

# Environmental impact on construction limestone at humid regions with an emphasis on salt weathering, Al-hambra islamic archaeological site, Granada City, Spain: case study

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**Abstract** Al-hambra is an immense and valuable archaeological site in Spain built on Sabika hill with red brick and natural sandy limestone. It exhibits weathering features indicating salt weathering process. The main aim of this study is to examine weathering processes and intensity acting on Al-hambra. Rock petrography and mineralogical composition have been examined using thin sections, scanning electron microscope, X-ray diffraction and X-ray fluorescence; limits of rock's physical parameters using ultrasonic waves and mercury porosimeter; rock salt content through hydrochemical analysis. Salts attacking this structure are mainly from wet deposition of air pollutants on the long term chemical alteration of rock's carbonate content to its equivalent salts. The salts' concentration limit within the examined rock samples is considerably low but it is effective on the long run through hydration of sulphate salts and/or crystallization of chloride salts. Rock texture type and its silica as well as clay content reduces its resistance to internal stresses by salts as well as wetting and drying cycles at such humid area. The recession in limits of physical parameters examined for deep seated and weathered limestone samples quantitatively reflects weathering intensity on Al-hambra.

**Keywords** Salt weathering · Wetting and drying · Red brick and limestone

## Introduction

Weathering processes and their severity acting on natural or artificial building stones at a given area are controlled by many parameters, the most important of them are; climatic conditions represented by air temperature and relative humidity that controls number and severity of weathering cycles (Smith and McGreevy 1983; Matsukura and Matsuoka 1996; Kamh 2005); limits of rock's geotechnical parameters that control its susceptibility (or durability) to weathering processes at a given area (Maria et al. 2000; Kamh 2004a); and mortar composition that either acts as salt source to itself and the surrounding construction rock (e.g. weak hydraulic lime mortar affected by acid rain) or act as a barrier (for hard mortars) enabling the environmental conditions to mainly act on its adjacent construction rock forming alveolar weathering form (Alvarez et al. 2000; Kamh 2004b).

Although the Islamic archaeological sites are very recent compared with the other sites that can be dated back to more than 5,000 years BP, they suffer weathering (particularly salt weathering) as well as the oldest sites do. This is not related to their ages, but mainly to the aggressive environmental conditions that act in the latest few decades (ages of atomic power).

Salt weathering has been recorded not only in the Middle East (with its arid and extremely arid climate, Fookes and Collis 1975; Cooke 1994; Kamh 2004b, 2005) but also at humid and preglacial regions (Robinson and Williams 1994). It can be detected and examined through field observations with its diagnostic features e.g. honeycomb, white salt efflorescence, stone surface contour scaling and exfoliation, rock meal and pop-outs (McGreevy 1983; Turkington and Philipps

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2004) and laboratory analysis for the extracted solutions prepared from the rock samples collected from Al-hambra.

Almeria province is located at southeast of Spain involving Granada City (Fig. 1). Its climate is semi-arid to arid with an annual precipitation approximately 200 mm, average annual temperature 10°C during winter and 32°C in summer (Gerd 1996). Al-hambra at Granada City is one of the most famous historical Islamic structures in Europe as it has an immense size and unique design attracting many tourists from everywhere. It has been built since 1238 (i.e. 768 years BP). It is situated above Sabika hill (one of the foothills of Sierra Nevada on the plain of Granada) that is nearly 3,400 m above sea level.

Water springs running in artificial channels through this structure downhill, percolating Gochar Conglomerate underlying Al-hambra, may affect the bedrock stability at the study area.

The main aim of the current study is to examine weathering processes and intensity acting on Al-hambra with an emphasis on salt weathering, as its weathering features are very common at the study area.

