Damage Diagnosis on Stone Monuments
– in Situ Investigation and Laboratory Studies

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ABSTRACT Stone monuments represent an important part of our world´s cultural heritage. The awareness of increasing stone damage on monuments coupled with the danger of irretrievable loss of cultural heritage has resulted in great efforts worldwide for monument preservation. Meaningful damage diagnosis is required for comprehensive characterization, interpretation and rating of stone damage. In situ investigation of monuments makes an important contribution to damage diagnosis on stone monuments. The monument mapping method is presented as an established non-destructive procedure for in situ studies on stone damage. It can be applied objectively and reproducibly to all stone types and to all kinds of stone monuments. The consequent use of weathering forms, damage categories and damage indices for precise registration, documentation, quantitative evaluation and rating of stone damage is explained. Furthermore, in situ measurements and well-directed sampling are discussed. Additionally, a wide range of analytical procedures in the laboratory and different types of weathering simulation tests contribute to modern damage diagnosis on stone monuments.

KEYWORDS

Natural stones, stone monuments, damage diagnosis, in situ investigation, monument mapping, weathering forms, rating of stone damage, damage categories, damage indices, in situ measurements, sampling, laboratory analysis, stone properties, weathering simulation.

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1. ANAMNESIS, DIAGNOSIS AND THERAPEUTICAL STEPS

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 (Figure 1).

Figure 1. Weathering damage. Palace Tomb, Petra / Jordan. Monument carved from sedimentary bedrocks.

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

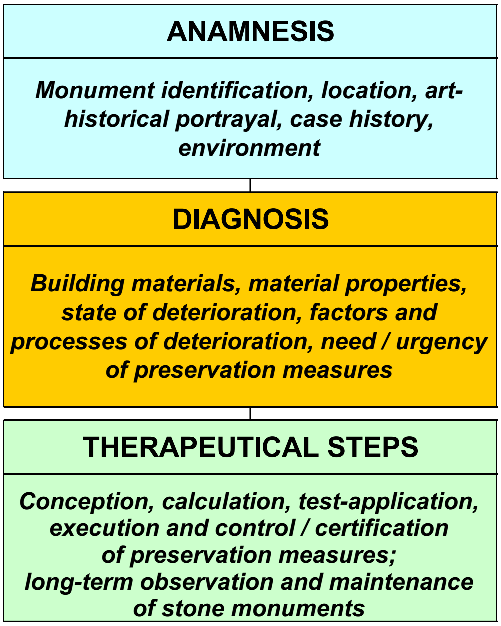


Figure 2. Anamnesis, diagnosis and therapeutical steps.

measures. The well-accepted systematic approach to sustainable monument preservation can be subdivided into the three important interdependent parts of anamnesis, diagnosis and therapeutical steps (Figure 2).

The anamnesis is to acquisite, compile and evaluate all available information, data and documents concerning the monument and its history. A comprehensive anamnesis has to consider all important aspects like monument identification, location, art-historical portrayal, case history and environment (Figure 3). The information provided by the anamnesis represents a first important contribution to the understanding of the monument situation and the state of damage.

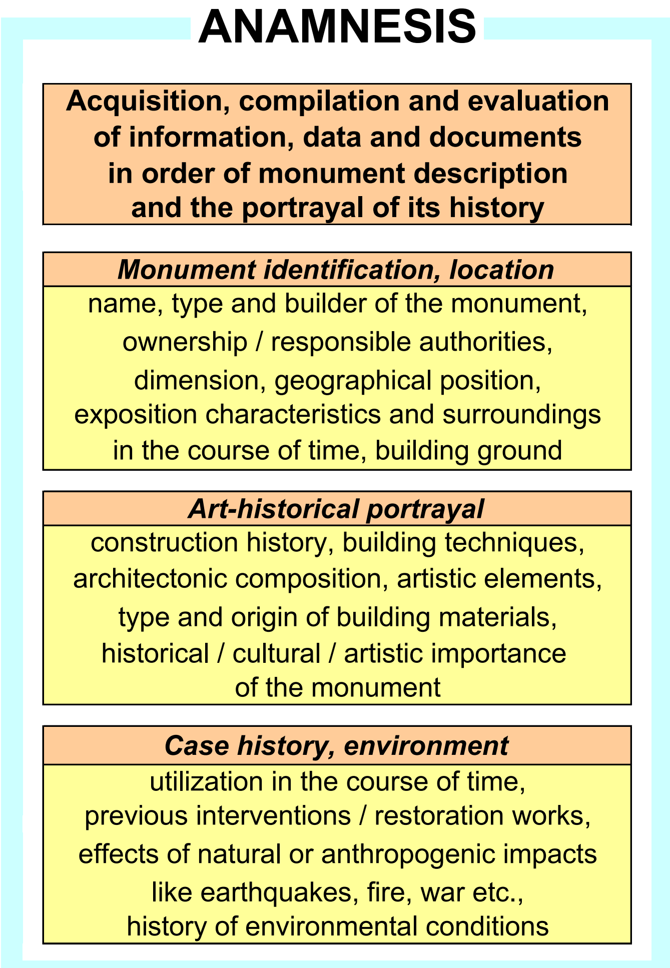


Figure 3. Monument anamnesis.

The anamnesis is consequently followed by the diagnosis. Here, the interdisciplinary research of geologists, chemists, architects and engineers etc. is required. 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. At the same time, optimization of diagnostical procedures is an important 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 alterations,
- characterization and quantification of weathering characteristics – weathering forms,
- weathering profiles, weathering products,
- early 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 damages,
- 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, repeated diagnostical activities facilitate control /certification of the preservation measures and, furthermore, prevention of new damages, long-term monitoring and maintenance of monuments.
The experienced diagnosis methodology applied by the Working group "Natural stones and weathering" / Geological Institute, Aachen University of Technology - combines the three important diagnostical activities of in-situ investigation, laboratory analysis and weathering simulation (Figure 4). The consequent application of these three complementary diagnostical steps and the joint evaluation of results contribute essentially to comprehensive and reliable damage diagnosis for stone monuments.

