Restoration and reconstruction

DETERIORATION OF THE BUILDING STONE OF THE THERMAL BATHS IN THE WEST OF CAESAREA OF MAURETANIA (CHERCHELL, ALGERIA)

Abla Brahmi*, Messaoud Hamiane, Kamel Bouzetine

Materials, Processes and Environment Research Unit (URMPE), Faculty of Technology, M'Hamed Bougara University, Boumerdes, Frantz Fanon, 35000, Algeria

*Corresponding author's email: a.brahmi@univ-boumerdes.dz

Abstract

Inroduction. The thermal baths located in the western part of ancient Caesarea Mauretaniae, dating from the late second century AD, were constructed using a combination of flat bricks and blocks made from stones of various lithologies, nearly 90 % of which are calcarenite. **This study aims** to assess the state of conseration of this stone used in one of the most significant thermal structures within the built heritage of Cherchell. **Methods.** The investigation involved determining the physico-mechanical properties of selected samples, collecting rainwater, and recording in situ thermo-hygrometric parameters. Sound and weathered surfaces were characterised using polarizing microscopy, scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM-EDX), and X-ray diffraction (XRD). **Results.** Field observations reveal advanced deterioration of the calcarenite, manifested by the formation of black crusts, alveolization, granular disintegration, and superficial salt efflorescences. Physico-chemical analyses confirm the presence of marine-derived salts, as well as deposits associated with atmospheric pollution. The combined dataset indicates that the deterioration dynamics of the calcarenite are driven by marine salt inputs and atmospheric pollutants, whose effects are amplified by local climatic conditions. These interacting factors account for the accelerated degradation processes observed within the studied thermal structures.

Keywords: West Cherchell thermal baths; calcarenite; alteration; sea salts; atmospheric pollution.

Introduction

The former Caesarea of Mauretania, now known as Cherchell, is a coastal town located approximately 100 kilometers west of Algiers and 28 kilometers west of Tipaza, the capital of the wilaya to which it is administratively attached (Gsell, 1952). The settlement lies on a Tyrrhenian sandstone terrace forming a narrow strip a few hundred meters wide between the sea and the first mountain slopes (Chennaoui, 2016; Leveau, 1984). It is situated at the foot of the Atlas Mountains in Cherchell (Benseddik and Potter, 1993). The climate of Cherchell lies within a transitional zone between the humid eastern region of Algeria and the arid western region. The precise boundary between these two climatic areas remains uncertain, with some sources placing it in the Chenoua region and others in Algiers (Yacono, 1955). Annual average rainfall reaches 635 mm, with temperatures ranging from 28°C in summer to 10.7°C in winter. Humidity levels vary considerably, from a minimum of 50 % in summer to a maximum of 90–95 % during winter (Leveau, 1984).

The city contains numerous public buildings dating to the Roman period, including theaters, amphitheaters, and thermal baths. Among these, the great thermal baths of the western sector are particularly noteworthy (Gsell, 1901). Their historical importance earned them the later designation "Sultan's Palace". They are among the few surviving ruins of Caesarea that remain visible today (Fig. 1).

The significance of any archaeological site is reflected in its cultural heritage value, which in turn justifies its preservation, conservation, and ongoing maintenance (Darvill, 1995; Feilden and Jokilehto, 1998).

The decision to focus this study on the thermal baths of western Cherchell was based on several factors: their cultural and historical importance, the exceptional quality of their architectural design, and their prominent position within the urban fabric. Their construction employed a combination of flat bricks and stone blocks from different lithologies, with calcarenite accounting for nearly 90 % of the material. The architectural layout was meticulously planned and executed according to a perfectly symmetrical scheme (Leveau, 1984).

Calcarenite is easily workable and transportable, particularly by sea, owing to its composition and
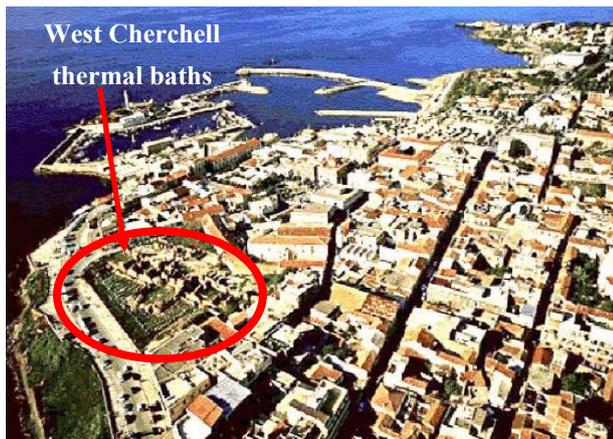
Fig. 1. Oblique photo of the thermal baths in the West of Cherchell (© Yann Arthus Bertrand)

grain size distribution. Its predominantly coastal occurrence further facilitated its use. Consequently, this stone has been widely employed in both domestic and monumental architecture (Jockey, 2006).

However, stone deterioration remains a persistent issue. The objective of this research is to contribute to the conservation of these archaeological remains by raising awareness of the need for multidisciplinary interventions and for analytical and testing methods adapted to heritage stone materials. Until recently, studies of stone decay focused exclusively on the intrinsic properties of the material itself; only in the last decades an environmental approach has been introduced to address this limitation. In this study, both approaches were used to analyze the phenomena occurring at the rock–atmosphere interface.

Indeed, the deterioration of building stones is often compared to the effects of disease — most commonly cancer — affecting the "health" of a building and ultimately leading to its decay (Malaga-Starzec et al., 2000). This phenomenon results from a combination of meteorological, architectural, and material-related factors (Camuffo and Bernardi, 1990; Dessandier, 1995; Thomas, 1938). Although rocks in their natural state and stones used in construction are subject to similar alteration factors and show comparable deterioration patterns, the kinetics of alteration are accelerated when stones are used in buildings (Jeannette, 2004). This is due to specific exposure conditions, including the use of stones laid against bedding (i.e., placed perpendicular to the strata), the juxtaposition of stones of varying quality or lithology, and the insertion of mortars between blocks — which may themselves act as a source of salts. One of the primary causes of stone decay in built structures is salt weathering (Arnold and Zehnder, 1989; Camuffo, 1998). It is widely accepted that stresses generated by salt crystallization in porous materials can exceed their mechanical strength.

Furthermore, air pollution — particularly from vehicle emissions and high concentrations of sulfur dioxide — significantly contributes to the deterioration of monuments. The dark deposits and black crusts frequently observed on monuments are largely composed of calcium sulfate formed through the reaction between sulfur dioxide and calcium carbonate in limestone (Zaouia et al., 2014).

Pollution in the Study Area

A synthesis of the findings from numerous studies and research projects examining the impact of industrial activities on the environment indicates that two principal categories of pollution sources affect the study area.

The first category comprises **stationary sources**. A total of 16 landfills have been identified across the 28 municipalities of the wilaya, in addition to other waste disposal sites. Most of these facilities fail to comply with technical standards and are located in close proximity to urban areas. The contamination of water sources is primarily attributable to the discharge of urban and industrial wastewater, directly affecting surface water, groundwater, and marine environments. Along the coastline of the Tipaza wilaya, 102 sea outfalls have been identified, discharging a total of 74,266 m³/day of wastewater.