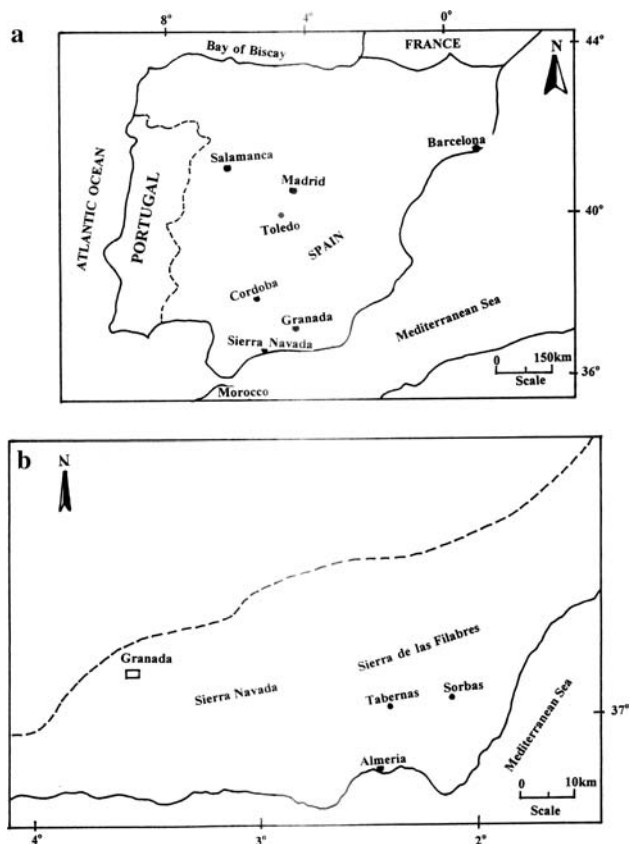
## Methodology

The weathering features have been reported, and rock samples from the weathered parts of this structure as well as deep seated (unweathered) samples have been collected to examine rock petrography and mineralogy that reflect its susceptibility to weathering on both macro- and micro-scale. This has been achieved through thin section study using a transmitting polarizing microscope, scanning electron microscope (Hitachi SEM), X-ray diffraction (Scintage XRD) and X-ray fluorescence (XRF). Acid insoluble residue test (AIR) has been conducted to indicate the purity of the construction limestone of this structure, based on Harrison classification (1993). The rock's purity limit throws light on rock's resistance to wetting and drying cycles that dominate at the study area, particularly in winter.

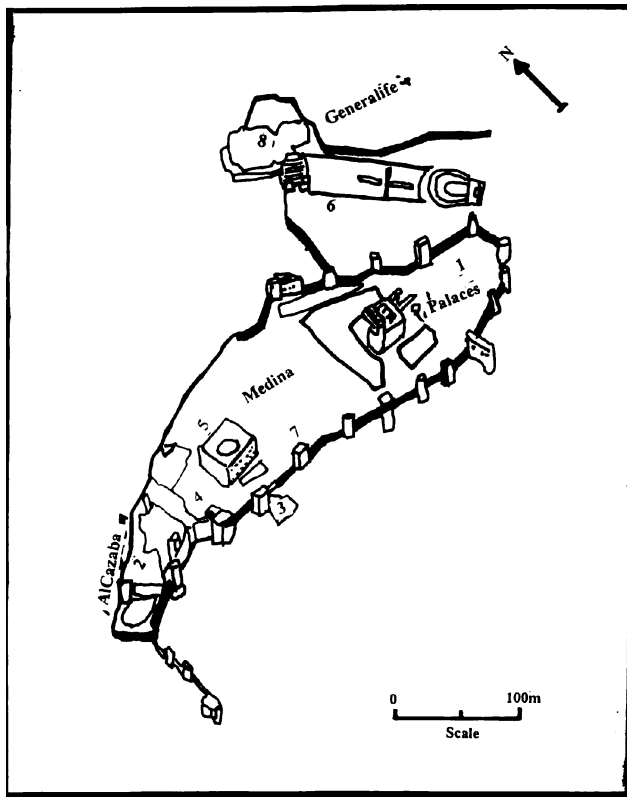
Hydrochemical analysis has been conducted on the extracted solutions (prepared from the collected samples) following the method of Rhoades (1982). This is to find out total dissolved salts, type and percentage of salt content to explain the role and severity of salt weathering at Al-hambra.

A quantitative measuring for weathering intensity on limestone constituting Al-hambra has been conducted by measuring the velocity of ultrasonic waves and rock internal friction as well as physical parameters (as total cumulative volume of rock pores, bulk density, rock pore diameter and total porosity) using mercury porosimeter for weathered limestone samples and deep seated samples of same rock type at Al-hambra. The ultrasonic velocity " $C_p$ " and rock internal friction " $Q^{-1}$ " have been measured using a magneto-structive ultrasonic at frequency up to 40 kHz and the samples have been prepared following the method of Kapranos et al. (1981) and both of  $C_p$  and  $Q^{-1}$  have been computed from the following equations:  $C_p = 2Lf/n$ ,  $X = [(A_o + A_t)/(A_o - A_t)]$  and  $\ln Q^{-1} = \{\ln [2/(1 - X)]\}/(1 + X)$ , where " $C_p$ " is velocity of ultrasonic waves (km/s), " $L$ " is the sample length, " $f$ " is the frequency of ultrasonic waves, " $n$ " is the mode number at which we get the best Echo-form for the ultrasonic waves, " $A_o$ " is the amplitude of initial waves, " $A_t$ " is the amplitude of the steady waves, " $Q^{-1}$ " is the rock internal friction.

