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Weathering Progress and Its Mapping Using Non-Destructive Tools and GIS, Eleven Years of Investigation, Aachen City Sandstone Walls, Germany, Case Study

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ABSTRACT

Rock's surface micro-topography and geotechnical properties' limits are almost altered, on weathering progress, to a new form(s) and limits respectively. The quantification of weathering damage for a given rock is of value to take a decision regarding conservation urgency. The current study aims to examine the variation/constancy of micro-topography, geotechnical properties' limits and the damage category distribution and its variation for the sandstone constituting the ancient Aachen City wall, on weathering progress over eleven years of investigation (2007 and 2018). The Micro-erosion meter (MEM) and Equitop Hardness Tester (EHT) are tools used for micro-topographic and rock's surface hardness investigations. Arc GIS (10.1) had been used to find out the distribution and mean damage category at four representative parts of this wall on 2007 and 2018. These tools are accurate, numerical, easily applicable and preferable particularly for ancient buildings where sampling is not recommended or prohibited. The wall side under investigation had been selected as its constructional blocks present a wide spectrum of weathering forms and damage categories. The net result of the current study indicated a noticeable variation in stone's micro-topography and reduction of rock's surface hardness over the period of investigation. The rock's mean damage category had been increased from slight to moderate over the eleven years of investigation as mapped and mathematically processed using GIS (10.1).

Keywords: *Field investigations, MEM, EHT, GIS mapping for rock's damage categories*

INTRODUCTION

Weathering is the deformation or decomposition of materials through physical and/or chemical processes respectively. It is acting on all sub-aerial materials, particularly constructional rocks of a given building, deforming or altering its original topographic and geotechnical (petrophysical and mechanical) properties' limits to a dramatic forms and limits respectively. Some diagnostic weathering forms can be noted at stone's surface characterizing weathering processes that took place over several decades ago (Smith and McGreevy, 1985; Turkington, 1998; Fitzner et al., 2002; and Fitzner and Heinrichs, 2002). The investigation of weathering progress on the constructional materials of a given building is of value to be considered, quantified and rated particularly before conservation decision is made. Fitzner et al (1995) is considered as a well-known literature regarding semi-quantification of rock's damage categories for a given structure (particularly ancient and archaeological sites) based on description of weathering forms and their dimensions. The weathering forms' dimensions include (depth, covering area percentage, density, length, width ….etc) to preciously define in a semi-quantitative form rock's damage category (Table 1).

Table1. *Damage Category Scale, Observed Damage And Its Explanation*

Damage category	Observed damage (Fitzner et al., 2002)	Explanation (Fitzner et al., 2002)
0	No visible damage	No visible damage on the stone's surface, inscriptions and/or paints
1	Very slight damage	Very slight weathering on inscriptions and/or paints to less than a 1-mm depth,

		or less than 5% of wall side has DD, DT and /or LS.
2	Slight damage	Slight back weathering on inscriptions and/or paints from a 1–2-mm depth, or 5 – 10% of the wall side presents DD, DT. LS and/or FD.
3	Moderate damage	Moderate weathering on inscriptions only, as paints are totally demolished at this DC, back weathering from 2 5mm depth, or 10 - 25% of the wall side presents DD, DT, LS and/or FD
4	Severe damage	Severe weathering on inscriptions and main rock body as back weathering from 5 -10mm depth, or 25 - 50 % of the wall side presents DD, DT, LS and/or FD
5	Very severe damage	Very severe weathering on inscriptions and main rock body as back weathering is 10mm, or 50% of the wall side presents DD, DT, LS and/or FD
DC damage category, DD discoloration/deposition, DT detachment, LS loss of stone material, FD fissure/deformation		

The current study aims to examine the variation/constancy of micro-topography, geotechnical properties' limits and the damage category distribution for the sandstone constituting the ancient Aachen City wall, on weathering progress over short duration (eleven years of investigation from 2007 to 2018). This sector of Aachen's City wall has a wide spectrum of weathering forms and intensities, also, it is well exposed to direct daily environmental conditions of solar heating and air humidity and/or rainfall variation. The aims of the current study can be achieved by tracing the deformation of stone's surface micro-topography (rock's surface roughness, recession range) and measuring the limits of the sandstone geotechnical properties (relative stone's surface hardness) on weathering progress over two periods (2007 and 2018) covering eleven years of investigation. The GIS (10.1) had been used to map damage category and compute its mean at the four parts of the wall under investigation. Some fixed points of hard recently man-made cement based mortar (only 15 years ago) had been taken as a reference points enabling field measurements, particularly by Micro-erosion meter (MEM), through profiles crossing the building stones' surface with its weathering forms either on 2007 or 2018.

The investigated part of the city wall is located at Latitude 50o 45' 25" N and Longitudes 6o 4' 5" and 6o 4' 20" E, with total length 200 meters and height ranges 10 – 25m above its surrounding ground level (Fig. 1). The constructional rock of this wall almost has quartz-wacke composition with medium to fine size, moderately sorted, spherical to sub-spherical quartz grains cemented by silica, iron oxide and kaolinite (Kamh, 2011).

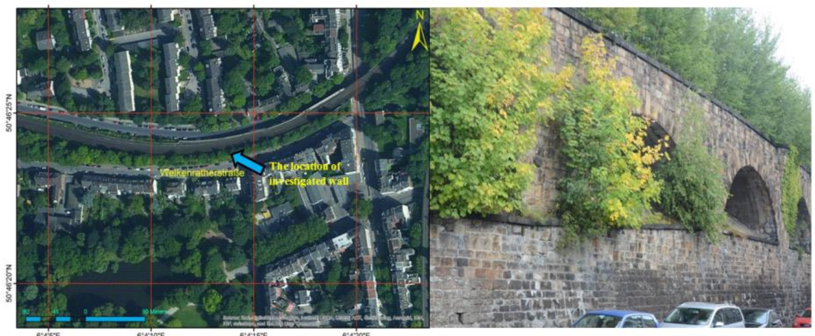


Figure1. *Location of the study area (left) and general view of a part of the investigated wall (right).*

Methodology

The following field investigations had been conducted to achieve the aims of the current study.

Field Investigations

Weathering Forms and Rocks Damage Category

The first step to do regarding weathering damage categories for a given wall side is to photo-document the weathering forms and describe each them considering its parameters e.g. length and inclination as that of fractures, density as that for caverns, area percentage affected by this weathering form, thickness of planar weathering form as that of scaling and exfoliation. Relating each of these forms to one of the four groups Fitzner and Heinrichs (2002) (Table 2). This is followed by defining rock's damage category based on the classification of Fitzner et al (1995) (Table 3). The wall under investigation has got a wide spectrum of weathering forms and damage categories, so, it had been selected to investigate weathering progress over eleven years of investigation applying such descriptive non-destructive field work that will be correlated with non-destructive measurements conducted at the field and processed in the laboratory. The weathering forms had been grouped (based on Fitzner and Heinrichs, 2002, Table 2) and the damage category at each of the four selected parts of this wall (on 2007 and 2018) had been defined based on Fitzner et al (1995) (Table 1).

