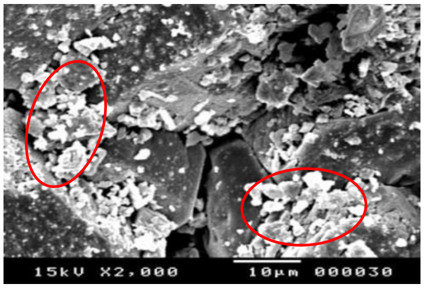

Figure (13) SEM micrographs of power niter within the statue body.

Based on the results of AAS and titration analytical methods, tab. (4), the detected salts in the stone samples can be classified into four main types: **1)** carbonates **(**41.53% *calcium bicarbonate* and 10.92% $Mg(HCO_3)_2$ *magnesium bicarbonate***), 2)** chlorides **(**5.77% $MgCl_2$ *chloro-magnesite* and NaCl 26.22% *halite)*, sulfates **(**13.58% Na_2SO_4 *thenardite*, and **4)** nitrates **(**1.96% $NaNO_3$ *nitratine* and KNO_3 *niter*). According to some specialists [24,89-92] these are considered the most aggressive salts affecting archaeological sites in Egypt. They are not only abundant in the Egyptian environment, but also the worst in affecting stone decay depending on the dominant degrees of temperature and humidity, in particular, thenardite [93]. In our case, severe effects resulted from the presence of halite, whose synergetic reaction with soluble sulfate, composing both thenardite and hydrochloric acid, led to the sever decay and corrosion of the statue body through granular disintegration [94]. Nitratine salts may have originated from the biodeterioration processes linked to the abundance of guano deposits in the study area. The main problem resulting from this salt is attributed to significant decay of 10-100 times more than that caused by gypsum [95] according to crystallization pressure coefficient [40], such as (28.2 MPa) for $CaSO_4 \cdot 2H_2O$ [96], NaCl (5 MPa) [97], $CaCO_3$ (1.2-4 MPa) [98], $Ca(NO_3)_2$ (101.3 kPa "normal atmospheric pressure") [99], and Na_2SO_4(up to 13.8 MPa) [100,101]. Finally, it could be asserted that these salts are strongly connected with water migration and evaporation cycles in stones and cause several decaying forms, fig. (14), especially with the presence of suitable TDS (880) and pH values (9.4) in addition to the above-mentioned coefficients of crystallization pressure [102, 103] and other affected values, such as porous media, concentration materials, and pores sizes [104,105].

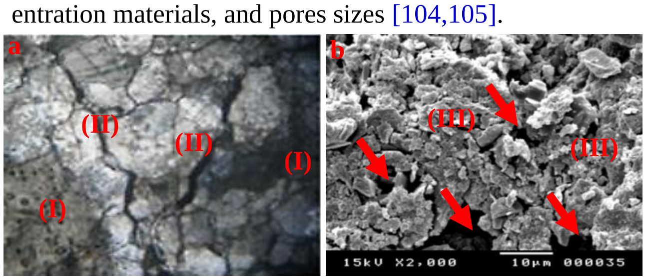

Figure (14) **a.** PM X-160/0.17 & **b.** SEM micrograph shows some decaying symptoms resulted from salt efflorescence such some spots of clays, cracks, cavities and grains disintegration

Pitting is a degradation phenomenon characterized by numerous blind holes, which can appear on the micro-scale or macro-scale [106]. It is generally associated with various factors, including petrographical properties, physio-chemical parameters of the surface morphology, and the inclination and exposure of the stone surface. As shown in fig. (5-b & c), it appears as a minor form, known as *bio-pitting*, which develops as a result of microhabitats for microorganisms, especially with the presence of some species of *Bacillus Cereus*, *Aspergillus niger, and Rhizopus nigircans*. These data agree with those presented by Nagy, et al [60] and Abdelhafez, et al. [107]. *Human effects*: Possible anthropogenic risks were evalua-ted to realize damage maps that account for potential decaying phenomena linked to gradual changes [25,108,109]. In our case, these risks are attributed to **1)** Vehicle emissions: cars passing by the location emitting large amounts of gas pollutants and dust, which accumulate on the monuments' surfaces. This not only distorts the aesthetic appearance but also accelerates chemical reactions that lead to surface deterioration. **2)** Proximity to a weekly market: a local weekly market is established near the statue's location; only a low wall of fewer than two meters high separates them. **3)** Heavy vehicle traffic: The heavy vehicles passing by cause vibrations that may compromise the structural integrity of the statue over time. **4)** Harmful cultural practices: Some inappropriate social behaviors further contribute to the degradation of the monument by encouraging microbial activity and staining.

6. Conclusion

A complementary study of the decaying factors and related forms affecting the Venus marble statue discovered in Merit-Amoun Park, Akhmim, Egypt. was carried out using various analytical and investigative techniques. The given scientific overviews demonstrated that there are multiple deterioration factors affecting the statue. The resulting data confirmed that these factors were highly affected through many decaying factors and mechanisms that ultimately created many decaying forms, such as the rising of saline groundwater, crusting, bird accumulation, granular disintegration in some parts, cracks and microcracks, and man-made damages, e.g., customs and traditions with ethical concerns. Digital microscopy (DM) results proved disintegration of calcite grains, color change, and the presence of some hard surface crusts. Polarized microscope (PM) investigation confirmed that the marble samples are composed essentially of calcite and minor amounts of dolomite. The marble is also characterized by a massive structure and an increasing porosity index. Scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM-EDX) confirmed the presence of the main elements of calcite and clay (Ca, Al, Si, and Fe), in addition to some salt deposits (Na & Cl), which was further confirmed by X-ray diffraction (XRD) and atomic absorption spectroscopy (AAS). Accordingly, some recommendations are proposed, including: ***a)*** *constructing a drainage system comprising wells and pumps around the park;* ***b)*** *coordination with local authorities to divert or reduce traffic congestion around the area; c**)*** *strengthening the marble, especially in areas showing powdering, along with repairing cracks and repointing the joins at the base of statue using suitable mortars;* ***d)*** *implementing a preservation plan aimed at preserving the park's deteriorating features, following a comprehensive strategic plan.*

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