Mercury porosimeter has been used to measure rock's physical parameters mentioned above at low and high pressure of mercury for weathered and deep-seated rock samples from Al-hambra. This is to quantify rock's weathering intensity by comparing limits of weathered limestone with that of deep-seated limestone.



**Fig. 1** Base map of Spain (a), Almeria Province, southeast Spain presenting Granada and its surroundings (b)



**Fig. 2** Sketch diagram of Al-hambra with location of the collected samples, Granada City, Spain



**Fig. 3** Stone surface disintegration, damp stone surface and obliteration of surface render at Salida, Al-hambra structure

**History and structure of Al-hambra**

Al-hambra was a palace, a citadel, a fortress and home of the Nadrid Sultans, high government officials, servants of the court and elite soliders of the Nasrid Dynasty (1238–1492), the last Islamic sultanate in the Iberian Peninsula. The Nasrid Sultans chose this site

for their court the Sabika hill, one of the foothills of Sierra Nevada on the plain of Granada, which constituted an excellent site from which to keep watch over the capital of their kingdom and the surrounding area. Al-hambra became a Christian Court in 1942 when the Catholic Monarchs (Ferdinand and Isabel) conquered the city of Granada. During the eighteenth century and part of the nineteenth, the Al-hambra fell into neglect and occupied by thieves and beggars. Incredible neglect continued until 1870 when Al-hambra was declared a national monument. Since that date, Al-hambra is protected and restored for the pleasure of all.

Structurally, Al-hambra is divided into four main parts, namely; the Generalife: “this means the garden of the architect which is consisted of beautiful gardens”; the Medina or Town: “It occupies the largest part of the walled area within the upper Al-hambra conserves, the ruins of several houses, baths and small workshops”; the Palaces: “Nasrid Palaces consist of a number of brilliantly designed and decorated function rooms and were used by the Muslim rulers for different purposes”; and Al-Cazaba or Fortress: “this military fortress was built on the oldest site of the Al-hambra, it was situated on the highest part of the hill watching over the surrounding area, the original construction had 24 towers but only a few remain” (Fig. 2). Some parts of Al-hambra have been constructed from red brick (Fig. 3) and others from natural limestone. The weathering features are noted as white salt efflorescence, pop-outs and damp stone surfaces (Figs. 4, 5), disintegration of construction stone surface and render (Figs. 3, 5); narrow single to map cracks associated with vegetation growth within these cracks can be noted (Fig. 6).

**Bedrock stratigraphy**

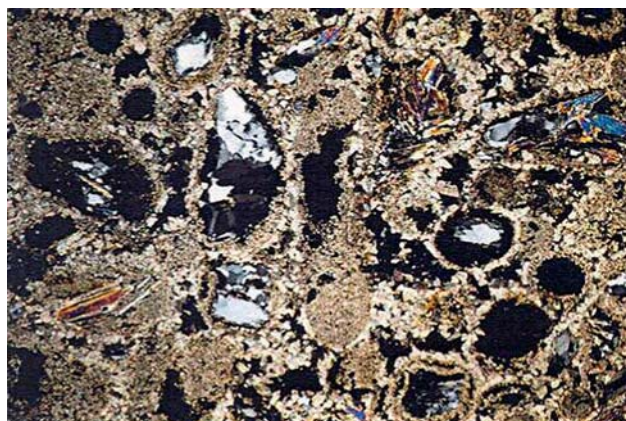
Al-hambra has been constructed on Sabika hill of Sierra Nevada on the plain of Granada of height 3,400 m above sea level. The stratigraphic sequence at the study area is as follows (Mather 1994):

- Youngest    Gochar Conglomerates
- Zorreras red marls and sands
- Sorbas white marls and sands
- Gypsum and laminites
- Basal Calcarenite
- Garnet Schist
- Oldest        Augen Gneiss

Gochar conglomerates are alluvial fans coming off the Sierra de los Filabres and Sierra Nevada. It is affected



**Fig. 4** White salt efflorescence on the Islamic ingaves at Al-Cazaba Palace, Al-hambra



**Fig. 7** Thin section photomicrograph presenting sandy limestone with evaporates “gypsum and halite”, Al-Hambra construction rock



**Fig. 5** Damp stone surface, pop-outs, white salt efflorescence and render obliteration noted on wall side of Al-hambra



**Fig. 6** Narrow single to map cracks at some parts of Al-hambra, 35% of the surface render are obliterated, tiny plants grow up through these cracks

by vertical normal fault that contain minor normal faults (Joanne 1993). From the field study, it can be noted that Gochar conglomerates underlying Al-hambra is dipping to the south at a measured dip angle of  $31^\circ$  and it is semi-lithified thickbed.

