Diagnosis of Weathering Damage on Stone Monuments

/ BERND FITZNER

Geological Institute, RWTH Aachen University. Wuellnerstrasse 2, D-52062 Aachen, Germany (http://www.stone.rwth-aachen.de)

Abstract

Stone monuments represent an important part of our world´s cultural heritage. The awareness of increasing stone damage on monuments and the danger of further irretrievable loss of cultural heritage have resulted in great efforts worldwide for sustainable monument preservation. A precise damage diagnosis with comprehensive characterization, interpretation and rating of stone damage represents the basis for effective and economic monument preservation measures. The experienced methodological approach to the assessment of stone damage combines in situ investigation and laboratory studies. The monument mapping method is presented as an established non-destructive procedure for in situ studies on stone damage. It can be applied to all stone types and to all kinds of stone monuments. The use of weathering forms, damage categories and damage indices for the registration, documentation, quantitative evaluation and rating of stone damage is explained. Furthermore, complementary in situ measurements are discussed.

INTRODUCTION

The alarming increase of weathering damage on natural stone monuments and the danger, that in near future a major part of built cultural heritage could be partially or completely destroyed, requires immediate measures in order of sustainable monument preservation (Figs. 1-4).

Profound knowledge of the material properties and the weathering behaviour of the natural stones used is necessary, as well as knowledge of weathering factors and weathering processes which initiate and control this weathering behaviour. High level of scientific knowledge is an important basis for effective and economic preservation measures. The well-accepted systematic approach to sustainable monument preservation can be subdivided into the three interdependent parts of anamnesis, diagnosis and therapy (Fig. 5).

The anamnesis is to acquire, compile and evaluate all information, data and documents concerning the monument and its history. A comprehensive anam-

fig 1. Gargoyle, Naumburg Cathedral (Germany).

fig 2. Moai, Easter Island (Chile).

fig 3. Aqueduct near Tarragona (Spain).

fig 4. Palace Tomb, Petra (Jordan).

Scales		Parameters	Investigation	Involved sciences
Non-visible deterioration	Nanoscale < mm	Changes of stone properties	Laboratory analysis	Geosciences, material sciences, chemistry, physics, micro-biology, ecology
Visible deterioration	Microscale mm to cm	Mass loss, micromorphology		
	Mesoscale cm to m	Deterioration phenomena	In-situ investigation	
	Macroscale - whole structures or monuments	Structural stability, aesthetic appearance		Structural engineering, architecture

fig 5. Scales of stone deterioration, modified from Viles et al. (1997)

palabras clave: monumentos de piedra, a la intemperie, diagnóstico de los daños, la cartografía monumento, mediciones in situ, conservación de monumentos

key words: stone monuments, weathering, damage diagnosis, monument mapping, in situ measurements, monument preservationhen.de

*corresponding author: fitzner@geol.rwth-aachen.de

nesis has to consider all aspects like monument identification, location, art-historical portrayal, case history and environment. The information provided by the anamnesis contributes to the understanding of the monument situation and the state of damage.

The anamnesis is consequently followed by the diagnosis. The overall aim of diagnosis is analysis, quantification, interpretation and rating of stone deterioration and stone damage considering weathering factors, weathering processes and weathering characteristics as well as stone types, monument characteristics and time factor. The optimization of diagnostical procedures is an additional scientific objective. Profound diagnosis represents the basis for sustainable monument preservation.

Particular aims of scientific diagnosis are:

- characterization of stone materials,
- characterization and quantification of stone alteration,
- characterization and quantification of weathering characteristics - weathering forms, weathering profiles, weathering products,
- detection of non-visible stone damage,
- information on weathering factors
- information on weathering processes,
- characterization and quantification of weathering progression / weathering rates,
- quantitative rating of stone damage,
- rating of stone quality, selection of durable stone materials,
- damage prognosis, risk prognosis,
- information on need / urgency of preservation measures,
- recommendation of appropriate preservation measures.

Subsequent to preservation measures, diagnostical activities facilitate the control / certification of the preservation measures and the prevention of new damage, long-term monitoring and maintenance of monuments.

The systematic investigation of stone deterioration at monuments must consider different scales of stone deterioration. Visible and non-visible stone deterioration can be distinguished. According to Viles et al. (1997), a subdivision can be made into nanoscale (<mm), microscale (mm to cm), mesoscale (cm to m) and macroscale (whole facades or buildings) of stone deterioration *(Fig. 6)*. The nanoscale corresponds to non-visible stone deterioration, whereas the microscale, mesoscale and macroscale refer to visible stone deterioration. Each scale is assessed by appropriate parameters and investigation methods for the evaluation of stone deterioration. For the comprehensive evaluation of stone deterioration, the interdisciplinary cooperation of scientists from different fields - geosciences, material sciences, chemistry, physics, microbiology -, engineers and architects is required.