The 14 coastal municipalities account for 60 of these outfalls (42,672 m³/day), representing 59 % of the discharges and 57.4 % of the total volume released (Grimes, 2011).

The city of Cherchell is characterized by a high concentration of pollution sources distributed along its coastline. Rapid population growth has led to a significant increase in wastewater production, resulting in the direct discharge of substantial volumes into the marine environment (Tazi and Touahir, 2011).

A study by Benderradji and Ferhat (2011) identified several discharge points near the study site, including:

- the outfalls from the city center and the El Kettar conurbation, located a few meters from the site, below the level of the bus stops;
- the outfall serving the city center and the fishery;
- the outfall from the Cherchell Military Academy, located below the level of the Bab El Ghareb monument;
- three outfalls east of the port, at a location known as Sidi Braham;
- additional discharges related to ongoing development and extension works at the port.

The second category consists of **mobile sources**. These derive primarily from transportation — private vehicles and public transit — whose emissions are released within the study area. The bus stop located at the exit of the thermal baths constitutes a major source of pollution, noise, and continuous vibrations. The high volume of daily traffic passing

directly in front of the site further exacerbates the environmental impact. The concentration of these pollutants has increased in recent years, largely due to the intensive use of diesel fuel, which is composed of a complex mixture of branched and cyclic alkanes. These emissions contribute significantly to the degradation of heritage materials, particularly stone, by promoting the formation of black crusts and other chemical alterations (Lefèvre and Ausset, 2001).

All these sources release harmful pollutants, including CO, CO_2, SO_2, and NO_2. Consequently, they play a major role in the accelerated deterioration of cultural heritage, particularly through oxidation processes affecting materials such as stone masonry, as highlighted in Ozga et al. (2009).

Main Forms of Deterioration Prevalent in the Study Area

The principal forms of destructive alteration observed at the thermal baths in the west of Cherchell, particularly affecting calcarenite stone, can be classified into three categories: alveolization and sandy disintegration, black crusts, and efflorescences and subflorescences (Fig. 2).

In the western thermal baths, efflorescences are evident in the central sections of the walls, on the northeastern sides of both promenades, and in the frigidarium. These appear as clusters of white, powdery crystals on the stone surface, which shows a high degree of disintegration.

It is also important to note that the walls of these thermal baths were constructed using a combination of flat bricks and stones of varying lithologies, with calcarenite accounting for 90 % of the total. The juxtaposition of visually similar stones with differing petrophysical properties can accelerate the degradation of one of them (Dessandier, 1995). For example, a stone that permits only limited fluid migration, when placed adjacent to a stone with higher permeability, will hinder the homogeneous circulation of fluids between them.

Methods

The study presented in this paper concerns the aging of the calcarenite stones that form the walls of the so-called Cherchell thermal baths. Since stone alteration results from its interaction with the environment, it is necessary to examine the aging processes by characterizing both the material and the local climatic conditions to which it is exposed.

The investigation began with the characterization of the physico-mechanical properties of stone
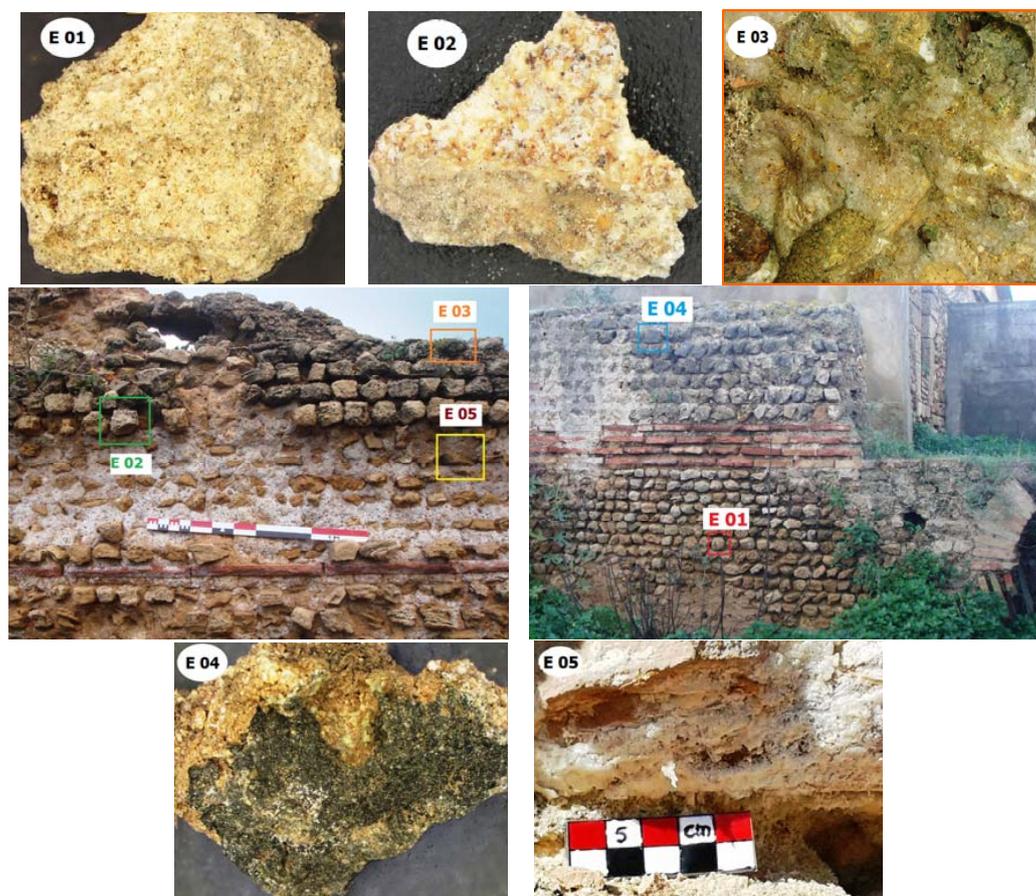

Fig. 2. Location of the stones selected for sampling (E01: stone considered sound; E02: stone exhibiting sandy disintegration; E03: stone with alveolization and incrustation; E04: stone with black crust; E05: stone with efflorescence), West Cherchell thermal baths

samples extracted from the West Cherchell thermal baths and from an ancient quarry located approximately five kilometers west of the site, at Cape Haouch Taberkoût Mohamed, in an area known as "la Cave Hardy" (Leveau, 1984), between Cherchell and Hadjret-en-Nous. The analyses revealed a perfect petrographic match between the stone from this quarry and that used in the thermal baths, confirming the probable exploitation of this deposit for the construction of the thermal complex.

The physico-mechanical properties of the samples were determined in accordance with the relevant standards: bulk density and total porosity were evaluated according to NF EN 1936, water absorption was measured following NF EN 13755, and uniaxial compressive strength was determined in accordance with NF EN 1926.

