Determination of the durability of some Egyptian monument stones using digital image analysis

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Abstract: The parade of historical monuments preserved in and around Cairo span a period of more than five thousand years and documents the entire civilization of the country. There is no one epoch of history, which has not left its numerous traces. However, stone damage or deterioration of monuments in Cairo due to weathering is a growing concern. Therefore preservation and remedial measures have become very important. A comprehensive survey of stone deterioration in general needs a range of studies including destructive testing of sample cores. However, the degree of weathering can also be determined non-destructively, using image processing based on recording surface color changes in the rocks, which are the first observed feature of deterioration. Image processing is a very recently developed technique being used to analyze digital photographs in order to predict the impact of weathering on stone monuments. In the present work, this technique has been adapted to investigate eight sites of Islamic monuments in Cairo. The "RGB" color system was used and a computer analysis of digital images taken of the monuments, as well as of the source stones used, was carried out. 330 cross-sections were taken from the photos of studied stones. By this method it was possible to carry out a detailed analysis of the deterioration of the monument stones. Using this image analysis, it was possible to predict quantitatively the degree of repair needed for the deteriorated monument without touching the stone, taking core sample or using destructive testing methods.

Resume: Le parad des monument historique ont preservees dans et autour le caire. Un period de plus du cinq mille d'annees et exprimee le civilization entiere du pays. Il n'y'a pas une époque historique qui n'a'pas laisser trainer des choses. Cependant, la deterioration de la pier monument du Caire a cause de la desagregration est parfait sondee. Donc la conversation et la mesure remede sont parfait important. Le degree de la desagregration peut determiner utlisee image operations qui est basee sur les couleurs des roches. Le changement des couleurs des roches est le premiere trait observee de la deterioration. Image operations est un plus recent technique pour analyzer photograph digital a affirmer l'impact de la desagregration sur les pierres monument. Dans ce travail, cette technique a ete adoptee pour etudier huit sites des monuments Islamiques du Caire. Le "RGB" comme couleur system et le programe d'ordinateur ont ete utilisee pour analyser des photographs digital des piers etudiees. Par cet etude, il peut possible a analysee en detaille les conditions des deteriorations des piers monuments. En resultant, il est tout a fait possible a predictee en quantitave le degree du remedie qui ont ete besoin pour etudier la deterioration des monuments sans toucher le pierr.

Key words: Image analysis, weathering, environmental impact, erosion, evaporation, expansion, fractures,

INTRODUCTION

Cairo's monuments are of outstanding historical and cultural importance ranging through Pharaonic to Roman, Coptic and Islamic periods. The Islamic monuments represent the main group of historical monuments in Cairo. It is an unequalled treasure house of Islamic monuments and buildings. More than six hundred Islamic monuments are concentrated in the center of Cairo. The majority of these structures such as mosques, city walls, gates, domes, minarets, etc date from the time of Amr Ibn Ass (AD 641), Abbassids (AD751), Tulunids (AD870), Fatimids (AD 969), Ayyubids (AD 1175), Mamlukes (AD 1250) to the Ottoman (AD 1513) period.

Stone damage or deterioration in the numerous monuments in Cairo is alarming. Weathering features such as surface soiling, blackened and whitish crusts are very common in the limestone monuments in the center of Cairo. The black crusts – mainly composed of gypsum – very frequently occur on the middle and upper parts of the monuments, whereas the whitish crusts – almost purely composed of halite – are mainly restricted to the lower parts of the monuments. Considerable loss of the stone fabric by this decay, failure and detachment process is very characteristic of the lower parts of many monuments in Cairo city and demonstrates the urgent need for preservation or remedial treatment measures.