The diagnosis methodology presented, which combines in situ investigation, laboratory analysis and weathering simulation / outdoor exposure, is focussed on nanoscale, microscale and mesoscale of stone deterioration. In situ investigation is targeted to information on stone deterioration in the range of mesoscale to microscale. Laboratory analyses provide information on stone deterioration at microscale and nanoscale. Weathering simulation procedures and outdoor exposure tests in combination with laboratory analysis and in situ investigation further contributes to the evaluation of stone deterioration at mesoscale, microscale and nanoscale. Evaluation of stone deterioration at macroscale will be the task of structural engineers and architects.

The consequent application of in situ investigation, laboratory studies and weathering simulation and the joint evaluation of results contribute essentially to comprehensive and reliable damage diagnosis for stone monuments.

Based on anamnesis and diagnosis, effective and economic therapeutical steps can be proposed and calculated. Test-application should precede the final execution of preservation measures. Important therapeutical and preventive preservation measures such as safeguarding, cleaning, desalination, stone repair, stone replacement, surface protection, sheltering or relocation of stone objects are presented in *Fig. 7*. The effectiveness of preservation measures should be monitored in the frame of long-term monument observation.

IN SITU INVESTIGATION

In situ investigation comprises monument mapping, in situ measurements and sampling. Monument mapping is applied for the precise registration, documentation and evaluation of lithotypes and deterioration phenomena. In situ measurements can provide complementary quantitative information for characterization of lithotypes and state of deterioration. Based on results obtained from monument mapping, in situ measurements can be well-directed. Monument mapping and in situ measurements contribute essentially to the optimization of sampling for laboratory analysis.

Monument mapping

Many stone monuments have suffered serious damage as a consequence of natural weathering processes, pollution, insufficient maintenance, utilization, use of sensitive materials or inappropriate conservation. Profound diagnosis is required for characterization, interpretation and rating of stone deterioration and for planning and execution of effective and econo-

Scales		Parameters	Investigation	Involved sciences
Non-visible deterioration	Nanoscale < mm	Changes of stone properties	Laboratory analysis	Geosciences, material sciences, chemistry, physics, micro-biology, ecology
Visible deterioration	Microscale mm to cm	Mass loss, micromorphology		
	Mesoscale cm to m	Deterioration phenomena	In-situ investigation	
	Macroscale - whole structures or monuments	Structural stability, aesthetic appearance		Structural engineering, architecture

fig 6. *Scales of stone deterioration, modified from Viles et al. (1997).*

fig 7. Monument preservation measures (Ashurst & Ashurst, 1988; Croci, 1998; Price, 1996; Petzet, 1999).

mic preservation measures. Precise information on factors, processes and characteristics of stone deterioration would be optimal for damage diagnosis and for the solution of scientific and practical problems. Experience has shown that the investigation of factors and processes of stone deterioration is difficult and time- and cost-consuming. Very often, results are insufficient and unsatisfactory. Investigation on deterioration characteristics - in particular deterioration phenomena, deterioration profiles and deterioration products - has turned out as most promising approach. Knowledge of the deterioration characteristics allows to deduce information on factors and processes of stone deterioration *(Fitzner et al., 1997c; Heinrichs & Fitzner, 2000)* and to recommend suitable complementary studies.

The monument mapping method has been developed as a non-destructive procedure for the detailed registration, documentation and evaluation of lithotypes and deterioration phenomena *(Fitzner et al., 1995, 1997a, c; Fitzner & Kownatzki, 1997; Kownatzki, 1997; Fitzner & Heinrichs, 1998a, b; Heinrichs & Fitzner, 1999; Fitzner & Heinrichs, 2000)*.

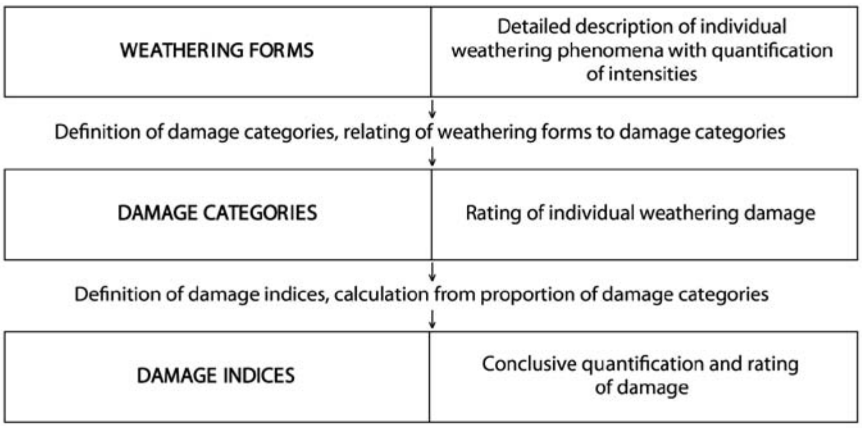

fig 8. Weathering forms, damage categories and damage indices.