A temperature and humidity logger was installed at the site to record meteorological data (temperature and humidity) for assessing the risk of damage to stones exposed to local environmental conditions. In-situ measurements were collected by placing sensors between calcarenite blocks at the most representative area of deterioration, located at the right walkway level on the northeast side. Data were recorded over an eight-month period (1 August 2017 to 1 April 2018).

Sampling and instrumental analysis: To provide a qualitative description of stone deterioration in relation to environmental parameters, it was essential to select samples representative of the material and to perform a detailed analysis in order to understand fully the harmful impact of pollution.

Laboratory investigations included a range of observational and analytical techniques applied to both the stone samples and the preliminary rainwater samples collected in situ in March 2018. This made it possible to compare altered and sound stones and to identify alteration products using qualitative methods.

Microscopic and mineralogical analyses were carried out using an Olympus polarizing microscope for the petrographic description of the stone and a Philips XL 30 ESEM scanning electron microscope (SEM-EDX) for direct analysis of unprepared samples.

In addition, powdered samples were analyzed using a BRUKER D8-FOCUS X-ray powder diffractometer. The results are presented in Table 1.

The total elemental concentration in the insoluble fraction of the three collected rainwater samples was determined by X-ray fluorescence spectroscopy (XRF). These concentrations were converted into micromoles per liter and are presented in Table 2. The soluble fraction was analyzed separately. The pH, conductivity and volume of each rainwater sample were measured immediately upon arrival at the laboratory. Major cations analyzed included sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), and hydrogen (H^+), while major anions included chloride (Cl^-), nitrate (NO_3^-) and sulfate (SO_4^{2-}). The pH was determined by pH-metry; Na^+, K^+, Ca^{2+}, and Mg^{2+} concentrations were quantified by flame atomic absorption spectrometry (FAAS); and Cl^-, NO_3^- and SO_4^{2-} by ion chromatography (IC).

The concentrations of major elements, expressed in micromoles per liter (μmol/L), are presented in Table 3. The ionic balances, expressed in milliequivalents per liter (μeq/L) and calculated from the sum of cations (Σ^+) and anions (Σ^-), are provided at the end of Table 3. Two ions — NH_4^+ and HCO_3^- — could not be measured.

Results and Discussion

The successive interactions between the environment and the material lead to progressive surface modifications. As alteration advances, it penetrates deeper into the stone, resulting in increasingly significant material loss. The rate and extent of deterioration depend on the intrinsic properties of the material and the aggressiveness of the surrounding environment.

Visual observations and analytical investigations have made it possible to identify the probable factors and mechanisms responsible for the alteration of the calcarenite used in the construction of the Western Cherchell thermal baths, particularly those linked to the influence of a coastal climate within an urban setting.

Petrographic Examination

The initial findings of our petrographic investigation of the calcarenite, particularly the stone sampled from the study site, show that it is a porous material with a reddish patina and gray fracture surface, exhibiting a lumpy appearance and belonging to the category of carbonate-cemented sandstones (microsparites). It is formed from consolidated or lithified dunes composed of carbonate and silicate grains (mainly quartz). These fossils attest to the high sea levels of the recent Pleistocene (Tyrrhenian) period.

In the thin section shown in Fig. 3, quartz grains of varying sizes with angular outlines are visible, embedded in a carbonate matrix containing abundant red algae (rhodophytes) and numerous fossils and fossil fragments. The fossil assemblage includes foraminifera such as *Globigerinoides sp.*, *Globorotalia sp.*, and *Miliolida*, as well as fragments of lamellibranch shells. The abundance of bioclastic components and their strong carbonate cementation result in a compact rock well suited for construction.

However, the rock displays high porosity, which facilitates water circulation and consequently increases its susceptibility to alteration processes.

Physical and Mechanical Properties

For sample E05, which exhibited efflorescence, the determination of physico-mechanical properties was not possible due to its extreme fragility.
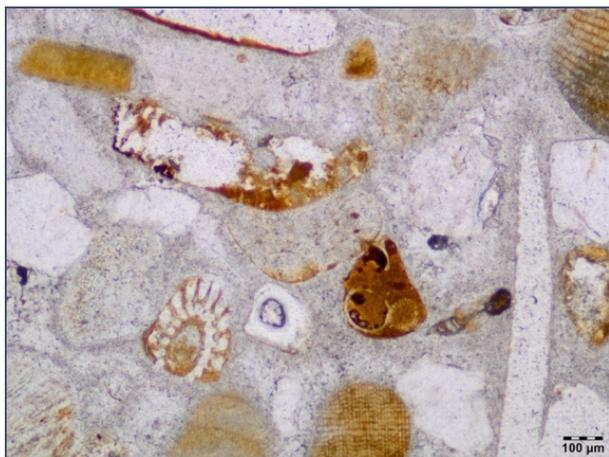
Fig. 3. Micromorphology of the calcarenite stone from the study site under an optical microscope

The analysis of the physical and mechanical properties of the calcarenite samples reveals a clear distinction between sound stones (C-H and E01) and altered stones (E02, E03, E04).

Samples C-H and E01 exhibit higher density values, indicating a more compact structure with fewer voids, compared with samples E02, E03, and E04. This contrast is especially marked in sample E03 (density = 1.4 g/cm³), reflecting significant material loss attributable to weathering processes such as dissolution or microcracking. With regard to porosity, samples C-H and E01 display values of 24 % and 31 %, respectively, corresponding to moderate porosity typical of calcarenites. In contrast, the altered samples show a substantial increase in porosity, reaching 46 % in sample E03, which indicates deterioration of the internal structure associated with a rise in interconnected voids. Similarly, the sound samples (C-H and E01) exhibit low water absorption, likely due to their limited porosity and discontinuous pore network. The altered samples (E02, E03, E04), however, display markedly higher absorption values, with sample E03 reaching up to 29 %. This confirms the presence of open porosity and a heightened sensitivity to water — conditions that accelerate weathering.

Finally, a pronounced decrease in mechanical strength is observed, most notably in sample E03,

directly resulting from the loss of internal cohesion induced by degradation processes.

SEM-EDX Observation

The use of a scanning electron microscope (SEM) enabled the identification of salts present both on the surface and within the internal structure of the stone samples.

SEM imaging of sample 470, taken from stone E04 and characterized by a black surface crust, revealed the presence of gypsum, appearing as prismatic crystals arranged without preferential orientation (Fig. 4A). In contrast, a combination of sodium, calcium, and sulfur was detected within the fissures of sample 544 from stone E03 (Fig. 4B). Furthermore, halite in its typical cubic habit (Fig. 4C) was identified within the pore spaces in the deeper zone of sample 464 from stone E02, which exhibited alveolization.

The examination indicates that the rate of corrosion and deterioration of the calcarenite is influenced by multiple factors, with atmospheric pollution functioning as a complex, multiparametric driver. As demonstrated by Haber et al. (1988) in comparable cases, the stone surfaces display varying degrees of damage resulting from severe air-pollution effects, which are modulated by several parameters, particularly the presence of water.