## Results

The following is presentation of the results of the laboratory analyses that have been conducted for the samples collected from Al-hambra to get the aims of this research.

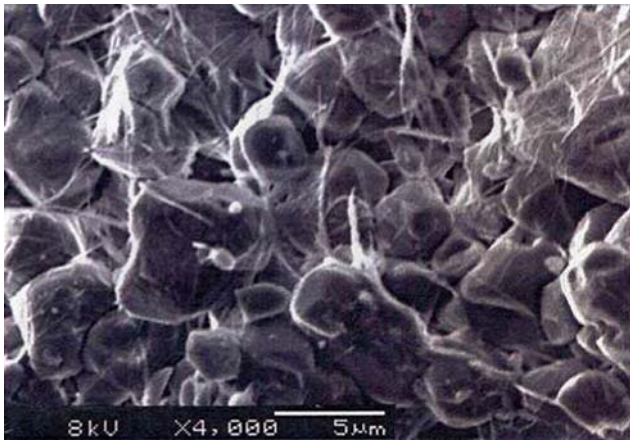
### Petrographic study

Thin section study has been conducted for the limestone constituting some parts of Al-hambra, indicating that this construction rock is sandy limestone with rounded carbonate allochems, mono to polycrystalline subrounded wavy extinction quartz grains. The allochems are cemented by micrite and microspars and inter and intragranular porosity can be noted (Fig. 7). Such limestone is defined as sandy limestone of wackestone texture.

Scanning electron microscopic study has been conducted on this construction rock to clarify in detail about the matrix. It indicated that the matrix is not only microspar but also illite as clay mineral (Fig. 8).

X-ray diffraction has been conducted for the sandy limestone of Al-hambra, indicating its mineralogical composition to be mainly calcite, then gypsum, quartz and halite (Fig. 9).

X-ray fluorescence has been conducted for four rock samples to examine the major elements composing the



**Fig. 8** Scanning electron photomicrograph presenting rock micro-porosity, cement type and illite within texture of construction rock of Al-Hambra

carbonate rock of Al-hambra and the results are listed in Table 1.

The major elements examined for these rock samples are so similar to the mineral analysis conducted for the same samples using XRD. It can be noted that calcium oxide indicated by XRF, is the dominant oxide followed by SiO<sub>2</sub> with noticeable content of other oxides as Fe<sub>2</sub>O<sub>3</sub>, MgO and Al<sub>2</sub>O<sub>3</sub> (Table 1). This construction rock also has a considerable sulphur content that ranges from 0.26 to 0.52% (Table 1), that is expected to be a result of wet deposition of sulphur on stone surface at conditions of high relative humidity (in winter or during moisture condensation on stone surface due to thermal gradient from the

sunny to the shady parts of this structure in Summer) (Piguet and Helal 1988; Rao et al. 1992; Haneef et al. 1993).

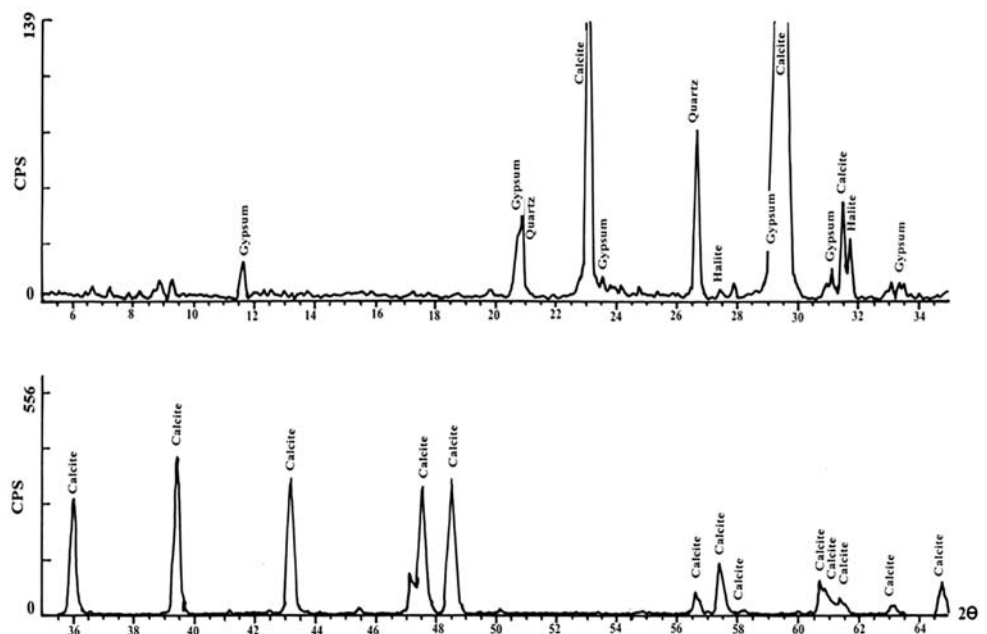
Acid insoluble residue test has been conducted for six rock samples collected from this construction carbonate rock (Table 2). It indicated that this rock has a considerable percentage of silica (sand and clay size) and so it is sandy argillaceous limestone. The insoluble residue ranges from 8.3 to 39.0% of the rock components. This may indicate the impact of sand and clay content on rock’s resistance to wetting and drying, where both of them reduce rock’s strength to stresses as that resulted from salt weathering on salt crystallization and/or hydration (Hugman and Friedman 1979; Waltham 1993).