The degree of weathering can be determined based on the color of rocks, because a change in rock color is commonly the first feature observed in rock weathering. By field observation, weathered rocks have been broadly divided into several weathering classes recognized by changes in their color and surface structure (Nagano and Nakashima, 1989; Fitzner et al., 1997,2002, 2003; Fitzner, 2002; Heinrichs and Fitzner, 2000). Satio et al. (1974) reported that the blue-green-gray tones in fresh volcanic rocks changed to brownish tones during weathering. Karmanov and Rozhkov (1972) pointed out the possibility of a quantitative relationship between color characteristics

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and soil compositions. The color of rocks, therefore, is considered to be one of the few parameters which can be used to determine weak levels of weathering in rocks due to small changes in their chemical or mineralogical properties.

Image processing is a very recent technique being used to analyze digital photographs in order to predict the impact of weathering on a stone structure. " ImagCraft " is a computer programme developed by Chang and Park (2001) which produces a histogram of color change for each color of the RGB color system. Evaluation, quantification and rating of stone deterioration by this method is based on color changes or color deterioration that occur between the original stone and the present weathered stone surface.

The aim of this paper is to evaluate the impact of the local environmental conditions on the color spectrum of Egyptian monument stones and to demonstrate, through changes in their color, the effect these conditions can have on the decay of the stone. The quantification of this deterioration process on the weathered monument stone surface can also been calculated using digital image processing.

MATERIAL OF MONUMENT STONES

All the present monument stones are made of Eocene rocks from the ancient quarries around Cairo. Limestone from local quarries have been used for the construction of monuments in Cairo from Pharaonic times until today. Eocene limestone outcrops within the boundaries of the Cairo area provided the material for the construction of most historical stone monuments in this region. These were, in particular, Mokattam limestone plateau east of Cairo, the Helwan limestone plateau in the southeast and the Giza limestone plateau in the western part of Cairo. The pyramids were mainly constructed from local Giza limestone. The historical monuments within Cairo were mainly constructed of limestones from the Mokattam and Helwan areas.

Most of the limestone used in historical monuments in Cairo are from the Mokattam Group of the Middle Eocene (Said, 1990). These Eocene rocks show a wide variety of limestone facies, which are also reflected in the building stones of the monuments studied here. The limestone facies may be described as a calcarenite formed of grains of calcite, quartz and some calcareous fossils in a micritic lime cement that may also contain substantial amounts of detrital clay minerals. In some cases the clay content is high enough to classified the rock as a marl.

The present study was carried out on limestone samples taken from the oldest quarries at Gebel Mokattam, the original stone source for the monuments. The deteriorated, weathered stones were taken from the walls of selected monuments in Cairo area.

WEATHERING PROCESSES OF MONUMENT STONES

Stone weathering as a natural process is actually one of the most important factor controlling the durability of stone monuments. Such weathering process can be divided into two groups: (i) physical weathering such as microcraking and disintegration; and (ii) chemical weathering such as discoloration and dissolution of component mineral grains. Both processes result in certain types of loss in volume of each mineral component. Any weathering factor normally has negative influence on durability and can be assessed quantitatively by the measurement of change in the rocks color by reference to its color in un-weathered stone (original stone). This can be determined by the use of digital image processing such as the RBG color system. The changes recorded can be considered as color deterioration between the original and weathered stones.

Factors influencing weathering of monument stones

The rate at which an exposed stone surface weathers depends on numerous factors, including moisture content, pollution load, ambient temperature, sunlight exposure and the mineralogical composition of the stone itself.

Moisture

Without moisture, most stone weathers very slowly. Moisture not only favours conditions for chemical attack, but also absorbs carbon and sulphur dioxide gases, carbonate and sulphate particles from the air. Surface moisture can thus greatly accelerate the rate at which stones deteriorate.

Volume change

Volume change of stone include the following mechanisms: (i) differential expansion of mineral grains, (ii) differential bulk expansion due to uneven heating, (iii) differential bulk expansion due to uneven moisture content and (iv) differential expansion of differing material at joints.