Table2. *Classification scheme of weathering forms based on Fitzner and Heinrichs 2002*

Group of weathering forms	Main weathering forms	Individual weathering forms	Parameters to be considered
Group 1 - Loss of stone material (LS)	**Back weathering** (uniform loss of stone material parallel to original stone surface)	**Back weathering due to loss of scales** (contour scaling)	Depth of Back weathering (mm, cm)
		Back weathering due to loss of stone layers dependent on stone structure (exfoliation)	
		Back weathering due to loss of crumbs (crumbly disintegration)	
	Relief (Morphological change of the stone surface due to partial selective weathering)	**Rounding/notching** (concave/convex soft forms)	Depth of Relief (mm, cm)
		Alveolar weathering (honeycomb)	
		Weathering out of stone components (pebbles, fossile fragments..etc)	
		Clearing out stone components (protruding compact stone components e.g. pebbles, fossils) due to selective weathering	
		Pitting (Relief as small pits due to induced corrosion esp. on carbonate rocks)	
		Relief due to anthropogenic impact (e.g. scratches by human being)	
	Break out (Loss of compact stone fragments)	**Break out due to anthropogenic impact** (due to war, vandalism etc)	Volume of Break out (cm3)
		Break out due to natural cause (wedgework of roots, earthquakes, intersection of fractures)	
Group 2 Discoloration/ Deposits (DD)	**Discoloration** (alteration of the original stone color)	**Coloration** (coloring due to chemical weathering e.g. oxidationof iron)	Degree change of color
	Soiling (Dirt deposits on the stone surface)	**Soiling by particles from the atmosphere**	Mass of deposits or degree covering of the surface
		Soiling by droppings (drops from birds e.g. from pigeons)	
		Soiling due to anthropogenic impact (paint, posters etc.)	
	Loose salt deposits (poorly adhesive salt aggregates)	**Efflorescence** (salt aggregates on the stone surface)	Mass of deposits or degree covering of the surface
		Subflorescence (salt aggregates below the stone surface)	
	Biological colonization (by micro-organisms or higher plants)	**Microbiological colonization** (by microflora e.g. fungi, algae, lichen) and bacteria	Degree covering of the surface
		Colonization by higher plants	
Group of weathering forms	**Main weathering forms**	**Individual weathering forms**	**Parameters to be considered**
Group 3 Detachment (DT)	**Granular disintegration** (detachment of individual grains or small aggregates)	**Granular disintegration into powder**	Mass of detaching stone material
		Granular disintegration into sand	
		Granular disintegration into grus	

	Flaking (detachment of small thin stone flakes parallel to the stone surface)	**Single flakes**	Mass of detaching stone material
		Multiple flakes	
	Contour scaling (detachment of larger, platy stone pieces parallel to stone surface but not following any stone struture)	**Single scale**	Mass of detaching stone material
		Multiple scales	
	Detachment of stone layers dependent on stone structure	**Exfoliation** (Detachment of sheets plates following stone structure. Structural feature is oriented parallel to the stone surface)	Thickness of detaching stone layer (mm, cm)
		Splitting up (Detachment of sheets plates following stone structure. Structural feature is NOT oriented parallel to the stone surface)	Number of detaching stone layers
Group 4 Fissures/ deformation (FD)	**Fissures** (Individual or system of fissures due to natural or constructional causes)	**Fissures independent of stone structure**	Number and dimensions of fissures as length, width (mm,cm)
		Fissures dependent on stone structure	
	Deformation (Bending of thin stone slabs due to plastic deformation)	**Deformation, convex**	Amplitude of bending
		Deformation, concave	

Table3. *Weathering forms, their dimensions and their damage category, on 2007 and 2018, based on Fitzner et al, 2002*

Group of weathering forms	**Main weathering forms**	**Individual weathering forms**	**Parameters to be considered**	**Part 1**				**Part 2**				**Part 3**				**Part 4**			
				2007	D.C.	2018	D.C.	2007	D.C.	2018	D.C.	2007	D.C.	2018	D.C.	2007	D.C.	2018	D.C.
Group 1 - Loss of stone material (LS)	Back weathering	(contour scaling)	Depth of Back weathering (mm, cm)	2mm	2	6mm	3	2mm	2	5mm	2	2mm	2	4mm	3	6mm	3	11mm	3
		(exfoliation)		1.5 mm	2	5mm	3	1.6 mm	2	3mm	2	1mm	1	3mm	2	5mm	3	7mm	3
Group 2- Discoloration/ Deposits (DD)	Loose salt deposits	Efflorescence	Mass of deposits or degree covering of the surface %	5	2	12	4	8	3	11	3	5	2	13	4	8	2	11	3
	Biological colonization	Microbiological colonization	Degree covering of the surface	0	0	2	1	5	2	7	3	5	2	7	3	3	1	4	2
		Colonization by higher plants		0	0	0	0	4	2	5	2	0	0	4	2	0	0	0	0
Group 3- Detach	Granular disinte	Granular disint-egration	Mass of detach	5	2	12	3	7	2	14	4	9	3	15	4	12	3	18	4

ment (DT)	gration	into powder	ing stone material (kgm/m3)																
		Granular disint-egration into sand		8	3	15	4	6	2	13	4	7	3	16	4	11	3	14	4
	Flaking	Single flakes	Mass of detaching stone material (kgm/m3)	4	1	7	2	5	2	9	4	5	2	7	3	6	2	8	3
		Multiple flakes		9	4	13	4	6	2	8	3	1	1	2	1	4	1	7	2
	Contour scaling	Single scale	Mass of detaching stone material (kgm/m3)	3	1	7	3	4	1	6	2	4	1	7	3	4	1	6	2
		Multiple scales		2	1	8	3	3	1	5	1	0	0	2	1	3	1	8	2
	Detachment of stone layers dependent on stone structure	Exfoliation	Thickness of detaching stone layer (mm, cm)	4	2	7	3	3	2	6	3	4	2	7	3	5	2	11	3
Group 4- Fissures/ deformation (FD)	Fissures	Fissures independent of stone structure	Number and dimensions of fissures as length, width (mm,cm)	30CmL, 2mmW	2	32CmL, 3mmW	2	3CmL, 2mmW	0	14CmL, 2mmW	2	40CmL, 2mmW	3	53CmL, 4mmW	3	45CmL, 4mmW	2	55CmL, 6mmW	3
N.B. CmL is centimeter in length; W is width			Mean DC by Fitzner et al, 2002		2		3		2		3		2		3		2		3
			Mean DC by GIS		2		3		2		3		2		3		2		3

Mapping Of Damage Category Using GIS

The rock's damage category at the selected four parts of Aachen walls had been defined based on the scale of Fitzner et al (1995) (Table 1), then, GIS(10.1) had been used to map the damage category of these wall parts. Not only that but also, statistical analyses had been done using GIS computing the mean damage category of each of these four parts. This enables taking a decision regarding the urgency of conservation by resin treating and/or reconstruction of the severely weathered parts of the wall.