This systematic approach has been applied very successfully on historical stone monuments in France, Spain, Italy, Malta, Turkey, Greece, Egypt (Cairo), Jordan, Brazil, Chile etc. In situ investigation, laboratory analysis and weathering simulation are described more detailed in the *chapters 2 - 5*.

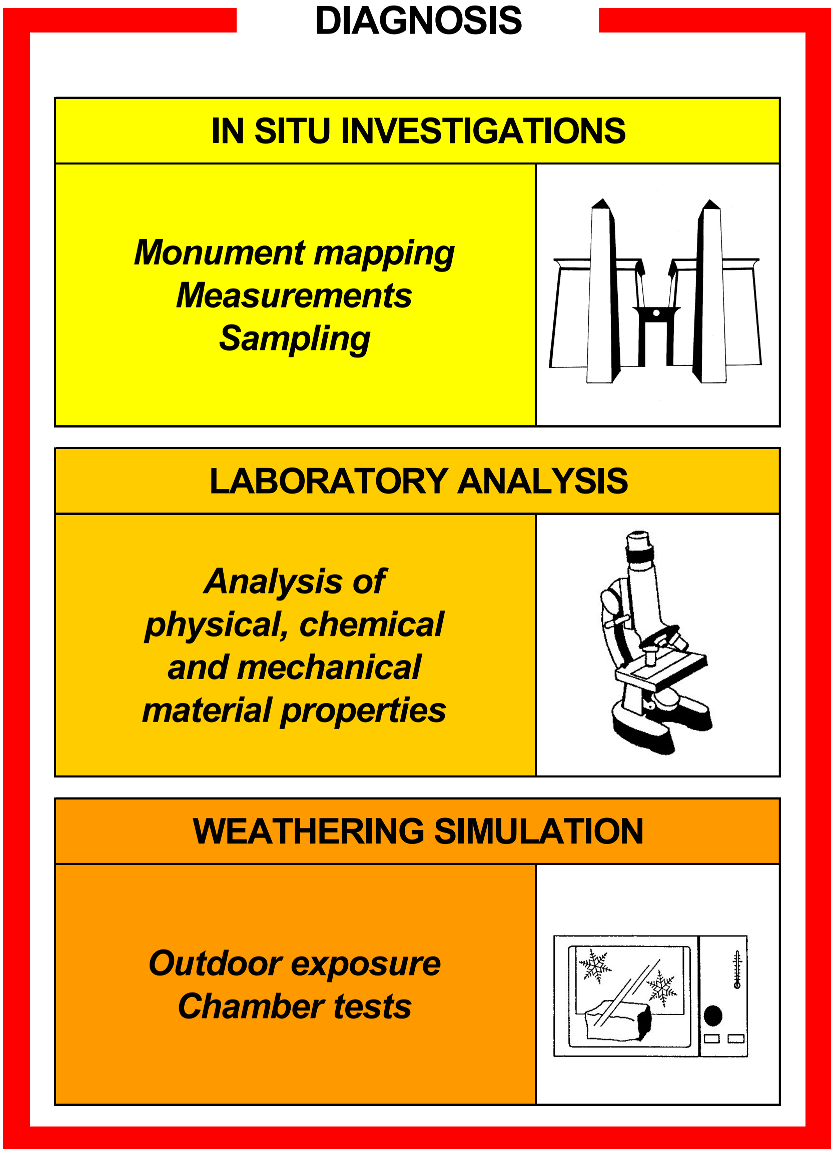


Figure 4. Diagnosis.

Based on anamnesis and diagnosis, effective and economic therapeutical steps can be proposed and calculated. Careful test-application should however precede 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 Figure 5. The effectiveness of preservation measures should be monitored in the frame of regular monument observation.

THERAPEUTICAL STEPS

Conception, calculation, test-application and execution of preservation measures
IMMEDIATE SAFEGUARDING MEASURES *Refixing of loose stone fragments, preconsolidation*
CLEANING *Washing, mechanical cleaning, chemical cleaning, biological cleaning, laser cleaning*
DESALINATION
STONE REPAIR *Piecing-in of stone, repair with mortar, crack-filling*
STONE REPLACEMENT
SURFACE PROTECTION CONSOLIDATION *Limewater technique, organic polymers, alkoxysilanes, epoxy resins, acrylics, acrylic total penetration* SURFACE COATINGS *Rendering, surface-grouting, paint* HYDROPHOBATION *Silanes, siloxanes, silicon* TREATMENT WITH REACTION INHIBITORS *Reaction inhibitors, crystal growth inhibitors* CONTROL OF BIOLOGICAL COLONIZATION *Biocides*
STRUCTURAL REINFORCEMENT *Grout injections, glues, dowels, repointings*
SHELTERING
RELOCATION OF STONE ELEMENTS TO INDOOR AREA
Control/certification, long-term observation maintenance of stone monuments

Figure 5. Therapeutical steps (e.g. ASHURST & ASHURST 1988, CROCI 1998 PRICE 1996, PETZET 1999).

2. DIAGNOSIS

The systematic investigation of stone deterioration at monuments must consider different scales of stone deterioration. On principle, visible and non-visible stone deterioration can be distinguished. According to VILES et al. (1997), a subdivision into *nanoscale (< mm)*, *microscale (mm to cm)*, *mesoscale (cm to m)* and *macroscale (whole facades or buildings)* of stone deterioration can be made (Figure 6). Nanoscale corresponds to non-visible stone deterioration, whereas microscale, mesoscale and macroscale refer to visible stone deterioration.

DIAGNOSIS

SCALES OF STONE DETERIORATION

SCALES		PARAMETERS	INVOLVED SCIENCES
Non-visible deterioration	Nanoscale < mm	*Changes of stone properties, composition, texture, porosity, strength*	*Geosciences, material sciences, chemistry, physics, microbiology*
Visible deterioration	Microscale mm to cm	*Discoloration, mass loss, micro-morphology*	
	Mesoscale cm to m	*Deterioration phenomena, weathering forms*	
	Macroscale whole facades or monuments	*Structural stability, aesthetic appearance*	*structural engineering, architecture*

Figure 6. Scales of stone deterioration (modified from VILES et al. 1997).