Monument mapping can be applied to all stone types and to all kinds of stone objects ranging from sculptures to facades or entire monuments. The mapping method meets great international acceptance and is approved as an experienced method contributing essentially to:

- improvement of scientific knowledge of stone deterioration,
- profound damage diagnosis,
- risk prognosis,
- risk management,
- sustainable monument preservation.

Monument mapping represents the only method which allows to describe and evaluate complete stone structures precisely and reproducibly according to type and distribution of lithotypes and deterioration phenomena. For detailed monument mapping accessibility of the investigation areas is necessary. Two modes of monument mapping can be distinguished: lithological mapping and mapping of weathering forms. The term "weathering forms" is synonymous with "ßdeterioration phenomena" and corresponds to visible stone deterioration at mesoscale (cm to m).

Plans of the investigation areas and classification schemes of lithotypes and weathering forms are required for monument mapping. Based on these classification schemes, in the course of monument mapping all lithotypes and weathering forms are registered and are recorded in plans. Computer-programmes are used for the processing, illustration and evaluation of mapping information.

While weathering forms are used for the description of deterioration phenomena according to type and intensity, damage categories and damage indices have been established as a tool for the rating of damage and as a contribution to risk prognosis and risk management *(Fig. 8)*. On the basis of defined schemes, all weathering forms - taking into consideration their range of intensity - get related to damage categories. Six damage categories have been defined: 0 - no visible damage, 1 - very slight damage, 2 - slight damage, 3 - moderate damage, 4 - severe damage, 5 - very severe damage. The damage categories are illustrated in maps and are evaluated quantitatively. Based on the quantitative evaluation of damage categories, damage indices are calculated for conclusive quantification and rating of damage. In this way, damage indices complete a consistent and convincing approach to the characterization, evaluation, quantification and rating of visible stone damage.

The mode of lithological mapping comprises survey, identification, petrographical characterization and registration of all lithotypes. Well-established petrographical classification schemes are used for the description of the lithotypes. Original stone material and stone material of former restoration phases should be distinguished. Based on the classification scheme of lithotypes, the investigation area is mapped stone by stone. So the distribution of lithotypes is documented. This is important for correlations between lithotypes and state of deterioration as well as for well-directed sampling. The lithotypes are evaluated quantitatively and the distribution of the lithotypes is illustrated in lithological maps.

Weathering forms on stone monuments represent the visible results of weathering processes which are initiated and controlled by interacting weathering factors. The term "weathering forms" is used for visible stone deterioration at mesoscale *(cm to m)*. Examples of weathering forms are shown in *Figs. 9 - 12*.

fig 9. Alveolar weathering, Citadel / Victoria - Gozo (Malta).

fig 10. Fissures, Karnak Temple / Luxor (Egypt).

The objective and reproducible description, registration and document-ttation of weathering forms require a precise classification scheme of weathering forms. Such a classification scheme has been developed, based on investigation at numerous monuments worldwide considering different stone types and environments.

fig 11. Biological colonization, sculpture / Torcello (Italy).

fig 12. Crust, sculpture / Naumburg Cathedral (Germany).

The classification scheme of weathering forms and an updated version with definitions, parameters for intensity classification and photo-atlas are presented by *Fitzner et al. (1995), Fitzner & Heinrichs (2002) and Fitzner & Heinrichs (2004).* The classification scheme has met great international acceptance. It shows a hierarchic structure. The uppermost level (I) com-prises four groups of weathering forms:

- group 1 - loss of stone material,
- group 2 - discoloration / deposits,
- group 3 - detachment,
- group 4 - fissures / deformation.

In level II each group is subdivided into *main weathering forms*. In level III several main weathering forms are further specified by means of individual weathering forms. In the most differentiated level IV, the individual weathering forms are further differentiated according to intensities.

The classification scheme of weathering forms can still be specified considering particular stone types or monument assemblies. Specification concerns the definition of individual weathering forms and the suitable intensity classification of the weathering forms. The intensity classification should be adjusted to the range of intensities surveyed at the monuments under investigation.