Environment and pollution loading

Like moisture, the concentration of air pollutants and their deposition affects stone deterioration. Two very important sources of pollution can be distinguished: i) The increase of air pollution in Cairo as a consequence of the rapid expansion of the city (industry, traffic etc.) results in increasing deposition of pollutants from the atmosphere onto the monuments with subsequent salt formation, especially gypsum, on the stone surface or in the near surface pore space of the limestone. ii) The water table (ground water, subsoil water) has risen significantly during the last few decades. It can be observed that in extreme cases the water table has reached the ground floor of buildings and monuments. Insufficient or leaking sewage systems have also caused increasing water pollution. Salt solutions from the subsurface intrude by capillary rise into the walls of the monuments and salts are precipitated – especially halite –

on the stone surface or in the pore space of the limestone close to the surface. In the center of Cairo, the most severe stone damage, in the lower parts of monuments, was found at those zones of the walls which correspond to the main level of salt precipitation due to increases in humidity. A clear correlation between extent of salt loading / precipitation and degree of stone damage or deterioration has been shown for the lower parts of Cairo's monuments (Hawass, 1993; Croci, 1994 and Vendrell-Saz et al., 1996).

Occurrence of pollution products in rain-water

The solid and gaseous particles present in a polluted atmosphere are naturally deposited by rain and dew. In such a polluted atmosphere, considerable amounts of acidic-water may be brought into contact with stonework solely by the formation of dew. Such dew formation may be more deleterious in its effects than acid rain. Acidic dew would be formed even in relatively sheltered areas, from which the resultant salts could not be readily removed.

Structure and texture

Limestones can exhibit considerable differences in their behavior on exposure, even within the same limestone succession. Some limestones, in acidic-polluted atmospheres, form a weathered skin rapidly which leads to exfoliation, while others may be more resistant to attack. In some limestones erosion takes place uniformly, in others it develops along an uneven surface. Such dissimilar weathering characteristics are due to differences in stone structure rather than to differences in chemical composition. Structural features can determine the degree of attack by acid gases, and the degree of resistance to the effect of crystallization of salts. The texture of the stone can also influence the thickness of any weathered skin developed, its strength and elasticity (also related to rock structure) and is likely to have a considerable influence in determining the susceptibility of a stone to exfoliation.

Decay forms and decay mechanisms of monument stones:

Various forms of decay are observed on the monuments - granular disintegration, differential erosion and development of black crusts and orange patinas. A number of processes have been established as being responsible for these decay forms – sulphate precipitation in the urban environment; differential thermal dilation; hydraulic and thermal expansion of the stone.

The damage is the result of the interaction of two groups of factors: the intrinsic characteristics of the rock and the extrinsic parameters, associated with environmental, physical, chemical, and biological changes. A number of different mechanisms have been determined as being responsible for the decay forms observed in the building stones. In this section we will summarize these mechanisms in order to establish their role in the development of the decay forms and consequently the color systems that have developed.

Sulphation

Black crusts formed mainly by gypsum and soot from vehicle exhausts have been reported at some points in the urban areas. A sulphation mechanism seems to be responsible for these black crusts. According to Skoulikidis (1982), the gypsum is the product of the reaction between sulphur dioxide and atmospheric aerosols and the carbonate surfaces. The composition of these black crusts depends on the form of local atmospheric pollution (Del Monte and Sabbioni,1986). The crust often suffers a loss of cohesion with the unweathered underlying rock, due to the differential expansion occurring between salt crystals and the surrounding carbonates. This process ultimately causes the crust to break away from the underlying rock whose shape is maintained by the gypsum crust until it breaks and falls, leaving the rock open to further attack by acid rain. If the rock is a bioclastic limestone, this attack is more effective on the micritic areas than on the grains because of the higher specific surface area exposed by the fine crystals.

Hydraulic and differential expansion

Thermal dilation is caused by the differential expansion shown by each rock-forming mineral crystal when the temperature rises. The anisotropy of this phenomenon produces a loss of cohesion between grains, causing granular disaggregation of the surface of the monument stone.