For each scale there is a series of appropriate parameters and investigation methods for evaluation of stone deterioration. For the comprehensive evaluation of stone deterioration – jointly considering nano-, micro-, meso- and macroscale – interdisciplinary cooperation of scientists (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 (Figure 7). The in situ investigations are applied in order to obtain information on stone deterioration in the range of mesoscale to microscale. Laboratory analyses provide information on stone deterioration at microscale and nanoscale. Weathering simulation 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.

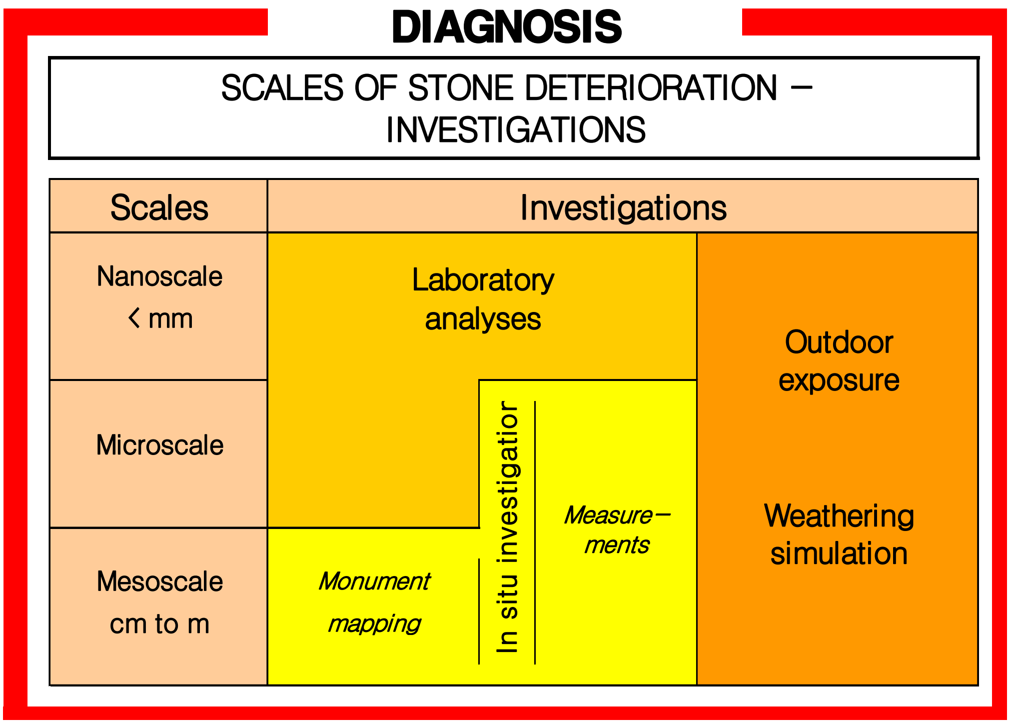


Figure 7. Scales of stone deterioration – investigations.

3. IN SITU INVESTIGATIONS

The in situ investigations comprise the particular activities of monument mapping (chapter 3.1), in situ measurements (chapter 3.2) and sampling (chapter 3.3). 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 consequent laboratory analysis.

3.1. MONUMENT MAPPING

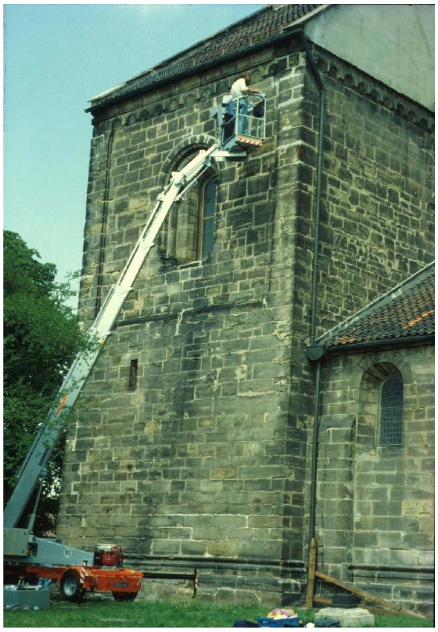
Many historical stone monuments have suffered serious damages as a consequence of natural weathering processes, influences of pollution, insufficient maintenance, utilisation, use of sensitive materials or inappropriate conservation. Profound diagnosis is required for characterization, interpretation and rating of stone deterioration and for planning and execution of effective and economic 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 direct investigation on factors and processes of stone deterioration is quite difficult and very 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. Precise knowledge of the deterioration characteristics allows to deduce information on factors and processes of stone deterioration (e.g. FITZNER, HEINRICHS & VOLKER 1997a; HEINRICHS & FITZNER 2000) and to recommend and select suitable complementary studies.

The monument mapping method has been developed by the German project partner as a non-destructive procedure for precise registration, documentation and evaluation of lithotypes and deterioration phenomena (e.g. FITZNER & HEINRICHS 1998a and 1998b; FITZNER, HEINRICHS & KOWNATZKI 1995; FITZNER, HEINRICHS & KOWNATZKI 1997; FITZNER, HEINRICHS & VOLKER 1997b; FITZNER & KOWNATZKI 1997, HEINRICHS & FITZNER 1999, KOWNATZKI 1997; FITZNER & HEINRICHS 2002).

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.

Today, monument mapping still represents the only method, which allows to describe and evaluate complete stone surfaces precisely and reproducibly according to type and distribution of lithotypes and deterioration phenomena. For detailed monument mapping accessibility of the investigation areas is necessary (Figure 8).



Mapping by using a lifting ramp

Mapping by using a scaffolding

Mapping at Karnak Temple, Luxor/Egypt

Figure 8. Monument mapping.

Two modes of monument mapping can be distinguished: lithological mapping and mapping of weathering forms. The term "weathering forms" is synonymous with "deterioration phenomena" and corresponds to visible stone deterioration at mesoscale (cm to m).

In the following, mapping procedures and steps of computer-enhanced data processing and evaluation are explained according to the scheme presented in Figure 9.