All weathering forms registered in the course of monument mapping are illustrated in maps and are evaluated quantitatively by means of computer-supported data processing. Illustration of weathering forms in maps according to the four groups of weathering forms "loss of stone material", "discoloration / deposits", "detachment" and "fissures / deformation" has turned out as a very suitable mode of illustration.

Illustration and quantitative evaluation of weathering forms provide information on:

- characteristic weathering forms,
- interrelations between weathering forms, especially as concerns loss of stone material, current detachment of stone material and deposits,
- distribution / zonation of weathering forms,
- chronological sequences of weathering forms,
- weathering progression, weathering
- causes and processes of stone deterioration.

In *figs. 13 - 15* the rock-cut Tomb No. 778 in Petra / Jordan, a map of its weathering forms of group 1 "loss of stone material" and a map of its average weathering rates derived from the evaluation of these weathering forms are shown.

The information obtained from the evaluation of weathering forms can be further specified considering selected lithotypes and monument exposition characteristics like location, geometry or orientation. With respect to transferability of results, elaboration of characteristic weathering forms in dependence on lithotypes, monument characteristics, environment and time represents an important step of evaluation. This also contributes to the development of weathering models.

Damage categories have been established for the comparative rating of individual damage *(Fitzner & Heinrichs, 2002; Fitzner et al., 2002).* Six damage categories have been defined: 0 - no visible damage, I - very slight damage, II

- slight damage, III - moderate damage, IV - severe damage, V - very severe damage. Based on defined schemes, all weathering forms are related to damage categories. The correlation schemes "weathering forms - damage categories" must consider weathering forms and their intensities, proportion "degradated stone parts - total dimension of the stone element", function of the structural elements as well as the historical and artistical value of the stone elements. An appropriate correlation scheme "weathering forms - damage categories" requires cooperation of all experts involved in monument diagnosis and monument preservation.

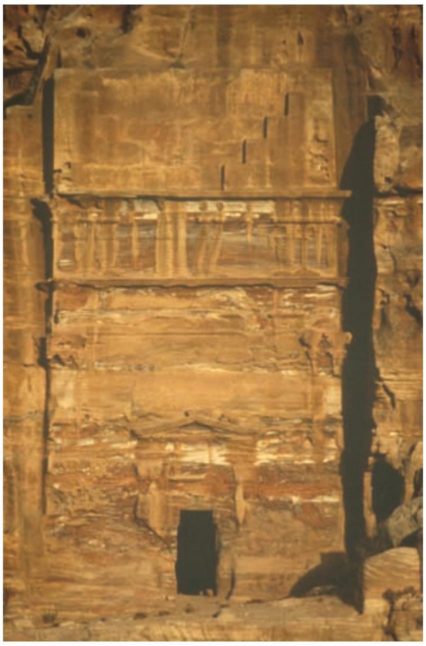

fig 13. Tomb No. 778, Petra (Jordan)

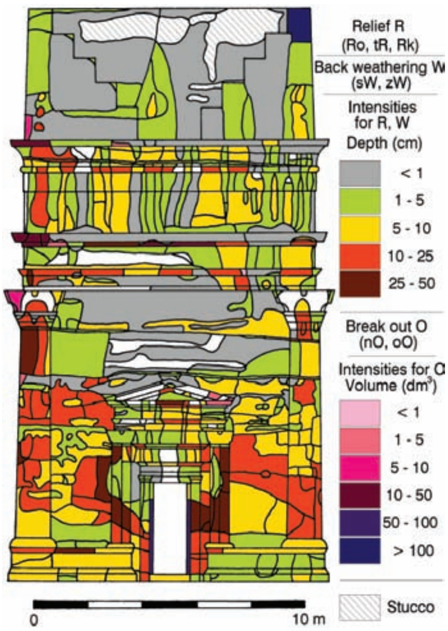

fig 14. Map of weathering forms - "loss of stone material". Tomb No. 778.

Damage indices are calculated from proportion of damage categories *(Fitzner & Heinrichs, 2002; Fitzner et al., 2002)*. A linear and a progressive damage index has been defined. The damage indices range from 0 to 5.0. According to the calculation modes, the linear damage index corresponds to average damage category, whereas the progressive damage index emphasises proportion of higher damage categories. Following relation arises: progressive damage index ≥ linear damage index.

The use of damage indices ensures the quantification and rating of stone damage for entire monuments or single structures.