### Hydrochemical results

It has been conducted for the extracted solutions prepared [following the method of Rhoades (1982)] for eight rock samples collected from the weathered parts (Figs. 4, 5), the results are listed in Table 3. This is to clarify how much total dissolved salts are present in these weathered parts as well as type of hypothetical dissolved salts that control weathering intensity (Cooke 1994).

The total dissolved salts of these samples range from 564 to 9,601 ppm and the hypothetical dissolved salts are represented by sulphates (mainly CaSO<sub>4</sub>, MgSO<sub>4</sub> and Na<sub>2</sub>SO<sub>4</sub>) and chlorides (mainly NaCl and KCl). The limit of total dissolved salts is not considerably high compared with other archaeological sites at arid

**Fig. 9** X-ray diffraction chart presenting mineralogical composition of rock



**Table 1** Major elements examined by X-ray fluorescence for four rock samples collected from Al-hambra

Code of rock sample	Major elements (%)							
	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MgO	CaO	SO <sub>2</sub>	K <sub>2</sub> O	MnO
AH3	7.06	1.77	0.63	2.52	86.23	0.49	1.12	0.03
AH4	20.99	4.98	1.88	5.93	64.25	0.51	1.09	0.04
AH5	8.48	1.66	0.53	4.45	83.40	0.26	1.09	0.01
AH7	4.70	1.26	0.47	1.67	90.53	0.52	0.72	0.03

**Table 2** Acid insoluble residue results for six rock samples collected from Al-hambra, Granada City, Spain

Code of rock sample	Carbonate (%)	Acid insoluble residue (%)	Weight percentage of each grain size fraction						Facies type
			1 mm	0.5 mm	0.25 mm	0.125 mm	0.0625 mm	<0.0039 mm	
AH1	67.0	33.0	0.0	0.0	30.0	10.0	0.0	60.0	SAL
AH2	91.7	8.3	10.0	5.0	0.0	5.0	0.0	80.0	SAL
AH3	79.7	20.3	30.0	10.0	3.0	7.0	0.0	50.0	SAL
AH4	61.0	39.0	45.0	0.0	0.0	0.0	0.0	55.0	SAL
AH5	78.7	21.3	38.0	0.0	2.0	0.0	0.0	60.0	SAL
AH6	69.6	30.4	36.0	14.0	10.0	0.0	0.0	40.0	SAL

SAL sandy argillaceous limestone

climatic regions (Kamh 1994) that ranges from 35,725 to 332,401 ppm or more than this limit, and it is a noticeably high limit if compared with total dissolved salts of the weathered Roman-Medieval Chester City walls at temperate regions, UK [ranging from 215 to 2,580 ppm, Kamh (2002)]. This considerable content of total dissolved salts is effective in the long term on both of construction rock, mortar and render, as noted at the study area.

#### Ultrasonic and mercury porosimeter results

A magneto-structive ultrasonic has been used to compute velocity of the ultrasonic waves and rock internal friction for the weathered and deep-seated limestone samples of Al-hambra to quantitatively reflect weathering intensity. The results are listed in the table below. Based on the above measurements and using Stefan and Anne (2000) classification (four classes started with class zero for fresh limestone up to class 3 for the totally damaged limestone) for limestone damage based on ultrasonic parameters, it can be noted that the deep seated limestone is within class 1 (slightly weathered or originally with considerable porosity), and the weathered limestone is within class 2 (moderately weathered rock).