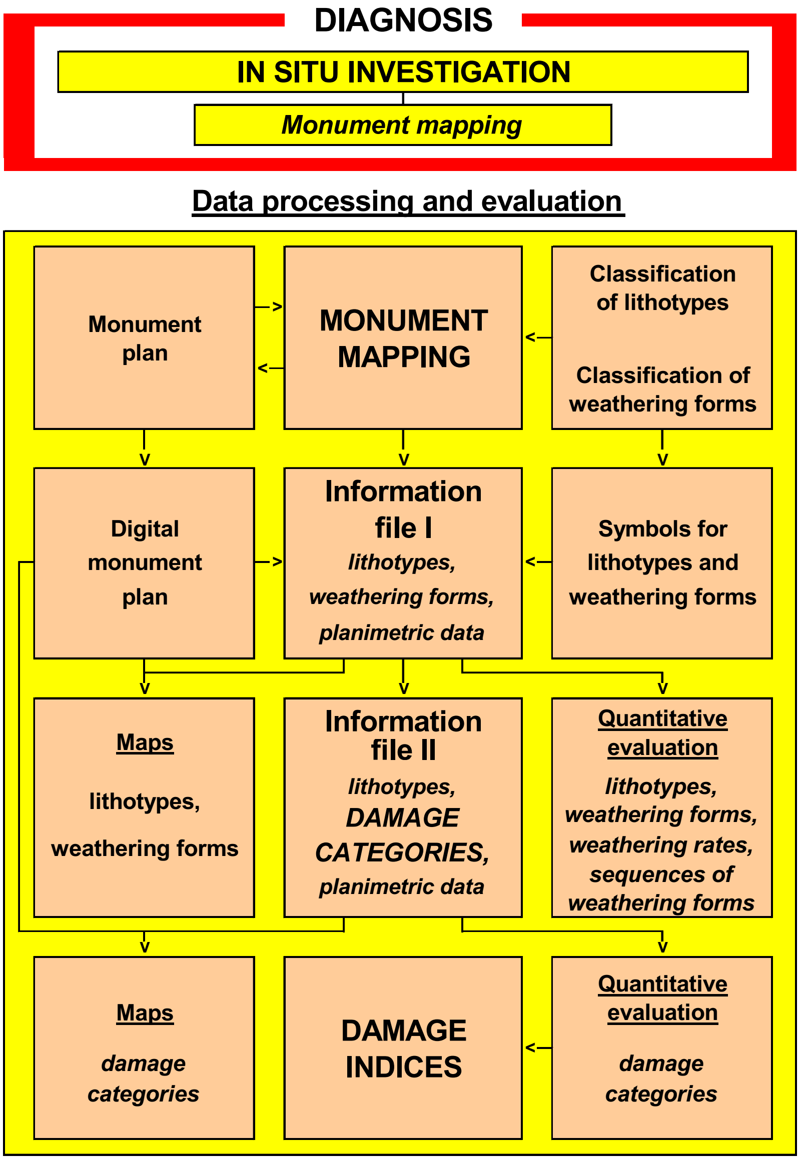


Figure 9. Monument mapping, data processing and evaluation (FITZNER, HEINRICHS & LA BOUCHARDIERE 2002).

MAPPING PROCEDURE AND DATA PROCESSING

Plans of the investigation areas and classification schemes of lithotypes and weathering forms are necessary for monument mapping. Based on these classification schemes, in the course of monument mapping all lithotypes and weathering forms at the investigation area are registered in detail and are recorded in plans by means of defined symbols. Areas of different weathering forms or different intensities of a certain weathering form are precisely delimited. The computer-programme *VIA* (*Virtual **I**mage **A**nalyser*) has been developed by the Working group "Natural stones and weathering" for optimal processing, illustration and evaluation of mapping information.

Basic steps of data processing are:
- digitalisation of monument plans with delimitations of all distinct areas,
- numbering and planimetric evaluation of all areas,
- integration of mapping information by means of defined symbols (information file I).

The digital plan and information file I represent the basis for all following illustrations and quantitative evaluations. The computer-supported processing of mapping information facilitates manifold possibilities of illustration and reliable quantitative evaluations.
While *weathering forms* are used for detailed description of individual deterioration phenomena according to type and intensity, *damage categories* and *damage indices* have been established as practical tools for consequent rating of damages and as important contribution to risk prognosis and risk management (Figure 10). On the basis of defined schemes, all weathering forms – taking into consideration their range of intensity – get related to damage categories (*information file II*). Six damage categories have been defined: 0 – no visible damages, 1 – very slight damages, 2 – slight damages, 3 – moderate damages, 4 – severe damages, 5 – very severe damages. 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 damages. In this way, damage indices complete a consistent and convincing approach to characterization, evaluation, quantification and rating of visible stone damages.