The formation of aggressive, hard saline crusts on the stone surfaces — such as gypsum ($CaSO_4·2H_2O$) and salts produced through calcite dissolution ($CaCO_3$) — observed on sample E05 is primarily attributed to corrosive chemical mechanisms triggered by atmospheric pollution (Van Grieken et al., 1998). These effects are further intensified by synergistic interactions with acid rain or other moisture inputs. For example, the sulfates observed on certain stone surfaces are generated through reactions between SO_2 and $CaCO_3$, as documented in numerous studies (Fassina, 1988; Russ et al., 1999). Once salts infiltrate the pore network and crystallize, cyclic recrystallization produces stresses that eventually cause the rupture of stone surfaces, as reported by Lewin (1982). This process is strongly influenced by salt concentration, chemical composition, and the number of wet–dry cycles (Binda et al., 1985).

Salt efflorescence and subflorescence affect both the pore network and the surfaces of samples

Table 1. **Physical and mechanical properties of the stone samples analyzed**

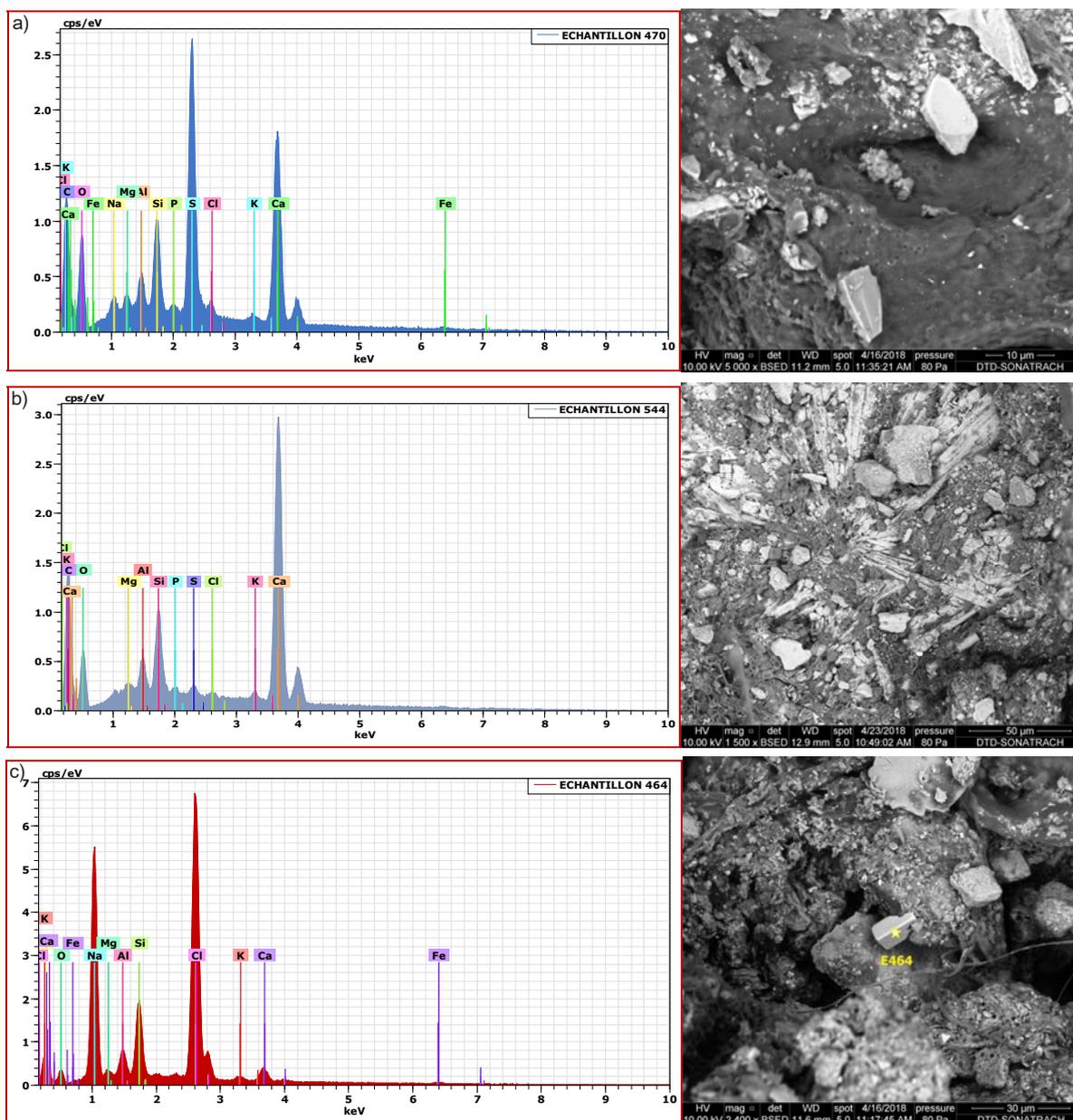|	Sample					
	C-H	**E01**	**E02**	**E03**	**E04**	**E05**
Density ρ_a (g/cm³)	2.2	1.9	1.7	1.4	1.8	–
Total porosity N_{tot} (%)	24	31	42	46	38	–
Water absorption (%)	11	16	22	29	21	–
Uniaxial compressive strength R_c (MPa)	16.57	13.21	7.2	5.45	9.67	–
C-H: Calcarenite sample from the ancient **Cave Hardy** quarry						

Fig. 4 (A, B, C). SEM micrographs and corresponding EDX spectra showing deterioration agents identified in the stone samples

E02 and E05. This is due to cycles of crystallization and recrystallization of salts originating from marine aerosols or acid rain, particularly following drying phases induced by air temperature or airflow. These phenomena are associated with the presence of halite crystals, which are considered the most potentially damaging salts to the rocks in which they precipitate, particularly limestone. This is because halite exerts one of the highest crystallization pressures, as discussed by Hammecker (1993) and Mirwald et al. (1988).

The concept of crystallization pressure has long been debated. However, Desarnaud et al. (2016) reported measurements obtained using highly specialized instrumentation indicating that disjoining pressures can reach — and even exceed — hundreds of megapascals. Such extremely high pressures surpass the mechanical strength of most rocks. In addition, salts crystallizing within porous media generate tensile stresses to which rigid stones offer little resistance. Therefore, these salts and their crystallization processes are highly effective in fracturing the stone due to its porosity (Bromblet, 2020). Moreover, in the absence of rainfall during the dry season, dissolution–crystallization cycles of salts may continue through simple halite solvation. The repetition of these cycles generates low-intensity bursts that promote deeper penetration of salts. The year-round continuation of these mechanisms amplifies these bursts and contributes

to the progressive degradation of the stone through alveolization and disintegration.

X-ray Powder Diffraction Analysis

According to the results presented in Table 2, the samples fall into two main categories based on their degree of preservation.

The first group comprises samples considered to be in satisfactory condition. The first sample (C-H) was collected from the ancient Cave Hardy quarry, while the second sample (E01) was taken from a sheltered wall within the Cherchell thermal complex, protected from direct weathering. Mineralogical analysis shows that both stones consist predominantly of calcite ($CaCO_3$), with a minor amount of quartz (SiO_2). In addition, traces of clinochlore associated with micas were detected in sample E01.