The variation in ultrasonic velocity from fresh (unweathered or deep seated samples) to weathered state can reflect in percentage the recession in rock's cohesion nature (its weathering intensity). This can be computed using Esbert et al.'s (1995) equation:

$\Delta V = \{(V_u - V_w)/V_u\} \times 100$ , where  $V_u$  is velocity of ultrasonic waves for unweathered sample, and  $V_w$  is velocity of ultrasonic waves for weathered sample. The average values will be considered here, as the weathered samples listed above are not from the same block of deep-seated samples.  $\Delta V = \{(2.9 - 1.93)/2.9\} \times 100 = 33.45\%$  which means that the weathering resulted in the limestone losing about one-third of its original cohesion.

Mercury porosimeter (140 Pa) has been used at low and high mercury pressure (140 and 400 Pa) for one fresh (deep seated) limestone sample and one weathered sample. The number of samples is insufficient to get a real view of recession in rock's physical parameters (pore volume, pore diameter, total porosity and bulk density) due to weathering, but laboratory facilities control such limited number and the results are listed below.

From the above results, it can be noted that limits of all examined parameters (either at low or high mercury pressure) recessed on weathering i.e. total porosity (TP), average pore diameter (APD) and total cumulative volume of rock pores (TCV) parameters have been increased, while  $\sigma d$  has been decreased on weathering.

#### Discussion

The weathering features as well as the hydrochemical analysis of the collected rock samples at Al-hambra

**Table 3** Hydrochemical analysis of rock and water samples collected from Al-hambra Islamic archaeological site, Granada, Spain

Code of sample	Sample type	TDS (ppm)	Cations (ppm)				Anions (ppm)			
			Ca <sup>++</sup>	Mg <sup>++</sup>	Na <sup>+</sup>	K <sup>+</sup>	Cl <sup>-</sup>	SO <sub>4</sub> <sup>-</sup>	CO <sub>3</sub> <sup>-</sup>	HCO <sub>3</sub> <sup>-</sup>
AH1	LS	564	16	19	69	47	27	288	0.0	98
AH2	LS	9,601	1344	691	667	410	1,893	4,474	0.0	122
AH3	LS	5,278	832	77	575	265	1,038	2,381	0.0	110
AH4	LS	5,015	752	163	474	195	837	2,496	0.0	98
AH5	LS	5,515	944	96	699	468	1,456	2,688	0.0	61
AH6	LS	2,429	400	96	122	78	146	1,478	0.0	110
AH7	LS	2,535	544	115	48	43	127	1,536	0.0	122
AH8	LS	2,185	464	67	46	47	36.5	1,402	0.0	122
W	Water	1,874	272	29	184	105	231	864	0.0	183

Percentage of hypothetical dissolved salts							
KCl	NaCl	CaCl <sub>2</sub>	K <sub>2</sub> SO <sub>4</sub>	Na <sub>2</sub> SO <sub>4</sub>	CaSO <sub>4</sub>	MgSO <sub>4</sub>	Mg(HCO <sub>3</sub> ) <sub>2</sub>
9.5	0.0	0.0	8.7	45.5	12.1	5.1	19.1
6.3	17.7	11.9	0.0	0.0	40.9	33.8	1.3
8.6	27.6	0.0	0.0	3.7	52.1	5.7	2.3
6.6	24.0	0.0	0.0	2.8	48.9	15.7	2.0
12.3	29.5	0.0	0.0	1.6	48.4	7.1	1.1
5.7	5.5	0.0	0.0	9.5	74.4	17.7	4.9
2.7	5.3	1.6	0.0	0.0	66.4	18.7	5.3
3.1	0.0	0.0	0.6	6.3	72.3	11.5	6.2
10.2	14.0	0.0	0.0	15.9	49.0	0.0	9.0

LS limestone sample

**Table 4** Velocity of ultrasonic waves and rock internal friction for Al-hambra limestone

Limestone state	Sample code	C <sub>p</sub> (km/s)	Q <sup>-1</sup> (MPa)
Deep seated (unweathered)	AH9	2.8	9.0
	AH10	3.0	8.6
	AH11	2.9	9.0
Weathered	AH2	1.9	11.9
	AH3	1.8	12.4
	AH4	2.0	11.2
	AH5	2.0	11.1

confirm that salt weathering has a great impact on both the red brick and the limestone forming this building. Sulphate salts (particularly CaSO<sub>4</sub> and MgSO<sub>4</sub>) on hydration at such region (particularly in winter) have a great impact on construction rock and render (Goudie 1977; Moses and Smith 1994). The climatic conditions for sulphate hydration at the study area are suitable where the dense plant-cover and the tall trees at most parts of this structure form a good environment for moisture condensation on stone surfaces as well as the thermal gradient from the sunny areas to the shady areas (Piguët and Helal 1988; Kamh 2005).