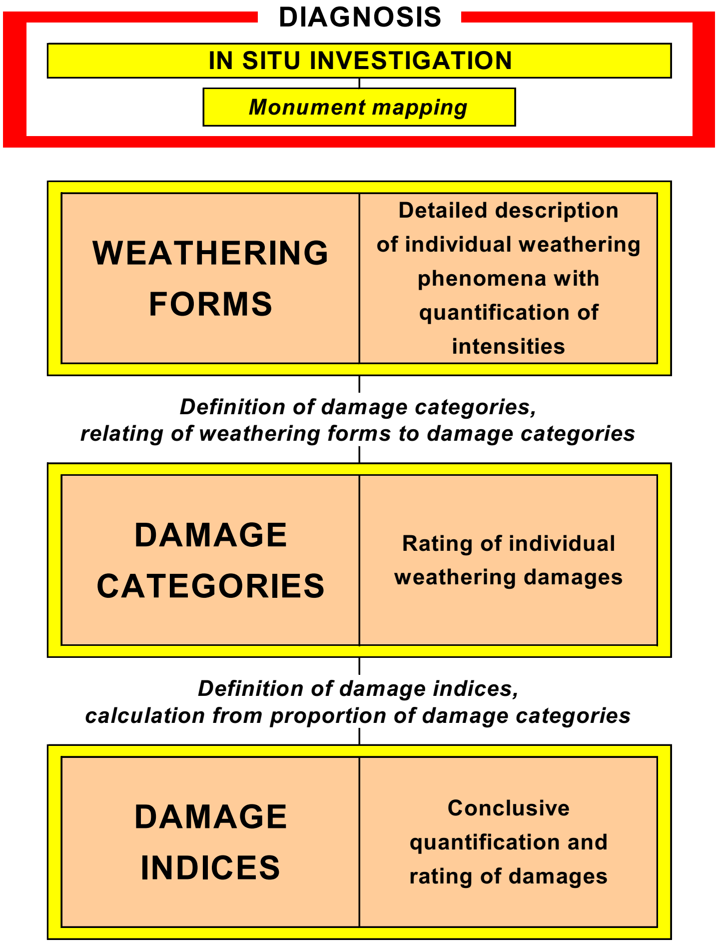


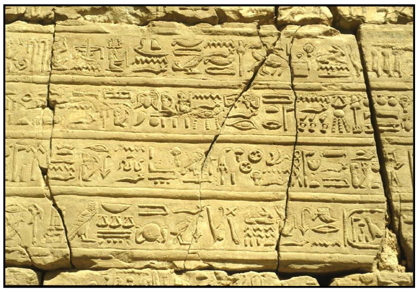
Figure 10. Weathering forms – damage categories – damage indices (FITZNER, HEINRICHS & LA BOUCHARDIERE 2002).

LITHOLOGICAL MAPPING

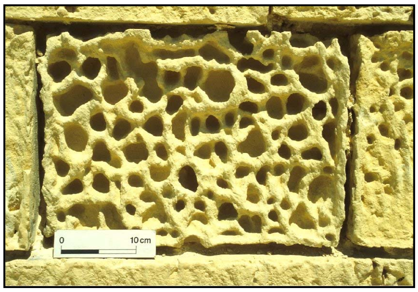
The mode of lithological mapping comprises survey, identification, petrographical characterization and registration of all occurring lithotypes. Well-established petrographical classification schemes are used for the description of the lithotypes. Original stone material and stone material of former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

CLASSIFICATION AND MAPPING OF WEATHERING FORMS

Weathering forms at stone monuments represent 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).*Some examples of weathering forms are shown in Figure 11.



Fissures



Alveolar weathering

Scratching lanes, anthropogenic

Break out, crumbling

Back weathering due to loss of scales, granular disintegration into grus.

Weathering out dependent on Stone structure (bedding)

Figure 11. Weathering forms (examples).

Objective and reproducible description, registration and documentation of weathering forms require a precise classification scheme of weathering forms. Such a classification scheme has been developed, based on investigations at numerous monuments world-wide considering different stone types and environments.

The complete classification scheme of weathering forms with definitions, suitable parameters for intensity classification and photo-atlas has been presented in FITZNER, HEINRICHS & KOWNATZKI (1995). The updated version of the classification scheme is presented in FITZNER & HEINRICHS (2002). The classification scheme has met great international acceptance. The hierarchic structure of the classification scheme shown in Figure 12. The uppermost level (I) comprises 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 of the classification scheme, the individual weathering forms are further differentiated according to intensities. Symbols have been proposed for recording of weathering forms and for computer-supported processing of mapping information. Symbols in level IV of the classification scheme are composed of letters for weathering forms and numbers for intensities of the weathering forms.

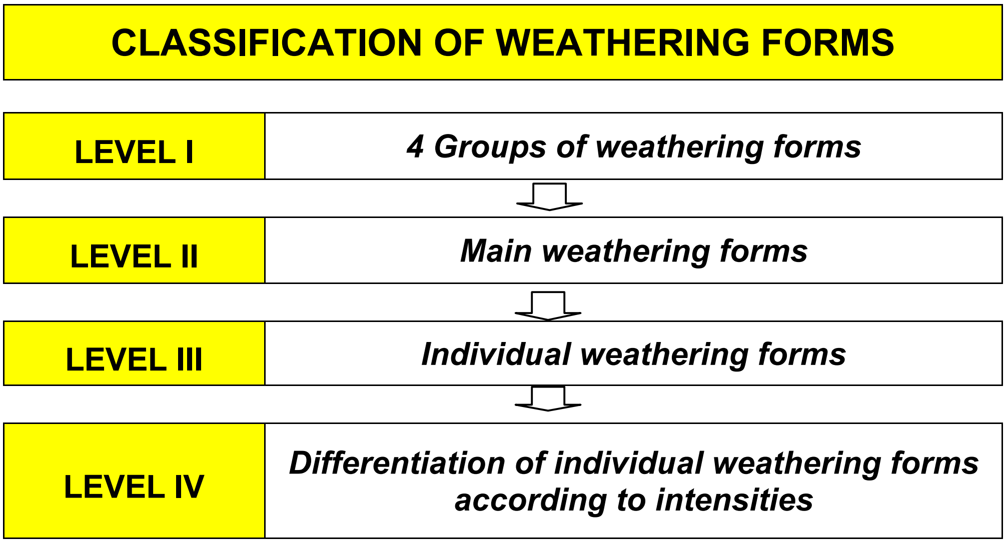


Figure 12. Classification scheme of weathering forms – structure.

This basic classification scheme of weathering forms can still be specified considering particular stone types or monument assemblies. Specification concerns definition of individual weathering forms and especially suitable intensity classification of the weathering forms. The intensity classification should be adjusted to the range of intensities surveyed at the monuments under investigation.
A section of the classification scheme is presented in Figure 13.

<table>
<tr><th colspan="6">LEVEL I – GROUPS OF WEATHERING FORMS</th></tr>
<tr><th colspan="6">GROUP I: “LOSS OF STONE MATERIAL”</th></tr>
<tr><th colspan="2">LEVEL II
MAIN WEATHERING FORMS</th><th colspan="2">LEVEL III
INDIVIDUAL WEATHERING FORMS</th><th colspan="2">LEVEL IV
INDIVIDUAL WEATHERING FORMS WITH DIFFERENTIATION ACCORDING TO INTENSITY</th></tr>
<tr><td rowspan="6">Relief

Morphological change of the stone surface due to partial or selective weathering.</td><td rowspan="6">R</td><td>Rounding /notching
Relief by rounding of edges or notching / hollowing out. Concave or convex forms.</td><td>Ro</td><td rowspan="6">Intensity classification according to depth of relief (cm)