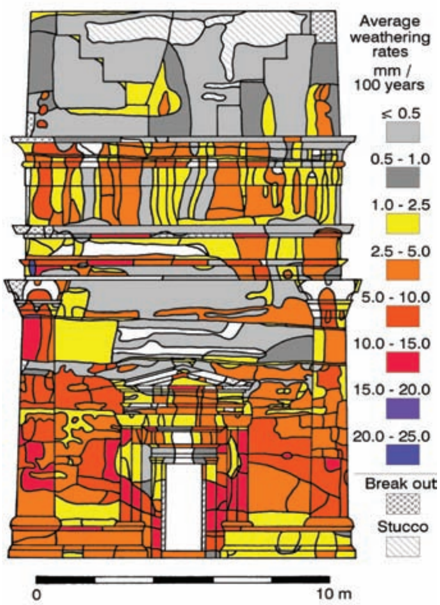

fig 15. Average weathering rates. Tomb No. 778, Petra (Jordan)

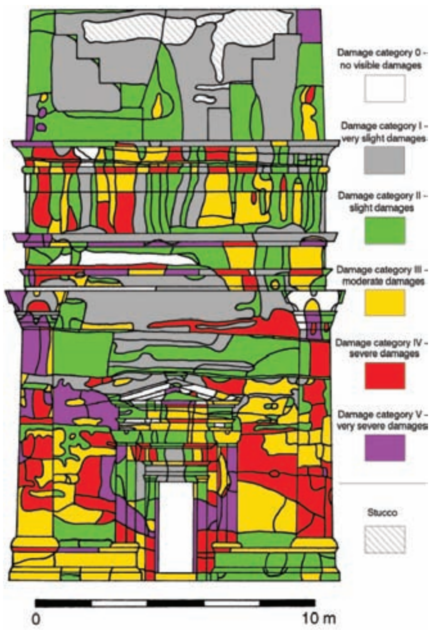

fig 16. Map of damage categories. Tomb No. 778, Petra (Jordan)

Damage indices allow comparison and ranking of different monuments or parts of monuments. The illustration of damage categories in maps and the quantitative evaluation of damage categories with the determination of damage indices are presented again for the Tomb No. 778 in Petra / Jordan *(Figs. 13, 16 and 17)*.

The use of damage indices contributes essentially to rating and comparison of stone materials regarding their susceptibility to degradation. It enhances risk estimation and contributes to risk management. Damage indices point out need and urgency of intervention. Damage categories locate those parts of a monument which intervention has to focus on. Weathering forms have to be considered for deduction of appropriate types of preservation measures. Damage categories and especially damage indices represent very practical tools for reliable judgement/certification of preservation measures. For the regular re-evaluation of monuments in the frame of long-term survey and maintenance the consequent application of weathering forms, damage categories and damage indices is advisable.

The use of weathering forms, damage categories and damage indices can be considered as an advanced approach and as an essential contribution to well-founded damage diagnosis at stone monuments and to sustainable monument preservation. The consistent strategy of linking weathering forms with damage categories and damage indices is well-addressed and recommended to end-users such as:

- organisations, monument authorities or monument owners involved in planning and decision of monument preservation policies and strategies,
- contractors involved in damage diagnosis and carrying out monument preservation activities like architects, engineers, restorers, conservators, consultants, project managers and construction companies.

In situ measurements

In situ measurements provide complementary quantitative information on stone materials and weathering characteristics. They enable examination of stone structures without any changes due to sampling or removal. During the last decades different measuring methods have been developed, often adapted from other disciplines and modified for application at stone monuments.