Expansion also takes place when the stone is wetted by rain or dew which can penetrate to different depths through the pore space. In this case the expansion is due to the adsorption of water by the clay minerals of the rock matrix causing them to expand, which in turn causes tension in the rock and can lead to disaggregation of the surface, but not necessarily inside the rock, which remains dry. This can cause surface flaking of the stone (Prost, 1990).

Skin formation

The action of acid sulphur gases on limestone monuments causes the formation of hard, impermeable surface skins, which tend to blister and exfoliate, leading to the development of disfiguring surface decay and structural damage. The surface skin has a greater coefficient of expansion than the stone behind it because the linear coefficient of thermal expansion of gypsum (in the pore space) is about five times the mean coefficient of expansion of calcite. When the temperature changes, the stresses produced by the differential expansion will tend to cause delamination of the surface. When the surface of a moist stone becomes warm by exposure to the sun or from a warm atmosphere, expansion occurs and, concurrently, evaporation-precipitation takes place. Crystals of calcium sulphate may thus be deposited in minute cracks produced during the expansion phase. Continued repetition of this process would tend to produce the observed expansion and blistering of the surface layers. In a polluted city, much disfiguration of building stones occurs by the accumulation of soot deposits with the gypsum. The soot fills the surface pores and the stone becomes uniformly darkened. In addition to its blackening effect, soot also contributes to chemical decay, because it carries with it free acids and soluble salts, which are brought into contact with the stone (Amoroso and Fassina, 1983).

Internal disintegration

In addition to the exfoliation associated with the formation of surface skins, limestones can also suffer a breakdown of their internal structure. Sometimes this takes the form of a powdering of the stone immediately behind the skin. This is probably due to the retention of fluids that are unable to escape by normal evaporation owing to the impermeable nature of the skin. Sometimes a series of cracks develop parallel to the exposed surface and the internal structure is effectively shattered.

Movement of moisture and salts in limestone and efflorescence

If, in a homogeneous material, differences in the external conditions may cause one area to undergo evaporation more quickly than another, moisture will flow towards the more rapidly evaporating portions. The soluble salts carried in the fluid are thus concentrated and, on crystallization, can initiate disintegration. The crystallization of soluble salts within the pores of building stone is an important cause of decay. Soluble salts may also crystallize on the stone surface forming unsightly deposits, commonly known as " efflorescence ". The danger associated with the presence of salts is rendered more acute by the fact that their deleterious action may continue so long as they remain in the stone. The absorption of moisture from the air is sufficient to cause changes in the hydrated condition of the salt, and thus bring about the further decay of grains (Charola, 1988; Vendrell-Saz et al., 1996).

EXPERIMENTAL WORK:

Investigated sites

Eight sites for monument buildings in Cairo were selected. They are:

- Sultan Hassan Mosque Walls	(H- Samples)
- Al- Rafaie Mosque Walls	(R- Samples)
- Magra El- Oyoon Walls	(M- Samples)
- Shikhone Mosque Walls	(S - Samples)
- Ahmed Ibn- Thulun Mosque Walls	(T - Samples)
- Amr Ibn- Al- Ass Mosque Walls	(A - Samples)
- Blue Mosque Walls	(B - Samples)
- Citadel Back Walls	(C - Samples)

Investigation procedures

Use of "RGB" color space system

Red, Green, Blue are three components of the RGB color system. Colors recorded using a digital camera are created by a blending of the R, G, and B components. A pixel is the fundamental unit of the image. Every pixel has Red, Green, Blue values. Red, Green, Blue values are defined by the proportional intensity of each of these components (in range of 0 – 255). Red, Green, Blue values can be separately measured for each pixel so that each component intensity can be measured in a digital photos using its pixel values. Each component can then be displayed in an X-Y chart, in which the X-axis represents the intensity values and the Y-axis represent its frequency.