Tracing Rock's Surface Micro-Topography Using Mem

Several previous literatures had been concerned with measuring rock's surface weathering and hardness (Viles et al., 2011; Moses et al., 2014). Over two separate periods of investigation (2007 and 2018), the deformation (by weathering) of the sandstone blocks' surface on micro-scale (for the wall under investigation) had been traced using MEM. The MEM had been recorded in previous literatures to be an efficient tool for such micro-scale measurements (Gill and Lang, 1983; Stephenson and Finlayson, 2009; Stephenson et al., 2010). The MEM (type Schmadtzu NB-70) that had been used in the current study is composed of 300 thin-pen moving forward-backward on a digital ruler enabling tracing all micro-topographic changes, with high accuracy of less than 0.1mm. It had been used at the stone's surface along profiles presented at each of the selected four parts of Aachen City wall, i.e. it had been used to draw the micro-topography of the weathered surface of the wall under investigation along profiles passing by the detected weathering forms. The MEM data has been used to create a roughness range scale (Ro.R.S.) and roughness classes (Ro.C.) regarding this wall (Table 4). The stone's surface roughness control its weathering susceptibility, on time progress, where stone's surface with low roughness class is expected to have lower weathering susceptibility than those with higher roughness class (Williams and Robinson, 1983; Kamh and Hanna, 2002).

Table4. *Roughness range scale and Roughness classes for the MEM data of the sandstone wall, Aachen City*

Roughness Range Scale "Ro.R.S."	Roughness Classes "Ro.C."
More than 1.26	Very high roughness
1.12 – 1.26	High roughness
1.05 – 1.12	Moderate roughness
1.03 – 1.05	Low roughness
1.00 – 1.03	Very low "negligible" roughness

The recession range (Re.R.) is the difference between two levels of the same point on two roughness profiles (i.e. on 2007 and 2018). This reflects weathering regime (uniform or non-uniform) and intensity, on time progress, at the constructional blocks of Aachen City wall. The recession range is not only controlled by weathering intensity but also by either rock-mortar interaction or non-uniform durability of the rock under investigation. The rock's surface backward recession is expected to continue, with rates based on weathering intensity-rock's surface durability, till the stability of rock's topography before the recession regime reverses forming a new topographic feature (Danny and Atle, 1996) e.g. the rock with dome form may be reversed to create concave form on weathering progress.

The profiles, on the wall under investigation, for MEM measurements have been selected to cross most if not all detected weathering forms considering reference points that stands at the two measuring episodes 2007 and 2018. The weathering forms detected and considered in the current study are: Contour scaling, Case hardening, Granular disintegration, Scaled stone margins resulting in Dome form, Scaling at stones' central part resulting in Concave form, Uniform back weathering "Exfoliation", Surface partly deformed by biological growth (plant and lichens) within rock pores.

Measuring of Relative Stone's Surface Hardness (RSSH)

The stone's hardness reflects its durability to deterioration by internal and/or external stresses e.g. salt's crystal growth within rock's pores and /or repeated cycles of weathering by natural environmental processes respectively. Not only that but also, the rock at each weathering form is expected to have different limits of geotechnical properties, particularly hardness, than at other form(s), consequently, its durability to weathering processes does. For more explanation, a given rock with case hardening compared with similar rock with contour scaling are different in their hardness (durability) as well as to further weathering susceptibility. As rock sampling for hardness measurement is almost prohibited for some buildings and as such measurement (e.g. by Schmidt Hammer) require considerably big size rock samples (Williams and Robinson, 1983), and as this study aims to keep the weathering forms for further investigations, so, a simple, accurate and non-destructive tool named Equitop Hardness Tester (EHT) had been used. This is to measure the stone's surface hardness (SSH) at each weathering form, as well as at control (reference) rock surface at this wall side. In turn, this is to compute the RSSH at each weathering form using the equation of Aye et al (2010):

RSSH = Lt / Li

Where Lt is the stone’s surface hardness (SSH) at the weathered part of stone’s surface; Li is the stone's surface hardness (SSH) measured at control (reference) stone’s surface

Five measurements of SSH had been conducted, to compute their average value, at each of control and weathered parts of this wall.

The measuring points have been selected following the method of Oguchi et al. (2002) i.e. dry, even surface parts; to avoid any technical errors during measurements conducted on hot dry season (e.g. August 2018). The interpretation of the resulted RSSH, for the selected parts on this wall, into low, moderate or high RSSH will be conducted based on the classification listed in table (5).

Table5. *Classification and interpretation of relative stone surface hardness for weathering grade*

RSSH range	RSSH class	Interpretation
Less than 0.45	Low	Severely weathered rock
0.45 ~ 0.75	Moderate	Moderately weathered rock
More than 0.75	High	Slightly weathered rock

Results

Field Investigations and Measurements

It is to investigate rock's weathering forms at the four parts under investigation and to preciously define their damage category based on the dimensions of the weathering forms with the aid of damage category scale of Fitzner et al (1995) (Table 1). The detected weathering forms had been photo-documented (Fig. 2 i - viii) and tabulated with their parameters and grouped (Table 3) based on the classification scheme of weathering forms of Fitzner and Heinrichs (2002)(Table2) .