The noticeable chloride salt content (particularly NaCl salt) facilitates moisture trapping in the stone surfaces, and its presence with sulphates facilitates hydration of these sulphates (Goudie 1977; Moses and

Smith 1994). In Summer time, the climate is arid at the study area and hence, chloride salts are able to crystallize within rock pores as well as at the stone surface. Such salts exert high crystallization pressure within rock pores, resulting in deterioration of rock texture and formation of salt weathering phenomenon as recorded at the study area (Figs. 3, 4, 5).

The noticeable sulphur content indicated by XRF and detected in the hydrochemical analysis as sulphate salts reflect the pollution level at the study area in the long term. This sulphur reacts with the calcium content of the construction limestone forming CaSO<sub>4</sub> salt. Sulphates are also expected to be derived from spray of the water running within Al-hambra where it has CaSO<sub>4</sub> and Na<sub>2</sub>SO<sub>4</sub> presenting the highest percentage of its hypothetical dissolved salts (Table 3). Generally, salt weathering impact is severely noted on the Islamic ingaves at some parts (e.g. Al-Cazaba) of this building.

The secondary minerals (particularly silica as sand grains and illite) as well as cement type (sparite) in the construction limestone of Al-hambra, have to an extent, a recession impact on rock's cohesion and resistance to weathering processes particularly salt weathering, wetting and drying (that are expected to dominate in Spain) (Kevin and Hall 1996; Fan et al. 1996; Kamh 2003). The recession in rock's cohesion is

**Table 5** Physical parameters tested for Al-hambra limestone using mercury porosimeter

Sample state	Physical parameters at low pressure (140 Pa)				Physical parameters at high pressure (400 Pa)			
	TCV (cc/gm)	APD (micron)	TP (%)	$\sigma_d$ (gm/cm <sup>3</sup> )	TCV (cc/gm)	APD (micron)	TP (%)	$\sigma_d$ (gm/cm <sup>3</sup> )
Weathered limestone	0.103	22.05	15.06	1.47	0.061	1.04	13.1	1.91
Fresh limestone	0.090	18.07	11.01	1.91	0.042	1.01	10.2	2.01

TCV total cumulative volume of rock pores (cc/gm), APD average pore diameter (micron), TP total porosity (%),  $\sigma_d$  bulk density (gm/cm<sup>3</sup>)

reflected quantitatively on measuring rock's physical parameters using mercury porosimeter for the weathered and deep seated samples as well as on measuring ultrasonic waves velocity (that is reduced for the weathered samples due to increasing rock's porosity) and rock's internal friction that is increased on weathering (Table 4).

Plant growth within some cracks of this building's walls (Fig. 6) is a reflection of air humidity or rock moisture content that enables salt hydration at low temperature. Such plant growths result in increasing the width of cracks' aperture and such cracks are good micro-environment for moisture condensation; consequently, wet deposition of air pollutants takes place reacting with rock's carbonates forming aggressive salts acting on Al-hambra as noted and examined in the current study Table 5.

## Conclusion

Al-hambra is an immense and valuable Islamic structure. It suffers weathering by several processes; arranged in a decreasing order of its severity as follows: salt weathering, wetting and drying, and growth of plant roots (physical biological weathering) through cracked walls of Al-hambra. These processes easily work on such porous and weak-texture construction rock of Al-hambra.