Use of 'ImageCraft' program

Start the 'ImageCraft' program, open the digital image file that you want to analyze. Note, however, there will be some difference between the color in the digital image and real color because of shadow effects, the location of the light source etc. It will, therefore, generally be necessary to calibrate the RGB values of the digital image by using a color chart with the standard RGB values. By siting the mouse pointer over each color of the chart, the RGB values for each color can be obtained. The relational equation between the RGB value acquired by 'ImageCraft' and the RGB values from the standard color chart - which is included with it – can then be determined for each color (Red, Green and Blue) using the Excel software. The constants thus derived can be applied in the calibration window in 'ImageCraft' program allowing a new calibrated image to be generated. The calibrated image can be divided into several sections and a histogram, with relevant information and data, can then be determined for each section using the color information menu and RGB statistics in the program.

STEPS FOLLOWED

- General images taken of the monument walls showing the entrance and wall stones (Plate 1).
- Images taken of stone decay seen in the monument walls showing different degrees of deterioration (light, medium, high) by the use of a digital camera (not less than 3 megapixels resolution) indicating the standard colors reference for each site (Plate 2).

- Images of the source stones taken from the ancient quarries at Mokattam. Fresh surface imaged after removal of surficial layers affected by weathering. For each photograph a standard color reference is given. This was carried out only once during the study period and used as the reference stone for comparison with the stones photographed from the monument wall.
- Image analysis of digital photos using 'ImageCraft' - applied to all photos taken for monument and for source stones.
- A cross-sectional survey from each photo was made for calibration of natural colors with standard colors.
- 330 cross-sections were taken of the stone samples from the eight monument sites (as indicated in Table 1).

RESULTS AND ANALYSIS

- By comparing the results obtained from the 330 cross-sectional surveys taken from digital images of deteriorated stones at the monument sites and from the source stones, it was possible to get good correlation between degree of deterioration and color mean intensity for each of the three colors – Red, Green and Blue – (according to the standard RGB color system). The results confirm a strong degree of correlation between stone deterioration and color change. The results also suggest that all stones in the monument walls were quarried from one source and have been exposed to very similar natural and chemical weathering conditions.
- Figure 1 integrates all deterioration color values in one table for each monument site.
- The ordinate of the integrated figure which represent degree of Color Deterioration is divided into five categories as follows:
  - Very low deterioration (zero to 20%)
  - Low deterioration (21 to 40 %)
  - Medium deterioration (41 to 60 %)
  - High deterioration (61 to 80 %)
  - Very high deterioration (81 to 100 %)
- All Color Deterioration points for each category of the five categories indicated were calculated. Consequently, the percentage in each category was known.
- From the percentage falling in each category, it was possible to make a detailed description of the deterioration in each of the studied monument stones. It was then possible to predict quantitatively the degree of repair needed (intensive, medium or simple remedial) according to the degree of deterioration indicated in Table 2.
- General conditions of deterioration of the monument stones at the eight studied sites are presented in Figure 2.

CONCLUSIONS

- A good correlation was obtained between the degree of deterioration and color mean intensity for each of the three colors (Red, Green and Blue) in the monument stones studied.
- All stones studied in the eight monument walls were probably quarried from one source and have been exposed to very similar natural and chemical weathering conditions.
- Relationships derived in this study could be used as a general reference for the neighbouring monument sites. Therefore, when the mean intensity value for one of the standard colors is measured for any of the deteriorated stones at these other sites, it should be possible to accurately determine the degree of deterioration of that stone without the elaborate studies usually needed.
- Using the above procedure a comprehensive survey can be made in very short time to evaluate the deterioration state and remedial measures needed for any sites without the need to take cores or carry out any destructive testing

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Sultan Hassan Mosque Wall (H-site)

Al-Rafaie Mosque Wall (R-site)

Magra El- Oyoon Wall (M-site)

Shikhone Mosque Wall (S-site)

Ahmed Ibn- Thulun Mosque Wall (T-site)

Amr Ibn- Al- Ass Mosque Wall (A-site)

Blue Mosque Wall (B-site)

Citadel Back Wall (C-site)