Intensity 1: <0.5
Intensity 2: 0.5 – 1
Intensity 3: 1 – 3
Intensity 4: 3 – 5
Intensity 5: 5 – 10
Intensity 6: 10 – 25
Intensity 7: >25</td><td>Ro1, Ro2, etc.</td></tr>
<tr><td>Alveolar weathering
Relief in the form of alveolae. Form comparable to honeycombs.</td><td>Ra</td><td>Ra1, Ra2, etc.</td></tr>
<tr><td>Relief dependent on stone structure
Relief dependent on structural features (bedding, banding etc.) Frequently striped patterns.</td><td>tR</td><td>tR1, tR2, etc.</td></tr>
<tr><td>Weathering out of stone components
Relief due to selective weathering out of stone components being sensitive to weathering (clay lenticles etc.) Hole shaped forms.</td><td>Rk</td><td>Rk1, Rk2, etc.</td></tr>
<tr><td>Clearing out of stone components
Relief in form of protruding compact stone components (pebbles, concretions) due to selective weathering.</td><td>Rh</td><td>Rh1, Rh2, etc.</td></tr>
<tr><td>Relief due to anthropogenic influence
Relief in the form of scratching marks etc.</td><td>aR</td><td>aR1, aR2, etc.</td></tr>
</table>

Figure 13. Classification scheme of weathering forms – section.

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”, “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:
- characteristical weathering forms,
- interrelations between weathering forms, especially as concerns loss of stone,
- material, present detachment of stone material and deposits,
- distribution / zonation of weathering forms,
- chronological sequences of weathering forms,
- weathering progression, weathering rates,
- stone quality, susceptibility to weathering,
- causes and processes of stone deterioration.

This information can be further specified considering particular 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 contributes to the development of weathering models, which has become an important objective of modern research in this field.

Beyond this, evaluation of weathering forms guarantees first information on suitability of interventions in order of monument preservation. For example, information on all weathering forms characterising loss of stone material allows a first evaluation concerning suitability of interventions like stone repair, stone replacement or structural reinforcement. Information on all weathering forms characterising deposits contributes to evaluate suitability of interventions like cleaning or desalination. Information on all weathering forms describing present detachment of stone material is relevant to suitability of interventions like fixation of detaching stone elements, stone treatment or surface coating.
Based on the mapping results, complementary in situ measurements and sampling for the characterization and quantification of stone deterioration, weathering profiles and weathering products can be well-directed.

DAMAGE CATEGORIES

Weathering forms are used for precise description of stone deterioration phenomena according to type and intensity. Damage categories have been established for the comparative rating of individual damages (FITZNER & HEINRICHS 2002, FITZNER, HEINRICHS & LA BOUCHARDIERE 2002). Six damage categories have been defined (Figure 14).

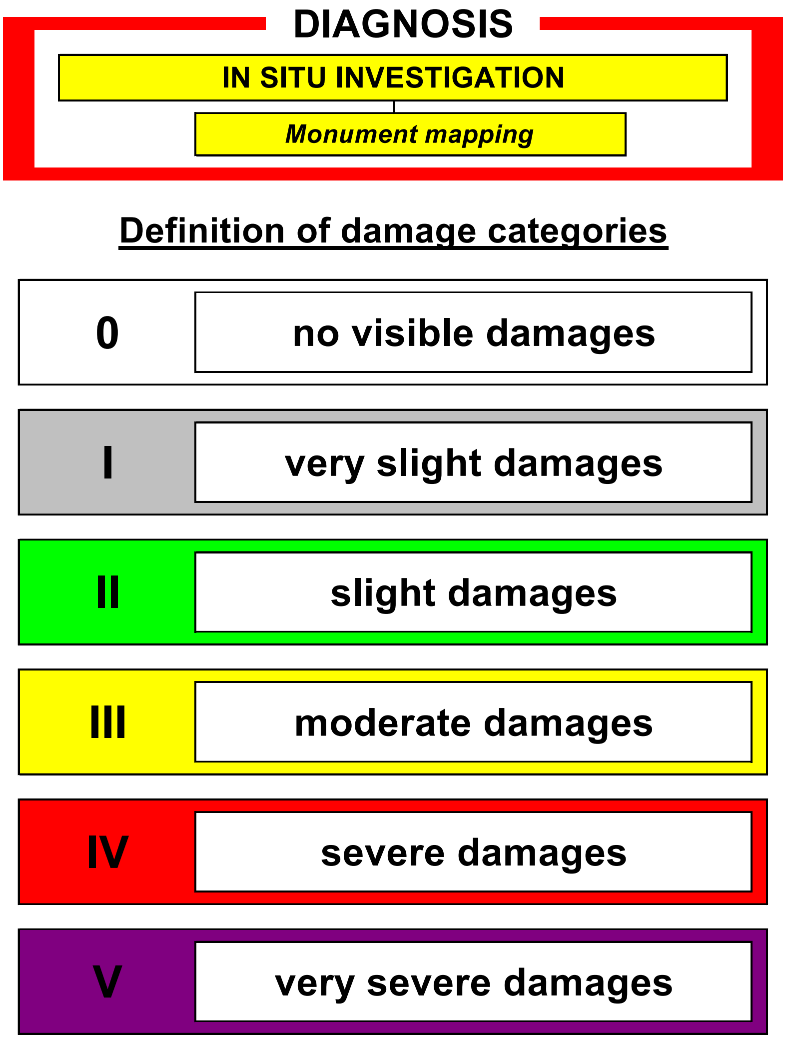


Figure 14. Definition of damage categories.

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 (Figure 15). The development of an appropriate correlation scheme “weathering forms – damage categories” requires cooperation of all experts involved in monument diagnosis and monument preservation.