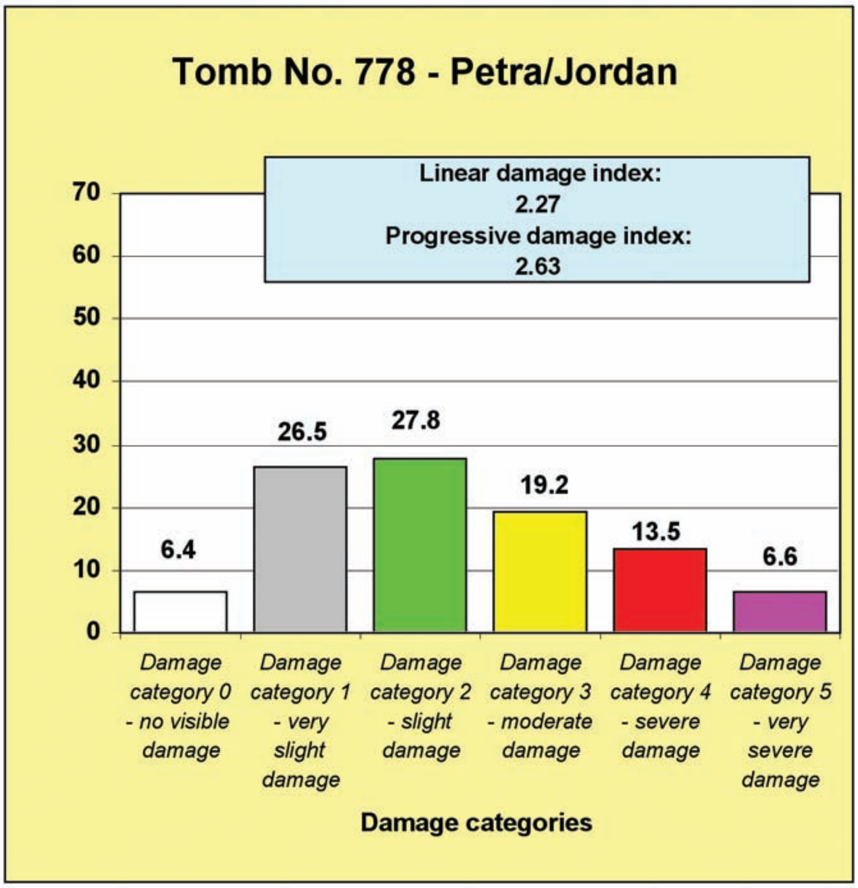

fig 17. Quantitative evaluation of damage categories and damage indices, Tomb No. 778, Petra (Jordan).

Surface measuring, acoustic methods, electromagnetic methods, geo-electric methods, water uptake methods, strength testing methods, bore-hole methods and chemical investigation procedures can be distinguished. The mode of operation ranges from non-destructive via slightly destructive to destructive. Preferably, non-destructive procedures should be applied *(Nappi & Côte, 1997)*. Expenditure regarding equipment, working procedure and costs can vary extremely. Most of the methods allow only spot measurements and provide information for very limited local parts of stone structures. Therefore, selection of characteristic areas at the monument and sufficient number of measurements are required in order of reliable and representative results. In the following some suitable in situ measuring methods are described briefly.

Ultrasonic measurements represent an appropriate non-destructive acoustic method for the characterization of stone type and weathering state.

Measurements according to the transmission mode can be applied successfully at natural stone monuments, especially at columns, pillars, pilasters, slabs or sculptural decoration. Ultrasonic velocities are calculated from transit time and measuring distance. Ultrasonic measurements are used for the supplementation, verification and quantification of results obtained from phenomenological studies. The geometry of fissures and pre-macroscopic stone degradation like micro-cracks can be detected. Classification schemes of ultrasonic velocities can be developed for individual stone types for rating the degree of damage. Ultrasonic measurements are very suitable for long-term monitoring of stone structures and they can also be applied successfully for rating the effectiveness of stone treatment measures. Ultrasonic tomography for stone structures is a modern scientific concern. Results of ultrasonic measurements are shown for the Lion horoscope of the famous Nemrut Dag in Turkey *(Figs. 18, 19)*. In the map of ultrasonic velocities (Fig. 19) the transition from high ultrasonic velocities (green) to low ultrasonic velocities (red) corresponds to increasing stone degradation.

The infrared-thermography represents an electromagnetic method. The heat-induced infrared radiation of stone materials is registered. Temperature gradients along a surface are detected. Measurements of surface temperatures are possible even for larger monument structures. The results on the temperature behaviour of the stone materials contribute to information on stone types, weathering state and exposition characteristics. Weathering damage can be detected by means of temperature anomalies. The results obtained from infrared-thermography can also indicate surface areas which are affected by high humidity load.

Water uptake measurements are carried out for the quantification of capillary water uptake and water penetration depth and for the characterization of water migration. Additionally, the results provide information on porosity

fig 18. Ultrasonic measurements, lion horoscope / Nemrut Dag (Turkey).

fig 19. Map of ultrasonic velocities, lion horoscope / Nemrut Dag (Turkey).

properties and surface condition of the building materials. Stone types and weathering states can be characterized and compared. A simple non-destructive method used very frequently for water uptake measurements is the KARSTEN tube method *(Fig. 20)*. Water uptake measurements are also very suitable for studies on the effectiveness of treatments with water repellents.