The second group includes samples taken from visibly deteriorated areas (E02, E03, E04, and E05). These samples contain significant proportions of major phases such as calcite ($CaCO_3$), as well as minor phases including quartz (SiO_2), micas, and gypsum ($CaSO_4 \cdot 2H_2O$). Trace minerals such as mirabilite ($Na_2SO_4 \cdot 10H_2O$), kaolinite ($Al_2Si_2O_5(OH)_4$), and nitratine ($NaNO_3$) were also identified as surface accumulations.

The X-ray analysis shows that the sound sample is mainly composed of the crystalline phases listed above, confirming that this calcarenite may be classified as a sandy limestone.

In contrast, the surfaces of the altered samples (E03, E04, and E05) exhibit highly deteriorated mineralogical characteristics. These surfaces contain saline alteration minerals, predominantly gypsum and halite. Gypsum forms through chemical alteration caused by reactions between polluting gases (SO_2 and NO_x) and the dominant ions present on the stone surface. This behavior is typical of carbonate stones exposed to polluted environments, especially following the evaporation of moisture, as demonstrated by El-Gohary (2008, 2011).

Many salts are inherently unstable and may transform into different states depending on the amount of water incorporated in their structure. For example, calcium sulfate can absorb moisture and convert into gypsum, accompanied by a 42 % volume increase. Similarly, thenardite (Na_2SO_4) can transform into mirabilite ($Na_2SO_4 \cdot 10H_2O$), which can exhibit a volume increase of approximately 300 % (Price, 1997).

Sample E03, taken from a calcarenite stone showing alveolization, contains the crystalline mirabilite phase. It is well established that crystallization of sodium sulfate solutions can produce three different phases depending on the water content: thenardite (Na_2SO_4, anhydrous phase), mirabilite ($Na_2SO_4 \cdot 10H_2O$, decahydrate), and a heptahydrate phase. Both the heptahydrate and the decahydrate (mirabilite) are unstable. The critical temperature — representing the threshold between slight and severe damage caused by salt crystallization — is approximately 32.4°C, which is also the stability limit for mirabilite. Tsui et al. (2003) showed that the most severe deterioration occurs when sodium sulfate crystallizes below the temperature at which mirabilite forms. These findings were corroborated by Angeli et al. (2010) through experimental aging tests on limestone conducted under controlled temperature and sodium sulfate concentration.

Temperature and Humidity Measurement

The temperature and humidity data reveal pronounced seasonal fluctuations. For instance, the lowest temperature recorded during the measurement period occurred on December 20, 2017 at 6:53 a.m., reaching 6.5°C with a relative humidity of 95 %. On March 23, 2018 at 7:09 a.m., another minimum of 5°C was recorded, accompanied by a relative humidity of 88 %. Conversely, the highest temperature, 37.5°C with a relative humidity of 32 %, was measured on August 1, 2017 at 5:33 p.m.

Table 2. **Mineralogical composition of the analyzed stone samples determined by X-ray diffraction (XRD)**

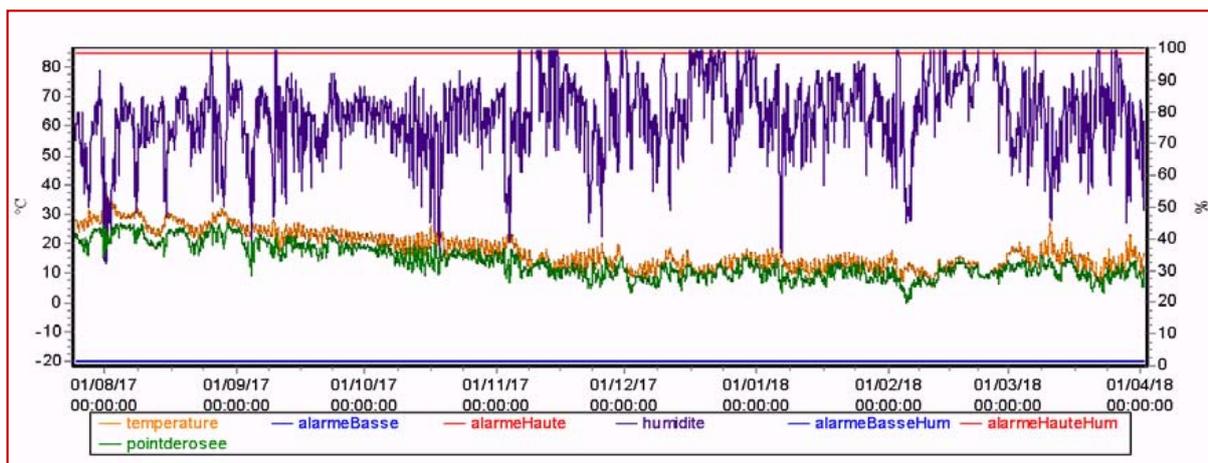| Detected minerals	Sample					
	C-H	E01	E02	E03	E04	E05
Calcite ($CaCO_3$)	***	***	***	***	***	--
Quartz (SiO_2)	**	**	**	**	**	--
Micas	--	*	--	*	--	--
Clinochlore($(Mg, Al)_6 (Si, Al)_4O_{10}(0H)_8$)	*	*	--	--	--	--
Kaolinite ($Al_2 (Si_2O_5) (OH)_4$)	--	--	--	*	--	--
Halite (NaCl)	--	--	*	--	**	***
Gypsum ($CaSO_4 \cdot 2H_2O$)	--	--	*	--	**	**
Mirabilite ($Na_2SO_4 \cdot 10H_2O$)	--	--	--	*	--	--
Nitratine ($NaNO_3$)	--	--	--	--	*	--
*** = major minerals ** = minor minerals * = traces -- = undetectable						

Fig. 5. Environmental measurements recorded at the site

Such climatic variations — particularly changes in air temperature — induce atmospheric weathering through alternating heating and cooling of stone surfaces. In climates combining high temperatures with elevated humidity, fluctuations in stone temperature regulate the presence of water within the material through evaporation–condensation processes. These fluctuations may cause direct deterioration of the stone through mineral dissolution, or may indirectly intensify weathering induced by other environmental factors.

It is evident that the severe deterioration of rocks containing salts is not solely due to the high crystallization pressures, but also to the frequency of dissolution–crystallization cycles. The recorded data clearly show variations in relative humidity between day and night. The studied stone was found to be contaminated with sodium chloride. During the daytime, when temperatures rise and relative humidity decreases, this salt crystallizes and remains stable. At night, as humidity increases and temperature drops, the salt dissolves, migrates within the pore network, and recrystallizes the following day once temperatures rise again and relative humidity falls below the threshold of 75 %. The hygroscopic behavior of halite enables the salt to remain mobile and active within the stone (Bromblet, 2020).