Plate 1. General views of studied sites

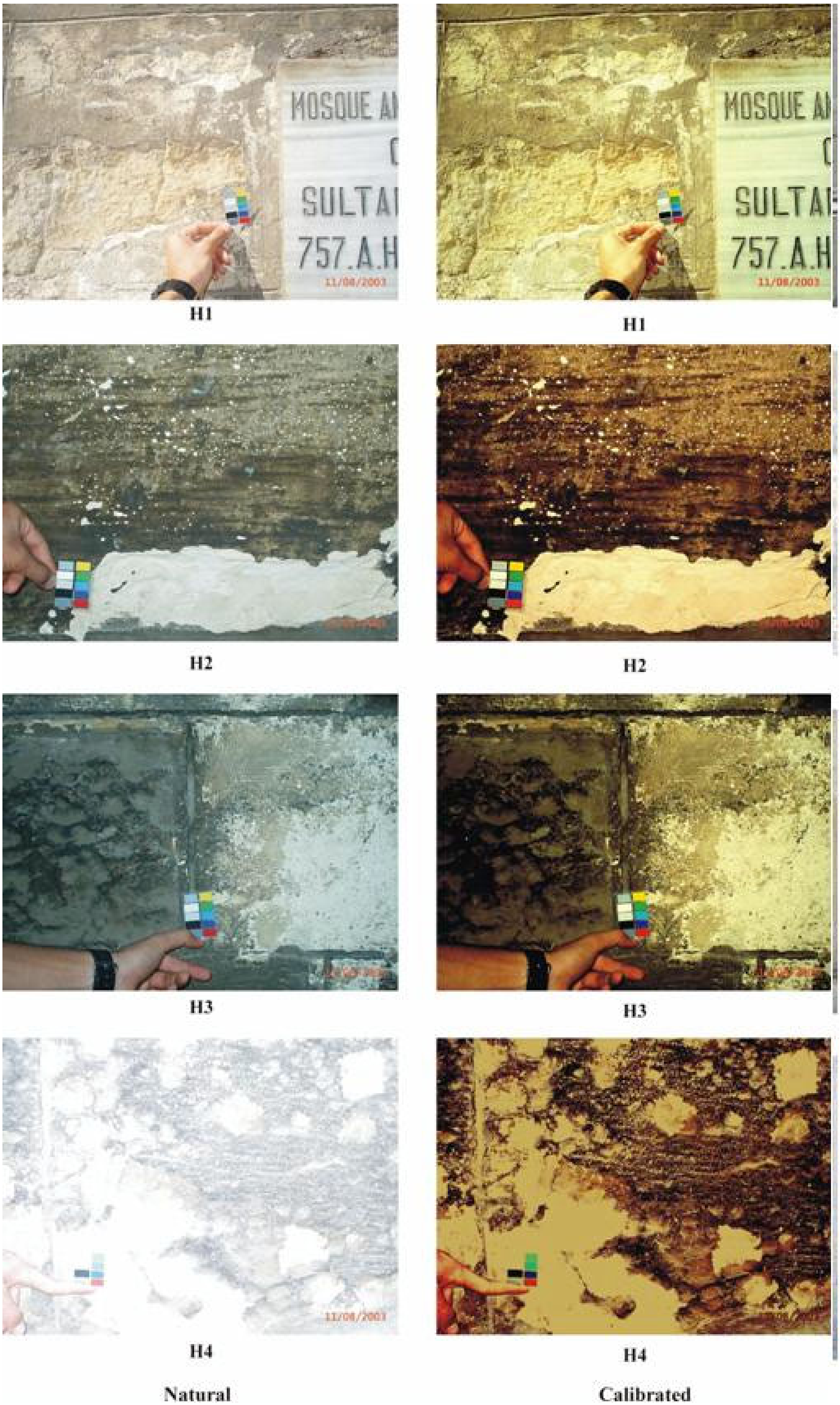

Plate 2. Natural and calibrated images of deteriorated stone in the wall of Sultan Hassan Mosque