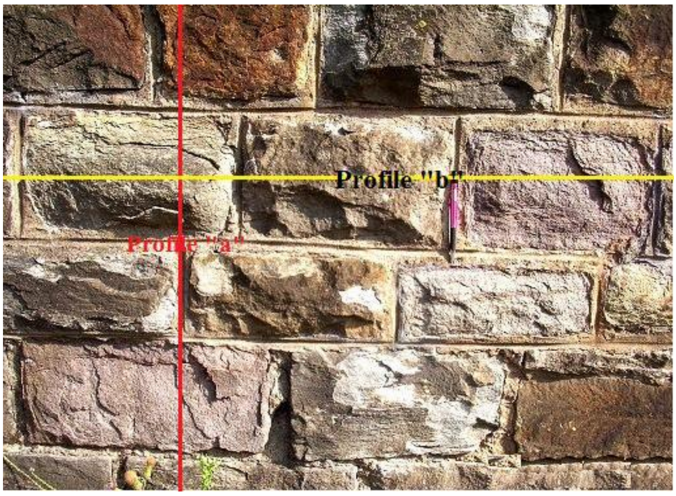


Figure2(1). *Profile "a and b" at Part 1 of the city walls on 2007*

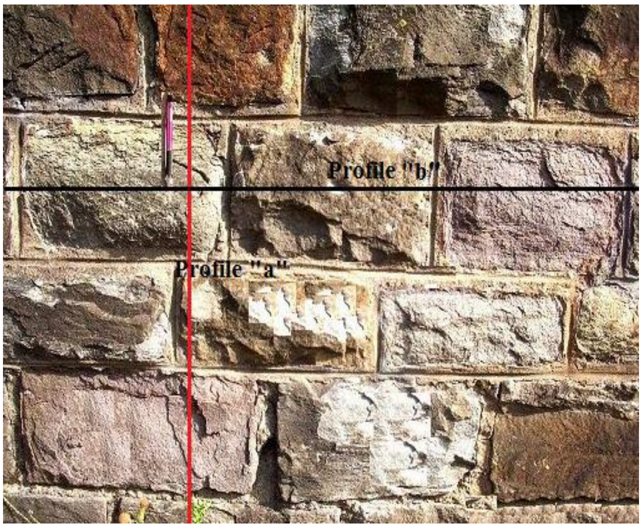


Figure 2(2). *Profile "a and b" at Part 1 of the city walls on 2018*

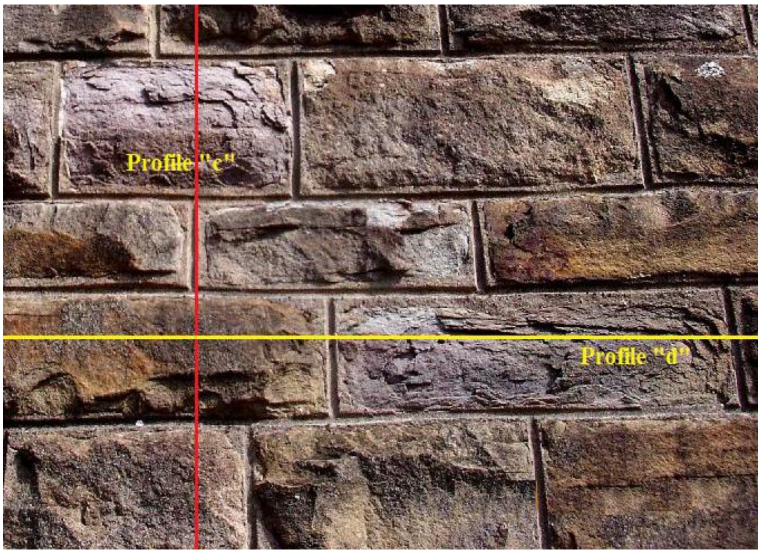


Figure 2(3). *Profile "c and d" at Part 2 of the city walls on 2007*

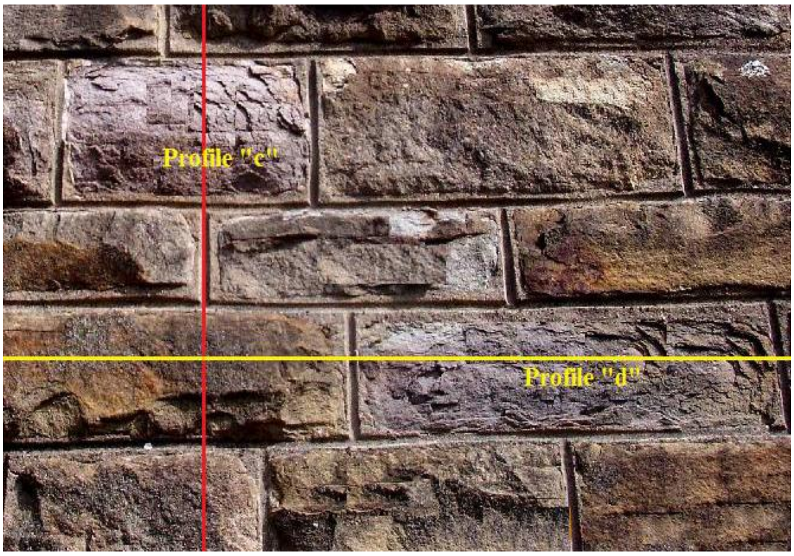


Figure 2(4). *Profile "c and d" at Part 2 of the city walls on 2018*

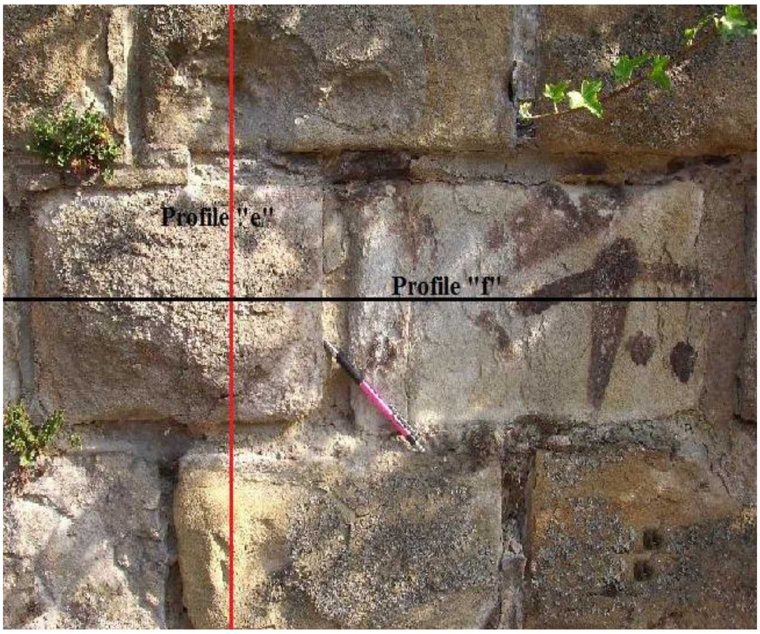


Figure 2(5). *Profile "e and f" at Part 3 of the city walls on 2007*

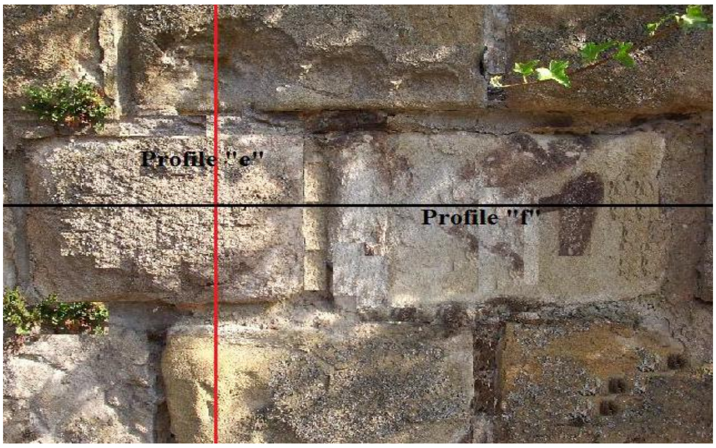


Figure2(6). *Profile "e and f" at Part 3 of the city walls on 2018*

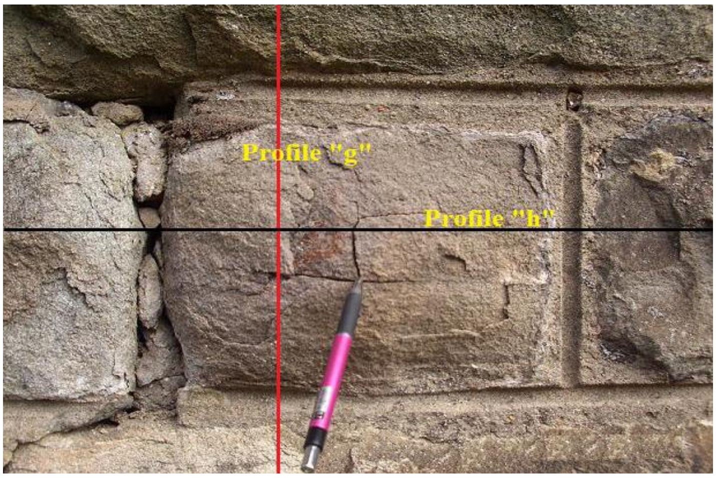


Figure2(7). *Profile "g and h" at Part 4 of the city walls on 2007*

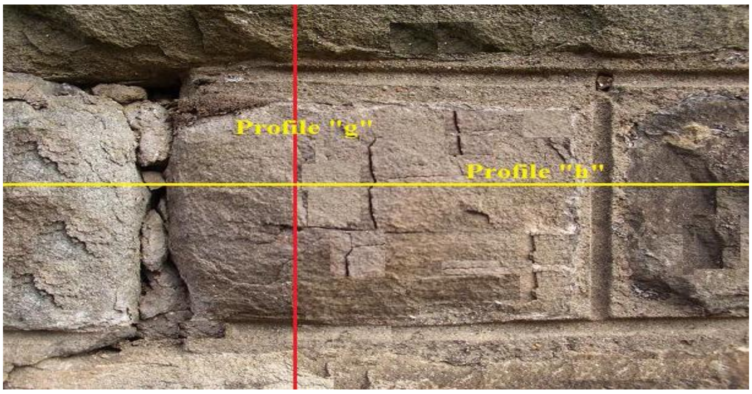


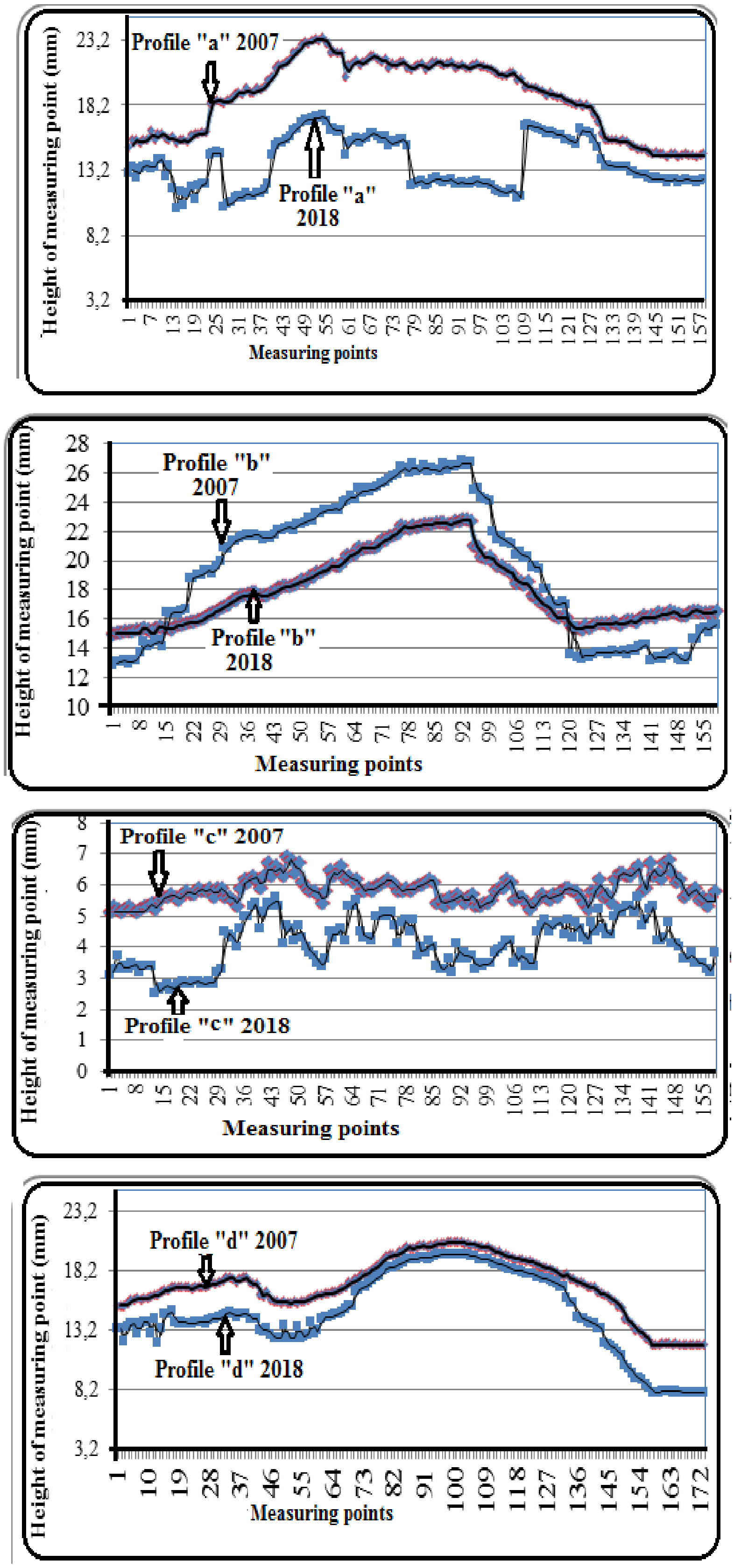
Figure2(8) *Profile "g and h" at Part 4 of the city walls on 2018*

Figure 2. *Weathering forms and profiles considered for MEM measurements across weathering forms at four representative parts consid, to cross the weathering forms noted on 2007 and 2018 at Aachen City walls.*

MEM and EHT Results

The Micro-erosion meter data including roughness (on 2007 and 2018), average roughness, roughness class and the computed recession range at the representative profiles under consideration are listed in table (5). This is to have a meaningful interpretation for the roughness data as roughness range measured for a given weathering form at the two periods of investigation. This can throw light on which weathering form(s) has higher susceptibility to weathering than other forms e.g. scaled or exfoliated forms as well as case hardened stone surfaces are expected to be more susceptible to weathering than surfaces with granular disintegration (Kamh, 2011). Where the formers have salts accumulates below scaled, exfoliated or case hardened stone surface resulting in more and rapid rates of weathering

(Kamh, 2011; Bamaga et al., 2013). These salts had been reported before to be chemically created by acid rain-hydraulic lime mortar interaction (Angeli et al., 2007; Fitzner and Heinrichs, 2002).The backward recession range of rock's surface has been computed, along the profiles crossing the weathering forms at the representative four wall parts (Fig. 2 i - viii), as the difference between each pair of points on rock's surface roughness measured at the two periods (2007 and 2018) (Fig. 3 a - h).