Rainwater Analysis Results
- *Insoluble fraction*
- *Soluble fraction*

Table 5 summarizes the marine contributions and excess levels of SO_4^{2-}, Cl^-, and NO_3^-, together with their respective percentages relative to total ion concentrations. It also reports both measured and calculated hydrogen-ion concentrations (H^+), as well as the neutralizing capacity (C_n).

Acid rain is defined as the deposition of gaseous pollutants and particulates that results in precipitation with a low pH. Atmospheric SO_2 and NO_2 are progressively oxidized to form two strong acids — H_2SO_4 and HNO_3 — which are subsequently incorporated into raindrops and transported to stone surfaces by acid precipitation (De Nevers, 2010).

Rainfall therefore acts as an efficient vector for transferring atmospheric pollutants to stone surfaces (Alomari, 2014).

Analytical results clearly show that the collected rainwater is slightly acidic (pH: 4.91; 5.12; 5.75), contrary to Algerian standards, which specify a pH range of 6.5 to 8.5 for natural waters.

Taking into account instrumental uncertainties and the inherent variability of atmospheric conditions, the pH of the first rainwater sample is distinctly more acidic (4.91) than that of samples 2 and 3 (5.12 and 5.74). These differences may be linked to the timing of rainfall events, during which partial neutralization of acids occurs within raindrops.

The analyses further show that marine-derived soluble elements — dominant in the soluble fraction (Table 4) — occur only in minor amounts in the insoluble fraction retained on filters (Table 3). In contrast, terrigenous elements (Al, Si, Ca, Fe) are markedly higher, particularly in rainwater sample 3.

Table 3. **Total elemental concentrations (µmol·l⁻¹) in the insoluble fraction retained on filters from the three rainwater samples collected at the West Cherchell thermal baths**

	Si	Al	Mg	Na	Cl	K	Ca	Ti	S	Fe	Mn	Zn
Rainwater sample 1	17.98	32.47	02.44	00.98	00.57	01.74	02.38	05.69	00.04	02.85	01.15	00.02
Rainwater sample 2	38.54	14.71	04.63	01.21	01.02	05.38	06.84	01.88	01.93	31.26	04.08	00.17
Rainwater sample 3	399.25	265.62	30.81	03.40	00.98	47.56	105.33	09.72	02.36	64.49	00.87	00.35

Table 4. **Concentrations of major elements (µmol·l⁻¹), pH, electrical conductivity (µS·cm⁻¹), and ionic balance (µeq·l⁻¹) of the three rainwater samples**

	Cond. (µS·cm⁻¹)	pH	H^+	Mg^{2+}	Ca^{2+}	K^+	Na^+	SO_4^{2-}	Cl^-	NO_3^-	Σ^+	Σ^-
Rainwater sample 1	21.01	4.91	12.30	39.87	63.15	7.88	451.10	69.13	422.47	70.34	677	631
Rainwater sample 2	22.35	5.12	7.58	21.93	57.63	4.67	95.44	54.29	90.23	41.51	267	240
Rainwater sample 3	25.87	5.74	1.82	18.01	15.92	9.48	205.31	20.05	225.67	20.12	304	286

Table 5. **Marine contributions and excess levels of SO_4^{2-}, Cl^-, and NO_3^-, together with the neutralizing capacity (C_n) expressed in µmol·l⁻¹**

	Concen-trations	SO_4^2 (sea)	SO_4^2 (excess)	Cl^- (sea)	Cl (excess)	NO_3^- (sea)	NO_3^- (excess)	H^+ (measured)	H^+ (calculated)	C_n
Rain-water sample 1	(µmol·l⁻¹)	27.07	42.06	527.79	0	0	70.34	12.30	154.46	142.16
	%	40	60	–	–	–	–	–	–	92
Rain-water sample 2	(µmol·l⁻¹)	5.73	48.56	111.66	0	0	41.51	7.58	138.63	131.05
	%	12	88	–	–	–	–	–	–	94
Rain-water sample 3	(µmol·l⁻¹)	12.32	7.73	240.21	0	0	20.12	1.82	35.58	33.76
	%	62	38	–	–	–	–	–	–	95

The main ions identified are Na^+, Cl^-, Mg^{2+}, K^+, Ca^{2+} and SO^{2-}. These inorganic ionic species (Na^+, Cl^-, SO_4^{2-}) and the crust-derived inorganic cations (Mg^{2+}, Ca^{2+}) influence the chemistry of precipitation. While the presence of H^+ ions increases the acidity of rainwater, variations in the concentrations of alkaline ions play a key role in neutralizing precipitation and reducing its acidity. In polluted environments such as the study area, emissions of SO_2 and NO_x promote the formation of acid rain. This acidic precipitation, in conjunction with other ions, accelerates stone decay in the thermal baths. Acid rain reacts with calcium carbonate and other minerals, causing surface erosion, discoloration, and a progressive loss of material integrity.

Furthermore, the widespread presence of black crusts on the limestone blocks of the West Cherchell thermal baths supports the interpretation proposed by Cachier et al. (2004), who demonstrated that black crusts are among the most common alteration forms affecting limestone in urban environments. This phenomenon is attributed to the interaction between SO_2, PM_{10} particles, and acidic precipitation, whereby calcium carbonate ($CaCO_3$), the principal constituent of limestone, is converted into gypsum ($CaSO_4 \cdot 2H_2O$), leading to both mechanical and chemical deterioration of the exposed stonework. Moreover, during crust formation, particles containing amorphous carbon and heavy metals become trapped within the gypsum matrix, imparting the characteristic blackened appearance to the surface (Rovella et al., 2021), as observed on the stones of the West Cherchell thermal baths.

The analysis of ionic balances and pH confirms that acidic inputs from polluted areas, together with crustal compounds (particularly calcite), contribute simultaneously to the neutralization of acidity within raindrops. All three rainwater samples reveal a strong marine influence, as indicated by elevated levels of Na^+ and Cl^-. This explains the presence of marine salts — particularly halite, with a solubility of 365 g·L⁻¹ at 20°C. Since these salts are readily soluble, they are easily transported by dilute aqueous solutions such as rainwater. Upon infiltration into stone and subsequent evaporation at the surface, these salts may re-concentrate and crystallize. The high solubility of these salts enables significant mobility and facilitates its accumulation in evaporation zones, especially at the stone surface. Salt crystallization is controlled by the porosity of the stone: it may occur at the surface as efflorescence, or several millimeters to centimeters beneath the surface as subflorescence, within the pore network (Bromblet, 2020).

Conclusion

The aim of this study was to identify the principal factors affecting the durability of the calcarenite used in the construction of the West Cherchell thermal baths. This involved assessing the conservation state of the material and evaluating several environmental parameters.

The observed alterations exhibit diverse morphologies, including disintegration, darkening, black crust formation, alveolization, and salt efflorescence. These forms of deterioration are intrinsic to the high porosity and specific textural characteristics of the calcarenite employed. Among the most common manifestations of sulfation in carbonate-rich stone are darkening and the development of superficial crusts. Surface soiling

is a complex process influenced by multiple factors, including ambient pollutant concentrations, deposition rates, the intrinsic properties of the stone (such as porosity and texture), and local microclimatic conditions. Surface orientation also significantly affects pollutant deposition, with vertical and shaded surfaces being particularly susceptible. As noted by Cioban et al. (2022), the interplay of these factors makes it difficult to quantify pollutant deposition rates precisely.