Drilling resistance measurements and rebound hardness measurements are often applied in situ for the measuring of mechanical stone properties. Drilling resistance measurements represent a modern, only slightly destructive method which registers drilling depth versus drilling time *(Fig. 21)*. The drilling with portable drilling equipment is performed with constant pressure, energy supply and rotation speed. The drilling resistance - also called drilling hardness - as indicator for stone strength is calculated. Profiles are obtained characterizing drilling resistance versus drilling depth. Results gained from drilling resistance measurements guarantee quantitative information for comparison of stone types, characterization of weathering profiles and correlation between weathering forms and weathering profiles.

fig 20. Water uptake measurements with Karsten tubes.

Additionally, drilling powder can be collected for laboratory analyses.

fig 21. Rebound hardness measurements, Schmidt hammer.

Rebound hardness measurements with the SCHMIDT Test Hammer represent a quite popular in situ method for the measuring of mechanical stone properties *(Fig. 22)*. A plunger strikes the stone surface. The mass then tends to rebound. Degree of rebound correlates to the energy absorption, which depends upon the stone hardness. The

fig 22. Drilling resistance measurements.

results allow the characterization and comparison of stone types as well as quantitative information on state of degradation. Attempts have been made to correlate stone hardness and strength properties.

Sampling

In the frame of comprehensive diagnosis, samples of unweathered, weathered and treated stone material are necessary for laboratory studies in order of:

- characterization and classification of stone materials,
- characterization, quantification and rating of stone alteration,
- identification and quantification of weathering products,
- rating of stone quality,
- characterization and rating of effectiveness of stone treatment.

Unweathered stone material for laboratory analyses, weathering simulation or outdoor exposure should be taken from relevant quarries. Sampling of weathered or treated stone material at monuments must be performed most carefully. Number and quantity of samples have to ensure that the scientific and practical problems can be approached systematically and can be solved satisfactory. Today, many analytical techniques need only small amounts of stone material. Based on results obtained from the preceding in situ investigation, representative sampling can be well-directed and can be reduced to necessary extent. Precise documentation of sampling is required.

CONCLUSIONS

Precise damage diagnosis is required for the characterization, interpretation, rating and prediction of weathering damage on stone monuments and is vital for sustainable monument preservation. The monument mapping method has been developed as a modern scientific procedure for in situ studies and evaluation of weathering damage. The mapping method ensures a modern contribution to comprehensive and reliable damage diagnosis. It has met great international acceptance and has been applied successfully on numerous monuments worldwide. The consequent use of weathering forms, damage categories and damage indices means a consistent strategy for the characterization, quantitative evaluation and rating of weathering damage on stone monuments as well as a basis for the deduction of appropriate and economic monument preservation measures. The evaluation of weathering damage is based on lithological mapping and mapping of weathering forms. A detailed classification scheme of weathering forms has been developed as prerequisite for the objective and reproducible description and registration of weathering phenomena. Damage categories have been established for the rating of individual damage. Damage indices have been introduced as very practical tool for the conclusive quantification and rating of weathering damage on stone monuments. With respect to monument preservation practice, the results obtained from monument mapping represent a contribution to deduction, test-application and execution of efficient and economic monument preservation measures. The mapping method ensures a high benefit-cost ratio. Costs for the in situ studies and the evaluation of results amorthize from effective and economic preservation measures. The consequent use of weathering forms, damage categories and damage indices means also a very suitable strategy for the control / certification of preservation measures and for the regular re-evaluation of monuments in the framework of long-term survey and maintenance of monuments.

In situ measurements provide complementary quantitative information on stone materials and weathering characteristics. They allow the examination of stone structures without any changes due to sampling or removal.

In the framework of comprehensive damage diagnosis, samples of unweathered, weathered and treated stone material are needed for laboratory analyses, weathering simulation and outdoor exposure tests. Based on the preceding in situ investigation, sampling can be well-directed and can be reduced to necessary extent.

The consistent evaluation strategy based on in situ investigation and laboratory studies can be recommended to organisations, monument authorities and monument owners involved in planning and decision making of monument preservation policies and strategies as well as to architects, engineers, restorers, conservators, consultants, project managers or companies involved in damage diagnosis and monument preservation activities.

REFERENCES

Ashurst, J. & Ashurst, N. (1988) Stone masonry. Practical Building Conservation. English Heritage Technical Handbook, 1, Gower Technical Press, England.

Croci, G. (1998) The conservation and structural restoration of architectural heritage.- Advances in Architecture Series, Computational Mechanics Publications, Southampton, United Kingdom.

Fitzner, B. & Heinrichs, K. (1998a): Damage diagnosis at natural stone monuments - mapping and measurements. In "Proceedings of the 4th International Congress on Restoration of Buildings and Architectural Heritage". Centro Internacional para la Conservación del Patrimonio, CICOP, Spain, 170-172.