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## References

- Alvarez JJ, Montoya C, Navarro I, Martin A (2000) Preliminary studies about the ancient mortars of the Church of Santa Maria de Irache Monastery (Navarra, Spain). In: Proceedings of 9th international congress on deterioration and conservation of Stone, 19–24 June 2000. Elsevier, Amsterdam, pp 873–880
- Cooke RU (1994) Salt weathering and the urban water table in deserts. In: Robinson DA, Williams RBG (eds) Rock weathering and landform evolution, pp 193–205
- Esbert RM, Valdeon L, Ordaz J, Gross CM (1995) Ultrasonic velocity and humidity in monumental stones. *J Stone* 18:597–600
- Fan C, Allison RJ, Mervyn EJ (1996) Weathering effect on the geotechnical properties of argillaceous sediments in tropical environments and their geomorphological implications. *Earth Surf Process Landf* 21:49–66
- Fookes PG, Collis L (1975) Problems in the Middle East. *Concrete* 9:12–17
- Gerd KM (1996) Cavernous weathering in the basin and range area, South-western USA and North-western Mexico. *Z Geomorph N F* 106:73–97
- Goudie AS (1977) Sodium sulphate weathering and the disintegration of Mohenjo-Daro, Pakistan. *Earth Surf Process Landf* 2:75–86
- Haneef SJ, Johnson JB, Thompson GE, Wood GC (1993) The degradation of coupled stones by wet deposition processes. *Corros Sci* 34(3):497–510
- Harrison DJ (1993) High purity of limestone in England and Wales. *Q J E G London* 26:293–303
- Hugman RH, Friedman M (1979) Effects of texture and composition on mechanical behavior of experimentally deformed carbonate rocks. *Am Ass Petrol Geol Bull* 63:1478–1489
- Joanne J (1993) An assessment of the contributing climatic elements to evaporation, Almeria Province, S. E. Spain. Modular Scheme, Kingston University
- Kamh GME (1994) The impact of geological conditions on the Islamic archaeological sites at El-Gammalia area, Cairo City, Egypt. MSc Thesis, Faculty of Science, Menoufiya University, Egypt
- Kamh GME (2002) Study of weathering processes and modes of restoration on Chester Medieval City walls, Chester City, UK. Project funded by Chester City Council
- Kamh GME (2003) Determination of the suitability of five limestone facies for reconstruction of archaeological sites, petrological, durability and geotechnical investigations. *Int J for Restor Build* 9(5):491–512
- Kamh GME (2004a) Geologic and geotechnical characterization of the sandstone for restoration of archaeological sites fourteen Triassic Red sandstone quarries in Great Britain, a case study. *Int J Restor* 10(4):347–366
- Kamh GME (2004b) Impact of hydraulic lime mortar on the construction sandstone of archaeological sites, Chester City walls, a case study. *Int J Restor* 10(1):51–72
- Kamh GME (2005) Weathering processes at Flint Castle, North Wales, Great Britain, Geo-environmental investigations. *Int J Restor Build Monum* 11(3):151–164
- Kapranos PA, Al-Helaly MMH, Whittaker VN (1981) Ultrasonic velocity measurements in 316 Austenitic Weldments. *Br J Non-destr Test* 23(6):211–222
- Kevin H, Hall A (1996) Weathering by wetting and drying: some experimental results. *Earth Surf Process Landf* 21(4):365–376

- Maria AG, Maria AV, Emilio G, Zezza F (2000) The physical-mechanical properties and ultrasonic data as criteria for evaluation of calcareous stone decay. In: Proceedings of 9th International Congress on Deterioration and Conservation of Stone, June 2000. Elsevier, Amsterdam, pp 309–312
- Mather A (1994) Cortijo Urra field week 1st–8th September, 1994, field guide
- Matsukura Y, Matsuoka N (1996) The effect of rock properties on rate of tafoni growth in coastal environments. *Z Geomorph N F* 106:57–72
- McGreevy JP (1983) Stone decay in an urban environment: observations from South Belfast. *Urban J Archaeol* 46:167–171
- Moses CA, Smith BJ (1994) Limestone weathering in the Supratidal zone: an example from Mallorca. In: Robinson DA, Williams RBG (eds) *Rock weathering and landform evolution*, pp 433–451
- Piguet JP, Helal H (1988) Geotechnical phenomena in sites and monuments of Egyptian antiquity. In: Marinos and Koukis (eds) *Engineering Geology of ancient works, monuments and historical sites, preservation and protection*, vol 1, pp 153–160
- Rao PS, Khemani LT, Momin GA, Phillai AG (1992) Measurements of wet and dry deposition at an urban location India. *Atmos Environ* 26B(1):73–78
- Rhoades JD (1982) “Soluble salts”, methods of soil analysis, part 2: chemical and microbiological properties, agronomy monograph No. 9 (2nd edition)
- Robinson DA, Williams RBG (1994) Sandstone weathering and landforms in Britain and Europe. In: Robinson DA, Williams RBG (eds) *Rock weathering and landform evolution*, pp 371–389
- Smith BJ, McGreevy JP (1983) A simulation study of salt weathering in hot deserts. *Geografiska Annaler* 65A:127–133
- Stefan S, Anne ML (2000) Decay of limestone blocks in the block fields of Karnak Temple (Egypt): non-destructive damage analysis and control of consolidation treatments. *J Stone* 14:743–749
- Turkington AV, Philipps JD (2004) Cavernous weathering, dynamical instability and self-organization. *Earth surf process landf* 29:665–675
- Waltham AC (1993) Crown hole development in the sandstone caves of Nottingham. *Q J E G* 26:243–251