It is clear that stone degradation has accelerated significantly over recent decades, coinciding with the substantial expansion of the bus and automobile fleet in Cherchell. The extent of alteration varies with the degree of exposure to atmospheric agents and is exacerbated by the lack of protective structures at the site, leaving the ruins particularly vulnerable to weathering, including acid rain.

To better understand the interaction mechanisms between the atmosphere and the material, rainfall characteristics, temperature and humidity values, and microscopic and mineralogical features of the selected stone surfaces were examined. The results confirm that the marine climate contributes to the deterioration of the stone in question. The amount of salts — primarily sodium chloride (halite) — together with their dissolution–crystallization cycles and the frequency of these cycles at the site, plays a major role in the deterioration process. These cycles promote the formation of surface efflorescences, reflecting a substantial marine contribution to the stone, which is continuously exposed to both natural and polluted marine aerosols. However, it is important to emphasize that the deterioration observed in the study area most likely results from a complex interaction between acidic precipitation, natural and polluted marine aerosols, and architectural and material-related factors. This interaction is manifested in the disintegration and alveolization of the stone, as well as in the discernible recession of the surface in several areas.

References

Alomari, A. (2014). *Evaluation des risques d'altération d'origine thermo-hydro-mécanique des pierres du patrimoine bâti*. [online] Available at: https://theses.hal.science/tel-01069417/file/asaad.alomari_3619_vm.pdf [Date accessed 31/12/2016].

Angeli, M, Hébert, R, Menéndez, B, David, C., and Bigas, J.-P. (2010). Influence of temperature and salt concentration on the salt weathering of a sedimentary stone with sodium sulphate. *Engineering Geology*, Vol. 115, Issues 3–4, pp. 193–199. DOI: 10.1016/j.enggeo.2009.06.001.

Arnold, A and Zehnder, K. (1989). Salt weathering on monuments. In: *1st International Symposium on the Conservation of Monuments in the Mediterranean Basin,* Bari, Italy, June 7–10, 1989. [online] Available at: https://www.researchgate.net/publication/260552681_Salt_Weathering_on_Monuments [accessed on 13/12/2025].

Benderradji, A. and Ferhat, A. S. (2011). *Erosion du littoral de Cherchell: causes, conséquences et solution d'aménagement*. [online] Available at: https://virtuallibrary.enssmal.edu.dz/collection/item/5762-erosion-du-littoral-de-cherchell-causes-consequences-et-solution-d-amenagement?offset=1[Date accessed12/02/2018].

Benseddik, N. and Potter, T. W. (1993). *Fouilles du forum de Cherchel*. 1977-1981, ANAPMSH, Alger, P14.

Binda, L, Barronio, G, and Charola, A. E. (1985). Deterioration of porous materials due to salt crystallization under different thermo hygrometric conditions. I. Brick. In: Felix, G. (ed.). *5th International Congress of Deterioration and Conservation of Stone.* Lausanne: Presses Polytechniques, pp. 279–288.

Bromblet, P. (2020). *La conservation de la pierre en milieu salin.*, in Chimie et Alexandrie dans l'Antiquité, Maison de la Chimie, EDP Sciences, p. 71–84.

Cachier, H., Sarda-Estève, R., Oikonomou, K., Sciare, J., Bonazza, A., Sabbioni, C., Greco, M., Reyes, J., Hermosin, B., and Saiz-Jimenez, C. (2004). Aerosol characterization and sources in different European urban atmospheres: Paris, Seville, Florence and Milan. In: Saiz-Jimenez, C. (ed.). *Air Pollution and Cultural Heritage.* London: CRC Press, pp. 3–14.

Camuffo, D. (1998). *Microclimate for cultural heritage*. Amsterdam: Elsevier, 432 p.

Camuffo, D. and Bernardi, A. (1990). Atmospheric pollution and deterioration of monuments. In: *Advanced Workshop: Analytical Methodologies for the Investigation of Damaged Stones,* Pavia, Italy, September 14–21, 1990.

Chennaoui, Y. (2016). Notes sur le modèle urbanistique des villes portuaires de fondation andalouse au maghreb, après 1492: la medina de Cherchell (Algérie). *Le rôle des villes littorales du Maghreb dans l'histoire, RM2E - Revue de la Méditerranée*, Vol. 3, pp. 153–168.

Cioban, L. A, Dochia, M., Mureşan, C., and Chambre, D. R. (2022). Weathering and deterioration of carbonate stones from historical monuments: a review. *Scientific and Technical Bulletin, Series: Chemistry, Food Science and Engineering,* Vol. 19 (XX), pp. 15–33.

Darvill, T. (1995). Value system in archaeology. In Carman, J., Cooper, M., Firth, A., and Wheatley, D. (eds.). *Managing Archaeology.* New York: Routledge, pp. 59–69.

De Nevers, N. (2010). *Air pollution control engineering*. 2nd edition. Long Grove, IL: Waveland Press, 586 p.

Desarnaud, J., Bonn, D., and Shahidzadeh, N. (2016). The pressure induced by salt crystallization in confinement. *Scientific Reports,* Vol. 6, 30856. DOI: 10.1038/srep30856.

Dessandier, D. (1995). *Étude du milieu poreux et des propriétés de transfert des fluides du tuffeau blanc de Touraine: application à la durabilité des pierres en oeuvre*, Sciences de la terre. Géomatériaux.Tours, 280 p.

El-Gohary, M. A. (2008). Air pollution and aspects of stone degradation "Umayyed Liwân - Amman Citadel as a case study". *Journal of Applied Sciences Research,* Vol. 4, Issue 6, pp. 669–682.

El-Gohary, M. A. (2011). Analytical investigations of disintegrated granite surface from the un-finished obelisk in Aswan. *ArcheoSciences,* No. 35, pp. 29–39. DOI: 10.4000/archeosciences.2909.

Fassina, V. (1988). Environmental pollution in relation to stone decay. In J. Rosvall & S. Aleby (Eds.), *Air Pollution and Conservation: Safeguarding our Architectural Heritage*. Elsevier Science Publishers B.V., Amsterdam, pp. 317–358.

Grimes, S. (2011). *Profil de durabilité dans quelques destinations touristiques méditerranéennes. La destination touristique pilote en Algérie : la zone côtière de Tipasa*. [online] Available at: https://planbleu.org/sites/default/files/publications/profil_ durabilite_tourisme_algerie.pdf [date accessed 14/07/2019].

Gsell, S. (1901). *Les monuments antiques de l'Algérie. Vol. 1.* Paris: Paris: Ancienne Librairie Thorin et fils Alberts Fontemoing, 534 p.

Gsell, S. (1952). *Cherchel: antique Iol-Caesarea*. rééd. par le Service des antiquités de l'Algérie avec mise à jour par M. Leglay et E. S. Colozier, Alger, 125 p.