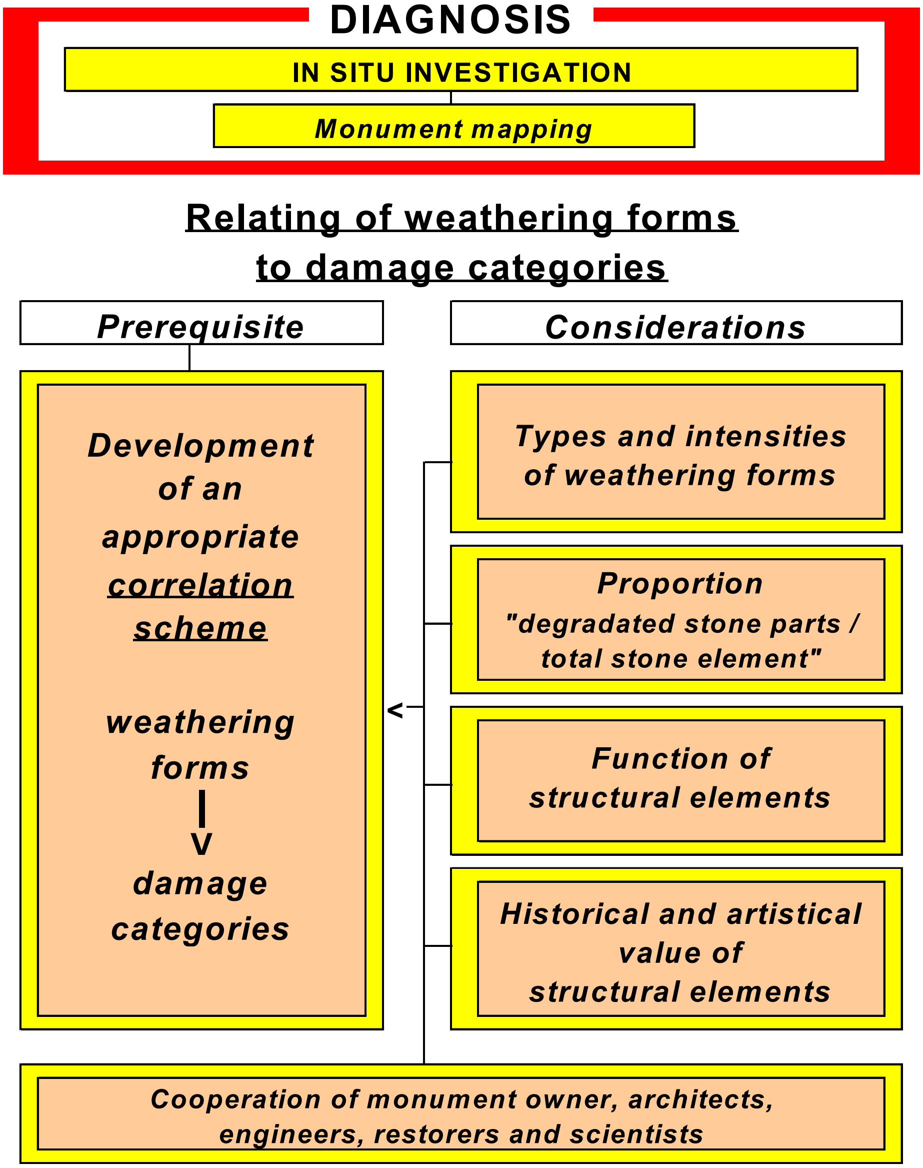


Figure 15. Relating of weathering forms to damage categories - considerations.

DAMAGE INDICES

Damage indices are calculated from proportion of damage categories (FITZNER, HEINRICHS & LA BOUCHARDIERE 2002; FITZNER & HEINRICHS 2002). A linear and a progressive damage index has been defined (Figure 16). 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. Differences between linear and progressive damage index increases as proportion of higher damage categories increases. Following relation arises: progressive damage index ≥ linear damage index.

DIAGNOSIS

IN SITU INVESTIGATION

Monument mapping

Calculation of damage indices

LINEAR DAMAGE INDEX

$$DI_{lin} = \frac{(A\cdot 0)+(B\cdot 1)+(C\cdot 2)+(D\cdot 3)+(E\cdot 4)+(F\cdot 5)}{100}$$

$$\downarrow$$

$$\frac{B+(C\cdot 2)+(D\cdot 3)+(E\cdot 4)+(F\cdot 5)}{100}$$

PROGRESSIVE DAMAGE INDEX

$$DI_{prog} = \sqrt{\frac{(A\cdot 0^2)+(B\cdot 1^2)+(C\cdot 2^2)+(D\cdot 3^2)+(E\cdot 4^2)+(F\cdot 5^2}{100}}$$

$$\downarrow$$

$$\sqrt{\frac{B+(C\cdot 4)+(D\cdot 9)+(E\cdot 16)+(F\cdot 25)}{100}}$$

A = Area (%) – damage category 0
B = Area (%) – damage category 1
C = Area (%) – damage category 2
D = Area (%) – damage category 3
E = Area (%) – damage category 4
F = Area (%) – damage category 5

$$\sum_{A}^{F} = 100$$

Figure 16. Calculation of damage indices according to FITZNER, B., HEINRICHS, K. & LA BOUCHARDIERE, D. (2002).

In Figure 17 objectives of damage indices are presented. Use of damage indices ensures scientific quantification and rating of stone damages for entire monuments or single structures. Damage indices allow comparison and ranking of different monuments or parts of monuments.

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.