– & – (1998b): Evaluation of the weathering state of natural stones by monument mapping.- In "Proceedings of the conference ENVIWEATH 96, Environmental aspects of weathering processes", Sulovsky, P. & Zeman, J., ed. Brno/Czech Republic, 55-64.

– & – (2002): Damage diagnosis on stone monuments °V weathering forms, damage categories and damage indices.- In "Understanding and managing stone decay, Proceedings of the International Conference Stone weathering and atmospheric pollution network (SWAPNET)" Prikryl, R. & Viles, H.A. ed. Prachov Rocks - Czech Republic, Karolinum Press, Charles University, Prague.

– & – (2004): Photo atlas of weathering forms on stone monuments. www.stone.rwth-aachen.de.

–, –, la Bouchardiere, D. (2002): Damage index for stone monuments.- In Protection and conservation of the cultural heritage of the Mediterranean cities, Proceedings of the 5th International Symposium on the Conservation of Monuments in the Mediterranean Basin?, Galan, E. & Zezza, F. ed. Swets & Zeitlinger, Lisse, Netherlands, 315-326.

–, –, Kownatzki, R. (1995): Weathering forms classification and mapping. Verwitterungsformen - Klassifizierung und Kartierung.- In "Denkmalpflege und Naturwissenschaft, Natursteinkonservierung I". Förderprojekt des Bundesministeriums für Bildung, Wissenschaft, Forschung und Technologie, Verlag Ernst & Sohn, Berlin, 41-88.

–, –, – (1997a): Weathering forms at natural stone monuments - classification, mapping and evaluation. Inter. J. Restor. Build. Monument, 3, 105-124.

–, –, Volker, M. (1997b): Model for salt weathering at Maltese Globigerina limestones.- In "Proceedings of the E.C. Research Workshop, Origin, mechanisms and effects of salts on degradation of monuments in marine and continental environment", Zezza, F., ed. C.U.M. University School of Monument Conservation, Bari, 333-344.

–,–, – (1997c): Monument mapping - a contribution to monument preservation.- In "Proceedings of the E.C. Research Workshop, Origin, mechanisms and effects of salts on degradation of monuments in marine and continental environment" .Zezza, F. ed. C.U.M. University School of Monument Conservation, Bari, 347-355.

— & Kownatzki, R. (1997): Erfahrungen mit der Kartierung von Verwitterungsformen an Natursteinbauwerken. - In "Bauwerksdiagnostik und Qualitätsbewertung, WTA-Schriftenreihe, Heft". 13. Leschnik, W. & Venzmer, H. ed. Aedificatio Verlag, Freiburg / Fraunhofer IRB Verlag, Stuttgart, 157-172.

Heinrichs, K. & Fitzner, B. (1999): Comprehensive characterization and rating of weathering state at monuments carved from bedrocks in Petra/Jordan - weathering forms, damage categories and damage index. Annual of the Department of Antiquities of Jordan, XLIII, 321-351.

– & –(2000) Deterioration of rock monuments. In Proceedings of the 9th International Congress of the Deterioration and Conservation of Stone", 2. Petra/Jordan, eds. Elsevier, Amsterdam, 53-61.

Kownatzki, R. (1997): Verwitterungszustandserfassung von Natursteinbauwerken unter besonderer Berücksichtigung phänomenologischer Verfahren.- Dissertation RWTH Aachen, Aachener Geowissenschaftliche Beiträge, Bd. 22, Verlag der Augustinus Buchhandlung, Aachen.

Nappi, A. & Côte, P. (1997): Non-destructive test methods applicable to historic stone structures.- In "Report of the Dahlem Workshop on Saving our architectural heritage: The conservation of historic stone structures", Baer, N. S. & Snethlage, R. ed.. John Wiley & Sons Ltd., 151-166.

Petzet, M. (1999): Principles of monument conservation.- ICOMOS Journals of the German National Committee, XXX, Lipp Verlag, München.

Price, C. A. (1996): Stone conservation - an overview of current research.- Research in Conservation Series, Getty Conservation Institute, USA.

Viles, H. A., Camuffo, D., Fitz, S., Fitzner, B. Lindqvist, O., Livingston, R. A., maravellaki, p. V., Sabbioni, C. & Warscheid, T. (1997): Group report: What is the state of our knowledge of the mechanisms of deterioration and how good are our estimations of rates of deterioration?- In "Report of the Dahlem Workshop on Saving our architectural heritage: The conservation of historic stone structures", Baer, N. S. & Snethlage, R., eds. John Wiley & Sons Ltd., Berlin, 95-112.