Table 1. Deterioration Percentage and Mean Intensity for Sultan Hassan Mosque (H samples)

Sample No.	**Section No.**	**Red Color**		**Green Color**		**Blue Color**	
		L *	**•D % ****	**L**	**•D %**	**•D %**	**%**
H1	H1-1	185	18.1	175	20	103	31.3
	H1-2	170	24.8	155	29.2	88	41.3
	H1-3	130	42.5	112	48.9	58	61.3
	H1-4	213	5.7	206	5.9	136	9.3
	H1-5	174	23	159	27.4	91	39.3
	H1-6	201	11.1	191	12.8	119	20.7
	H1-7	195	13.7	106	51.6	114	24
	H1-8	217	4	204	6.8	119	20.7
	H1-9	226	0	219	0	150	0
H2	H2-1	120	46.9	77	64.8	30	80
	H2-2	144	36.3	100	54.3	42	72
	H2-3	83	63.3	38	82.6	11	92.7
	H2-4	85	62.4	39	82.2	10	93.3
	H2-5	226	0	219	0	144	4
H3	H3-1	74	67.3	58	73.5	20	86.7
	H3-2	164	27.4	151	31	83	44.7
	H3-3	43	81	26	88.1	5	96.7
	H3-4	183	19	168	23.3	95	36.7
	H3-5	217	4	213	2.7	137	8.7
H4	H4-1	161	28.8	124	43.4	68	54.7
	H4-2	117	48.2	72	67.1	39	74
	H4-3	190	15.9	158	27.9	83	44.7
	H4-4	81	64.2	31	85.8	17	88.7

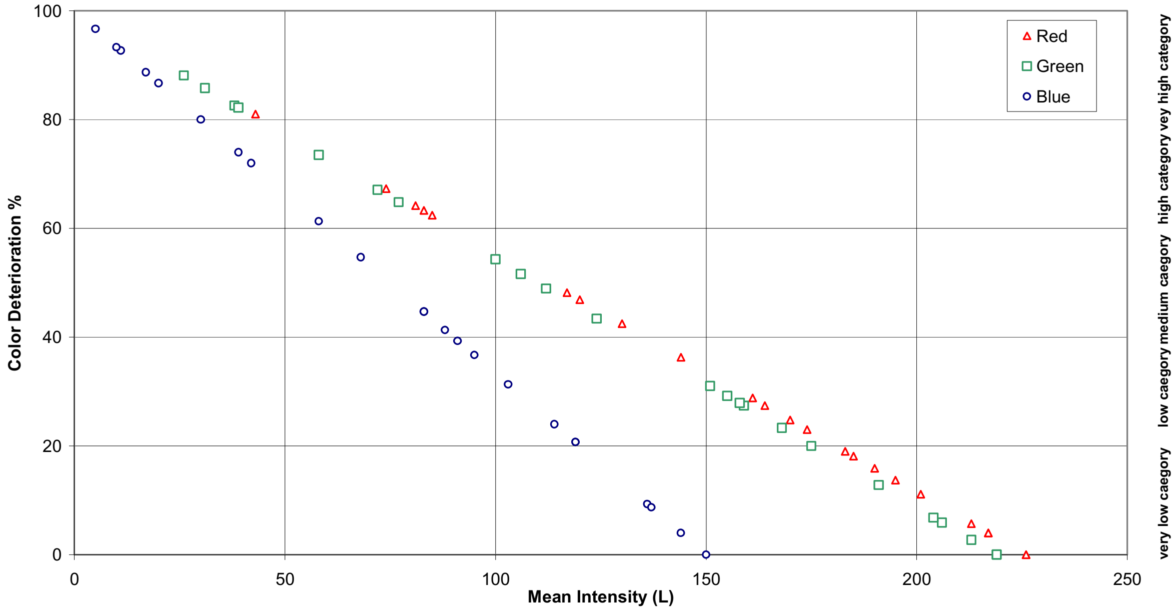

Figure 1. A classified chart to calculate number of effected color points for each proposed deterioration category (H sites)