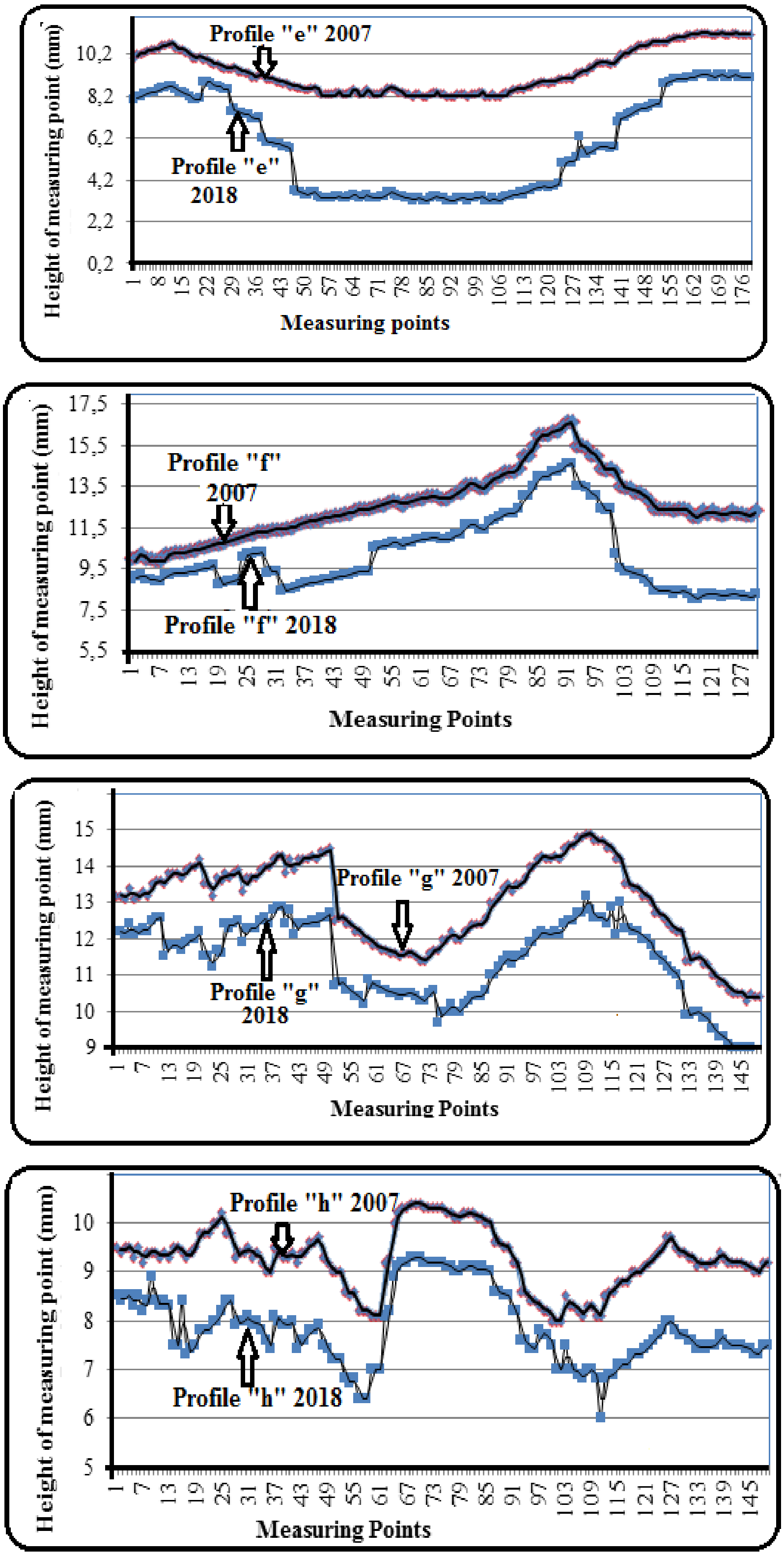


Figure 3. *Graphical representation of rock's surface roughness "using MEM" along two right angled profiles at each of the four representative parts at Aachen ancient City Walls examined on 2007 and 2018.*

The stone's surface hardness (SSH) had been tested in the current study (August 2018) using EHT as a non-destructive tool concerning the weathering forms under investigation as well as control points. Then, the relative stone's surface hardness (RSSH) had been computed by dividing the SSH of each weathering form by that of the control points (Table 6). Simply, on weathering progress, the stone's surface hardness is expected to be decreased creating one or more of weathering forms, but on detachment of these weathering forms, slightly weathered to fresh rock's surface (with higher RSSH) outcrops (Bamaga et al., 2013). The RSSH listed in table (6) have been classified and interpreted based on the classification shown in table (5) and graphically plotted (Fig. 4) with its classes in conjunction with the weathering forms under investigation.

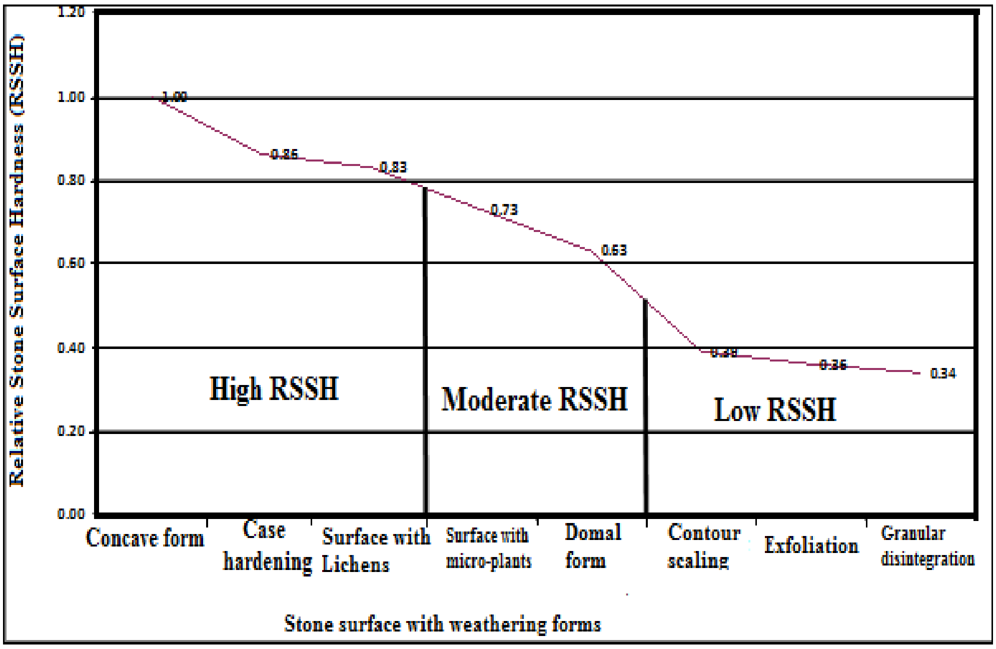


Figure 4. *Graphical representation of relative stone's surface hardness and its classes at the weathering forms under investigation.*

Table6. *Micro-erosion meter and Equotip hardness tester results measured for the eight profiles passing by the weathering forms under consideration, sandstone wall, Aachen City, Germany*

Sandstone wall (South-South west facing wall side), Aachen City							
Weathering profiles	Main weathering forms	MEM results				EHT results (2018)	
		Roughness (Ro) in mm (2007 – 2018)	Average roughness (A.Ro) in mm	Roughness Class (Ro.C)	Recession Range (Re.R) in mm (2018)	Average RSSH	Classes of RSSH
A - B	Contour scaling	1.15 ~ 1.17	1.16	High	1.8 ~ 9.0	0.39	Low
	Exfoliation	1.14 ~ 1.17	1.16	High	1.82 ~ 8.8	0.37	Low
C - D	Case hardening	1.09 ~ 1.00	1.05	Low	- 0.30 ~ 4.0	0.86	High
	Concave form	1.07 ~ 1.00	1.36	Low	0.2 ~ 2.9	0.9	High
E - F	Granular disintegration	1.09 ~ 1.11	1.1	Moderate	0.6 ~3.0	0.34	Low
	Surface with micro-plants	1.17 ~ 1.22	1.2	High	1.71 ~ 6.2	0.73	Moderate
	Surface with Lichens	1.15 ~ 1.2	1.17	High	1.75 ~ 6.9	0.85	High
G - H	Domal form	1.31 ~ 1.35	1.33	Very high	1.0 ~ 4.0	0.63	Moderate

Laboratory Data Mapping Using GIS

Mapping of rock's damage category for a wall side of a given building, particularly archaeological site, is of value to specify the parts with severe and very severe damage categories for the restoration decision. Not only this, but also to statistically compute the mean damage category of the whole site to throw light on impact of weathering processes on it. Defining the damage category for the wall under investigation had been conducted using the damage category scale of Fitzner et al (2002, Table 1) for the two periods (2007 and 2018) of investigation (Table 7). This mapping also enables precious definition of the parts with severe and very severe damage to specify parts requiring urgent restoration to avoid rapid and uncontrolled damage that might result in a deleterious deterioration for this ancient wall. This mapping can also throw light on the rate of weathering at this ancient valuable wall of

Aachen City through correlation of damage category maps for the same part over two specific periods of investigation.