Haber, J., Haber, H., Kozlowski, R., Magiera, J., and Pluska, I. (1988). Air pollution and decay of architectural monuments in the city of Cracow. *Durability of Building Materials,* Vol. 5, Issues 3/4, pp. 499–547.

Hammecker, C. (1993). *Importance des transferts d'eau dans la dégradation des pierres en oeuvre*. PhD Thesis in Applied Sciences.

Jeannette, D. (2004). Les grès de la cathédrale : origines, évolutions et altérations. *Bulletin de la Société des Amis de la cathédrale de Strasbourg,* Vol. 26, pp. 157–172.

Jockey, P. (ed.) (2006). Marbres et autres roches de la Méditerranée antique : études interdisciplinaires. In: *Proceedings of the 8th International Conference of the Association for the Study of Marble and Other Stones Used in Antiquity (ASMOSIA),* Aix-en-Provence, France, June 12–18, 2006, 998 p.

Lefèvre, R.-A. and Ausset, P. (2001). Les effets de la pollution atmosphérique sur les matériaux du patrimoine bâti: la pierre et le verre. *Pollution Atmosphérique,* No. 172, pp. 571–588. DOI: 10.4267/pollution-atmospherique.2953.

Leveau, P. (1984). *Caesarea de Maurétanie. Une ville romaine et ses campagnes.* Rome: École Française de Rome, 576 p.

Lewin, S. Z. (1982). The mechanism of masonry decay through crystallisation. In *Conservation of Historic Stone Buildings and Monuments.* National Academy Press, Washington, D.C, pp. 120–144.

Malaga-Starzec, K, Sahlin, T., and Lindqvist, O. (2000). Laboratory investigations of weathering behaviour of fresh and impregnated limestone and sandstone from Central Sweden. In: Fassina, V. (ed.). *Proceedings of 9th International Congress on Deterioration and Conservation of Stone.* Amsterdam: Elsevier, pp. 349–356. DOI: 10.1016/B978-044450517-0/50117-3.

Mirwald, P., Kraus, K., and Wolff, A. (1988). *Stone deterioration on the Cathedral of Cologne, Rome*. Amsterdam, Oxford, New York: Elsevier, 22 p.

Ozga, I., Ghedini, N., Bonazza, A., Morselli, L., and Sabbioni, C. (2009). The importance of atmospheric particle monitoring in the protection of cultural heritage. *WIT Transactions on Ecology and the Environment,* Vol. 123, pp. 259–269. DOI: 10.2495/ AIR090241.

Price, C. (1997). Salt damage in porous materials: a threat to the cultural heritage. *Archaeology International,* Vol. 1, No. 1, pp. 47–48. DOI: 10.5334/ai.0114.

Rovella, N., Aly, N., Comite, V., Randazzo, L., Fermo, P., Barca, D., Alvarez de Buergo, M., and La Russa, M. F. (2021). The environmental impact of air pollution on the built heritage of historic Cairo (Egypt). *Science of the Total Environment,* Vol. 764, 142905. DOI: 10.1016/j.scitotenv.2020.142905.

Russ, J., Kaluarachchi, W. D., Drummond, L., and Edwards, H. G. M. (1999). The nature of a whewellite-rich rock crust associated with pictographs in southwestern Texas. *Studies in Conservation,* Vol. 44, Issue 2, pp. 91–103. DOI: 10.2307/1506721.

Tazi, C. and Touahir, N. (2011). *Détermination de l'influence des rejets des eaux usées brutes sur la qualité bactériologique et physicochimique des eaux de mer. Cas d'EL KATTER (a proximité de port de Cherchell, wilaya de TIPAZA*. P22. [online] Available at: https://dspace.enssmal.edu.dz/items/4dff3aa5-110b-4367-8728-c8bef165b8aa [accessed on 14/12/2025].

Thomas, W. N. (1938). Experiments on the freezing of certain building materials. Building Research Technical Paper No. 17, Department of Scientific and Industrial Research, London

Tsui, N., Flatt, R. J., and Scherer, G. W. (2003). Crystallization damage by sodium sulfate. *Journal of Cultural Heritage,* Vol. 4, Issue 2, pp. 109–115. DOI: 10.1016/S1296-2074(03)00022-0.

Van Grieken, R., Delalieux, F., and Gysels, K. (1998). Cultural heritage and the environment. *Pure and Applied Chemistry,* Vol. 70, No. 12, pp. 2327–2331. DOI: 10.1351/pac199870122327.

Yacono, X. (1955). *La colonisation Des Plaines du Chélif.* Algiers: Impr. E. Imbert, Vol. 1, 136 p.

Zaouia, N., El Wartiti, M., Nahraoui, F. Z., and Dabi, S. (2014). Etude de l'altération de la calcarénite des monuments de Rabat: influence de la pollution atmosphérique et des aérosols marins. *MATEC Web of Conferences,* Vol. 11, 03015. DOI: 10.1051/matecconf/20141103015.

ДЕГРАДАЦИЯ СТРОИТЕЛЬНОГО КАМНЯ ТЕРМ ЗАПАДНОЙ ЧАСТИ КЕСАРИИ МАВРИТАНСКОЙ (ШЕРШЕЛЬ, АЛЖИР)

Абла Брахми*, Мессауд Хамиан, Кэмел Бузетин

Научно-исследовательский отдел «Материалы, процессы и окружающая среда», технологический факультет, Университет M'hamed Bougara, Бумердес, Франц Фанон, 35000, Алжир

*Email: a.brahmi@univ-boumerdes.dz

Аннотация
Введение. Термальные бани, расположенные в западной части древней Цезареи Мавретанской, датируемые концом II века н.э., были построены с использованием плоских кирпичей и блоков из камней различной литологии, почти 90 % которых составляют калькарениты. **Цель данного исследования —** оценить состояние сохранности этого камня, использованного в одном из наиболее значимых термальных сооружений в архитектурном наследии Шершеля. **Методы.** Исследование включало определение физико-механических свойств выбранных образцов, сбор дождевой воды и регистрацию термогигрометрических параметров на месте. Здоровые и выветренные поверхности были охарактеризованы с помощью поляризационной микроскопии, сканирующей электронной микроскопии в сочетании с энергодисперсионной рентгеновской спектроскопией (SEM-EDX) и рентгеновской дифракцией (XRD). **Результаты.** Полевые наблюдения показывают значительное разрушение калькаренита, проявляющееся в образовании черных корок, альвеолизации, гранулярном распаде и поверхностных солевых выцветаниях. Физико-химические анализы подтверждают наличие солей морского происхождения, а также отложений, связанных с загрязнением атмосферы. Совокупность данных указывает на то, что динамика разрушения калькаренита обусловлена поступлением морских солей и атмосферных загрязнителей, воздействие которых усиливается местными климатическими условиями. Эти взаимодействующие факторы объясняют ускоренные процессы деградации, наблюдаемые в исследуемых термальных структурах.

Ключевые слова: термы западной части Шершеля; калькаренит; выветривание; морские соли; атмосферное загрязнение.