Table 2. Quantitative description of Deterioration Categories for the studied monument sites

Site label	Percentages of Deterioration Categories					Description
	Very low	Low	Medium	High	Very high	
H	31.9	26.1	15.9	15.9	10.2	• many stones in low category • some stones in medium & high categories
R	9.5	14.9	24.3	27.0	24.3	• many stones in high category • some stones in low & medium categories
M	8.8	13.8	28.3	28.7	20.4	• many stones in high category • some stones in low & medium categories
S	2.4	17.9	35.0	39.0	5.7	• many stones in high category • some stones in low & medium categories
T	29.5	37.2	23.5	7.8	2.0	• many stones in low category • some stones in medium category • traces stones in high categories
A	38.4	39.6	21.4	0.6	0	• many stones in low category • some stones in medium category • traces stones in high categories
B	20.4	22.2	28.7	13.0	15.7	• many stones in low category • some stones in medium & high categories
C	3.1	32.3	42.7	20.8	1.1	• many stones in medium category • some stones in low & high categories

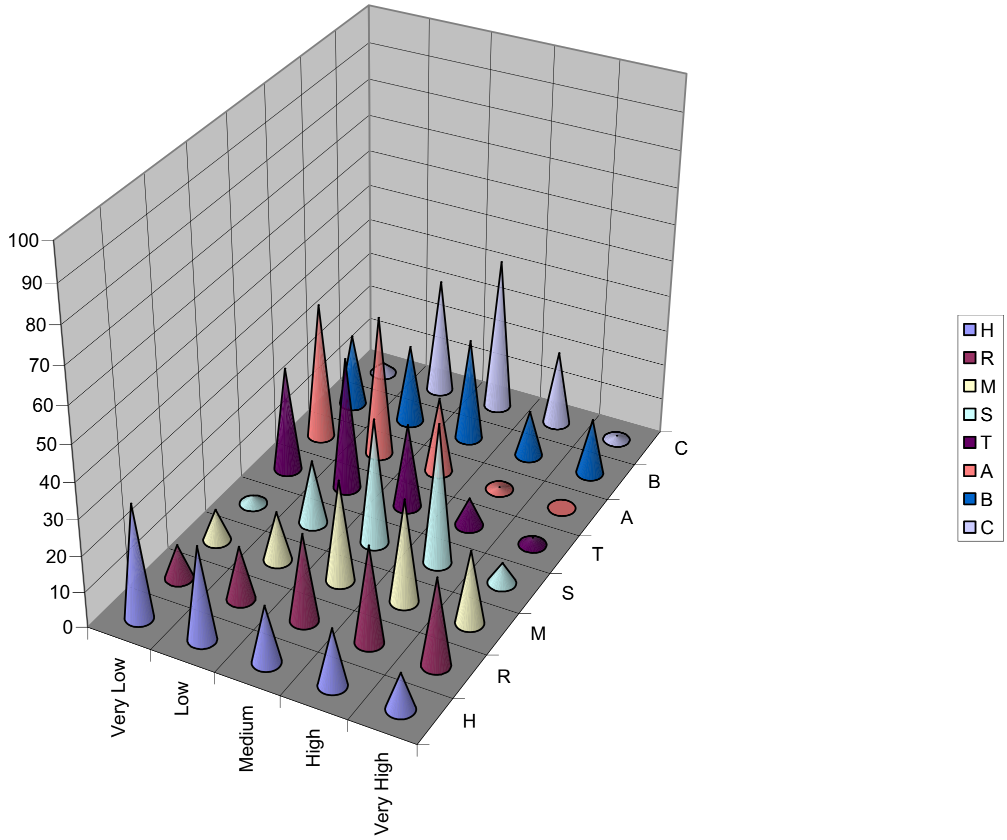

Figure 2. A representative chart for the proposed deterioration categories occuring in the studied monument stones. (Sites: H; R; M; S ; T ; A ; B ; C)

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