Table7. *Range, mean, their interpretation and standard deviation of damage categories processed by GIS(10.1) for the four representative parts at the ancient wall of Aachen City, Germany*

	Year	D.C. range	Interpretation of D.C. range	Mean D.C.	Interpretation of Mean D.C.	St. D.
Part No. 1	2007	1.0 - 3.0	V.L. to M.	1.86	L.	0.68
	2018	1.0 - 4.0	V.L. to S.	3.13	M.	0.93
Part No. 2	2007	1.0 - 3.0	V.L. to M.	1.72	L.	0.62
	2018	2.0 - 4.0	L. to S.	2.71	M.	0.62
Part No. 3	2007	2.0 - 3.0	L. to M.	2.41	L.	0.50
	2018	2.0 - 4.0	L. to S.	3.21	M.	0.69
Part No. 4	2007	1.0 - 3.0	V.L. to M.	2.38	L.	0.62
	2018	2.0 - 4.0	L. to S.	3.17	M.	0.79

D.C. is Damage Category; Mean D.C. is mean damage category; St. D. is standard deviation; V.L. is very low; L. is low; M. is Moderate; S. is severe

Four representative parts of this wall showing all weathering forms prevailing on this wall had been considered for field and laboratory investigations over the two periods of study (2007 and 2018). Mapping for the damage categories considering all weathering forms and their dimensions, as listed in the damage category scale of Fitzner et al (2002), had been conducted using GIS (10.1) for the four parts over 2007 and 2018 (Figs. 5 a - h). The damage categories, mean damage category, and the standard deviation had been computed using GIS (10.1), the results of the four parts under investigation are listed in table (7). The GIS data will be correlated and discussed with the MEM and EHT data. This is to find out the efficiency of software investigation (using GIS) in defining and specification of the severely weathered parts requiring urgent restoration rather than the numerical measurement (using MEM and EHT) that is time consuming and/or probably harm the stone under investigation. An error in such numerical data is expected using EHT e.g. for the weathered, rough and/or wet stone surfaces (Gill and Lang, 1983; Stephenson and Finlayson, 2009; and Moses et al.,2014).

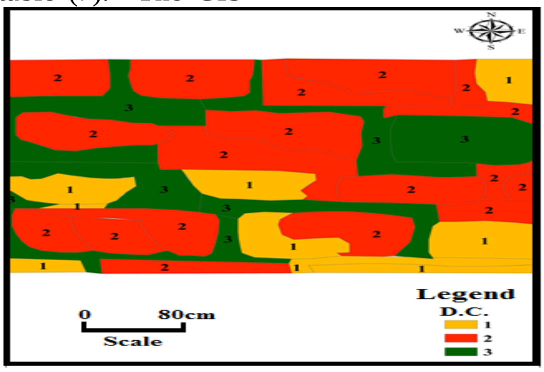


Figure 5(a). *GIS mapping for rock's damage categories at part one on Aachen's City walls, 2007*

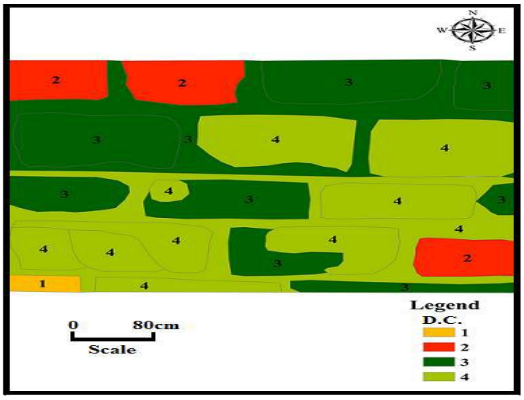


Figure5b. *GIS mapping for rock's damage categories at part one on Aachen's City walls, 2018.*

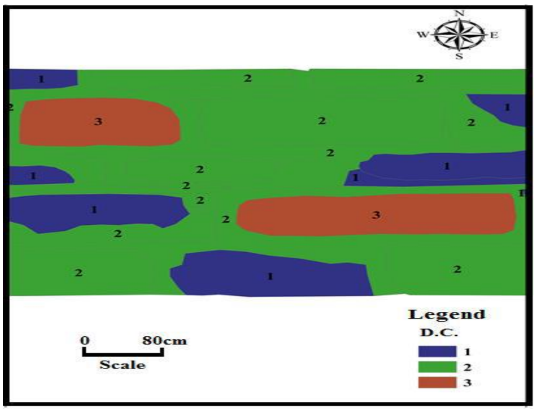


Figure5c. *GIS mapping for rock's damage categories at part two on Aachen's City walls, 2007.*

Figure5d. *GIS mapping for rock's damage categories at part two on Aachen's City walls, 2018*

Figure5e. *GIS mapping for rock's damage categories at part three on Aachen's City walls, 2007.*

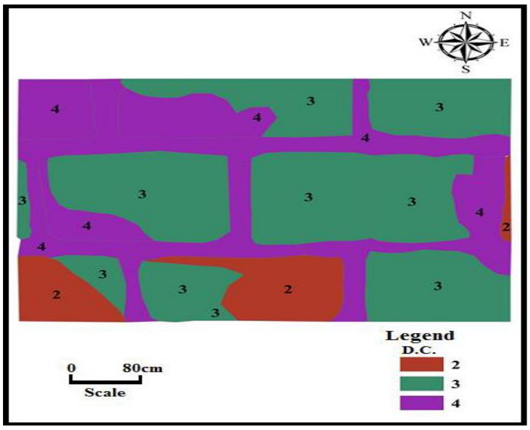


Figure5f. *GIS mapping for rock's damage categories at part three on Aachen's City walls, 2018.*

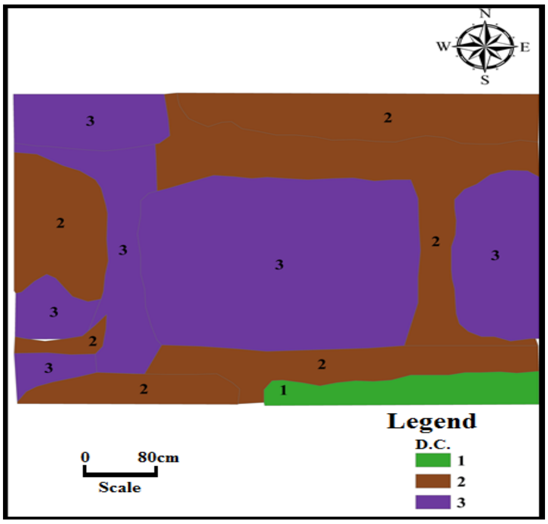


Figure 5g. *GIS mapping for rock's damage categories at part four on Aachen's City walls, 2007.*

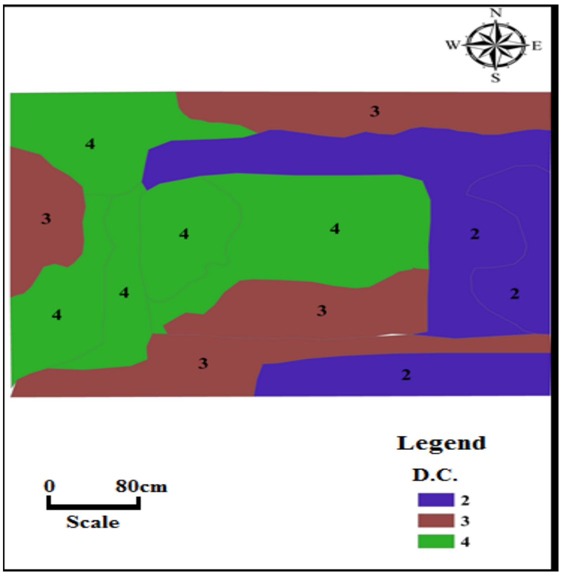


Figure 5h. *GIS mapping for rock's damage categories at part four on Aachen's City walls, 2018.*

Discussion

The investigation of weathering damage for a given structure (e.g. Cathedral, Church, building with unique design or decoration) must be conducted using non-destructive tools or techniques requiring tiny size rock samples to avoid more deterioration for the structure. The micro-erosion meter data is one of the field non-destructive measuring tool for rock's surface micro-topographic change. It indicated that the backward recession of stone's surface is variable from one weathering form to the other and even on the same form but at its different parts over the same period of investigation (2007 or 2018) (Fig. 3). This is due to the weathering susceptibility of each weathering form and the environment-rock interaction on time progress. For example, creation of hardened stone surface (by pores filling with air dust and/or leaching rock's mineral content e.g. iron oxide, leached from inside to stone's surface, Fig. 2 vii) resulted in reduction of weathering rate but on detaching this hardened surface, rapid weathering is expected (Fig. 2 viii) (Livingston and Bear, 1984; Charola, 1988; Sweevers et al., 1998). So, the MEM profile varies on time progress, consequently, the recession range varies considering the stone surface with its weathering form (Fig. 3). The Re.R computed and listed in table (6) can be noted to be unequal with the highest range for constructional sandstone with contour scaling, due to un-equal recession at the different parts of this scaling, followed by other weathering forms with moderate to high Re.R. Another point that must be addressed is the Ro.C. and Re.R interrelation, the rock's surface with dome topography (Fig. 2 vii and viii) has very high Ro.C. but with 3mm Re.R compared with Re.R of contour scaling that reaches 7.2mm and high Ro.C. (Table 6). The reason behind that is the A.Ro. that is the outcome of dividing the line's length passing across the profile of the weathering form by the straight line between the same two fixed points of measurements. While the Re.R, that had been computed as the range of minimum and maximum difference between each pair of the same points on the roughness profiles of 2007 and 2018, seems to be low (due to micro-topographic stability for dome form) compared with contour scaling that still progressing presenting considerably high roughness class with the highest Re.R over these eleven years.

Theoretically, there is an inverse proportional relation between rock's surface roughness and its RSSH class. This is almost approved for the four profiles (over the two periods 2007 and 2018) including the weathering forms under investigation with two exceptions, the first one is for profiles (e) and (f) for the building stones with granular disintegration has low RSSH but with moderate (not high or very high) Ro.C. The second exception is for the profiles (g) and (h) for the building stones with dome form due to weathering having very high Ro.C. and moderate (not low) RSSH (Table 6). The interpretation of that is the stone can be with granular disintegration that doesn't affect on the stone's roughness as other weathering forms do but has low RSSH as this roughening reversely affect on the records of the EHT (Williams and Robinson, 1983). Also, the stones with dome form, due to weathering, have very high roughness class and so it is supposed to be with low RSSH but it is found to be with moderate RSSH (Table, 6). The main reason behind that is the central parts of these stones are less weathered compared with their margins due to rock-mortar interaction by salts chemically formed on mortars alteration to salts by acid rain that dominate in Europe (Turkington, 1998).

The wall under investigation presented, using MEM and EHT data, that weathering act with different intensities creating number of weathering forms having variable limits of roughness and hardness. On time and weathering progress, these weathering forms are increased in their dimensions and damage categories. The damage categories, defined in the field using the scale of Fitzner et al (2002), have been mapped using GIS(10.1) to preciously define the progress in damage category at each sector or part of this wall as well as the whole wall under investigation. Not only that but also, the mean damage category had been define on data processing using GIS. It had been indicated that the damage category ranges from 1.0 (Very low D.C.) to 3.0 (Moderate D.C.) with mean D.C. 2.09 (Low D.C.) for the four parts on 2007 and increased to be from 1.0 (Low D.C.) to 4.0 (Severe D.C.) with mean D.C. 3.04 (Moderate D.C.) on 2018 (Table 7, Figs. 5 a -h). This indicated considerable weathering rates and intensities as well as weathering susceptibility particularly for some weathering forms, e.g. contour scaling, rock surface powdering and case hardening, raising the damage category of this wall over this short duration. The parts with very low RSSH indicated by EHT and severe damage category indicated by GIS are comparable together proofing that GIS can be considered as an efficient non-destructive technique for semi-quantification of rock's damage category. Not only that but also, the mean damage category defined on using the scale of Fitzner et al (2002) is highly comparable with that mean computed by GIS (Tables 3 and 7) indicating slight damage category for the profiles examined on 2007 and moderate damage category for the same profiles on 2018. It must be mentioned that the mean damage category defined based on the scale of Fitzner et al (2002) for each of studied four parts is slightly lower than that defined by GIS (Tables 3 and 7). The explanation of this is that the mean D.C. defined by Fitzner et al (2002) scale is based on measuring dimensions of weathering forms along specific profiles while that defined by GIS is for the rock surface including the whole weathering forms on it at each of the four parts under investigation. The high matching between GIS mean D.C. and mean D.C. defined by either field or laboratory investigations confirm that GIS as an advanced technique is quite enough for weathering investigation for a given site facilitating taking a conservation decision and planning for conservation technique.

Conclusion

The current study aimed to examine and semi-quantify the micro-topography (weathering and recession) of the sandstone wall at Aachen City exposed to repeated weathering cycles over eleven years of field investigation using MEM. Not only that but also to find out the recession in stone's surface hardness at the different weathering forms, on this sandstone, using EHT. The results indicated that noticeable alteration of rock's surface micro-topography, hardness and damage category had been occurred over this short duration (eleven years from 2007 to 2018). The end product of this study can be concluded in the following points: the progress in deformation of rock's micro-topography is noticeably increased with a range based on the resultant weathering form; the blocks with granular disintegration, exfoliation and contour scaling have low RSSH, moderate to high roughness class. The sandstone surface with dome form and that one covered with micro-plants have moderate RSSH, high to very high roughness class. The sandstone surface with case hardening and that one with biological cover have High RSSH. GIS enabled mapping of rock's damage categories at some representative parts of this wall, the mean damage category as well as the standard deviation had been computed with GIS. It has been proved in the current study that GIS is an efficient, quick, accurate and non-destructive tool for mapping of rock's damage category particularly in the field of archaeology to preciously define parts with urgent requirement of restoration.

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MEM is Micro-erosion meter; EHT is Equitop hardness tester; Ro.R.S is Roughness range scale; Re.R is recession range; Ro.C is roughness class; SSH is Stone surface hardness; RSSH is Relative stone surface hardness; A.Ro is average roughness; GIS is Geographic Information System.

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