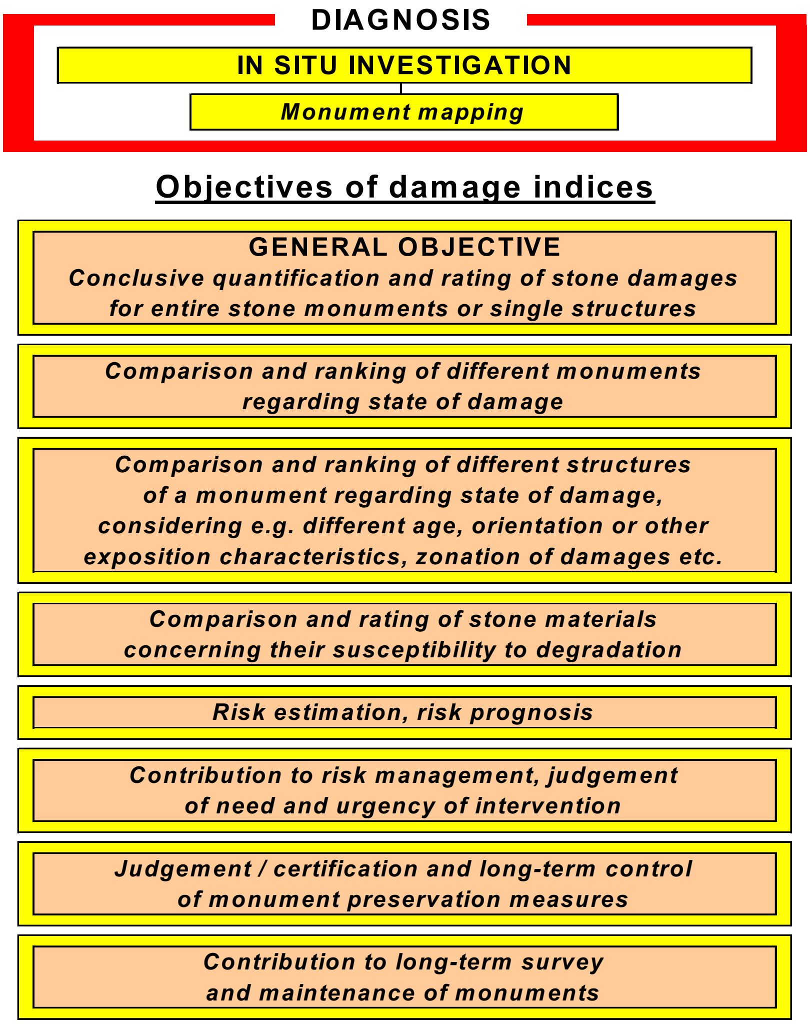


Figure 17. Objectives of damage indices.

The consequent 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, construction companies etc.

3.2. IN SITU MEASUREMENTS

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

In Figure 18 frequently applied methods are listed. 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. 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 characteristical areas at the monument and sufficient number of measurements are required in order of reliable and representative results. In the following some very suitable in situ measuring methods are briefly described.

DIAGNOSIS

IN SITU INVESTIGATION

Measurements

GROUP OF METHODS	*METHOD*	*PARAMETER*	*OPERATION*	*EXPENDITURE*
Surface measuring	Profile measurement Roughness measurement	Relief	non-destructive	low to moderate
	Photogrammetry	Relief, morphology, deformation		high
	Laser-optical measuring			high
	Fissure measuring	Fissure characteristics		low
Acoustic methods	Ultrasonic measurement	Interfaces	non-destructive	moderate
Electromagnetic methods	Radiography	Moisture content, voids, inclusions	non-destructive	extreme
	Multispectral photography	Spectral behaviour		moderate
	IR-Thermography	Surface temperature		moderate
	Radar	Interfaces		moderate
Geoelectric methods	Resistivity measurement	Moisture content, salt content	non-destructive / slightly destr.	moderate
Water uptake methods	Water uptake measurement	Adsorption capacity	non-destructive	low
Strength testing methods	Pull-out test	Adhesive tensile strength	destructive	moderate
	Drilling resistance measurement	Strength	slightly destructive	moderate
	Rebound hardness measurement		non-destructive	low
	Penetration hardness measurement		non-destructive	low
Bore-hole investigation	Endoscopy	Structure, texture	slightly destructive	high
	Radiography	Moisture content		
Chemical methods	Colouring test Respiration test	Microbiological activity	non-destructive	low

Figure 18. In situ measurements (e.g. NAPPI & CÔTE 1997, KOWNATZKI 1997).

Ultrasonic measurements represent an appropriate non-destructive acoustic method for characterization of stone types and weathering states (Figure 19). Especially ultrasonic measurements according to the transmission mode can be applied successfully at natural stone monuments, e.g. at columns, pillars, pilasters, slabs, sculptural decoration etc. Ultrasonic velocities are calculated from transit time and measuring distance. Results of ultrasonic measurements can be important for supplementation, verification and quantification of results obtained from phenomenological studies (differentiation of stone types, anisotropies of stone material, weathering state etc.).

Ultrasonic measurements can also be used for information on geometry of fissures. Furthermore, already pre-macroscopic stone degradation can be detected (e.g. granular disintegration, microcracks etc.). Classification schemes of ultrasonic velocities can be developed for individual stone types in order to rate degree of damage. Ultrasonic measurements are very suitable for long-term monitoring of stone structures and they can also be applied successfully for information on effectiveness of preservation measures, especially stone treatment. Ultrasonic tomography for stone structures is a modern scientific concern.

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 even for larger monument structures are possible. The results on the temperature behaviour of the stone materials contributes to information on stone types, weathering state and exposition characteristics. Weathering damages can be detected by means of temperature anomalies. The results obtained from IR-thermography can also indicate surface areas which are affected by high humidity load.

Water uptake measurements are carried out for quantification of capillary water uptake and water penetration depth in dependence on time and for the characterization of water migration (Figure 20). Additionally, the results provide information

Figure 19. Ultrasonic measurements.

Figure 20. Water uptake measurements with Karsten tubes.

on porosity properties and surface condition of the stone materials. Stone materials 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. Water uptake measurements are also very suitable for studies on effectiveness of stone treatment, especially treatment with water repellents.

Drilling resistance measurements and rebound hardness measurements are very often applied in situ for information on mechanical stone properties. Drilling resistance measurements represent a modern only slightly destructive method which registers drilling depth versus drilling time (Figure 21). The drilling with portable drilling equipment is performed with constant pressure, energy supply and rotation speed. Drilling resistance resp. 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. Additionally, drilling powder can be collected for laboratory analyses.

Rebound hardness measurements with the SCHMIDT Test Hammer represent a quite popular in situ method for information on mechanical stone properties (Figure 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.

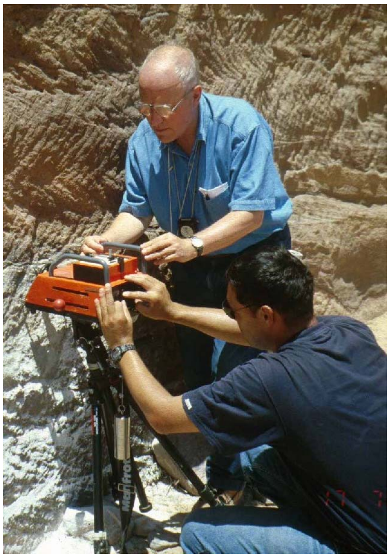


Figure 21. Drilling resistance measurements.

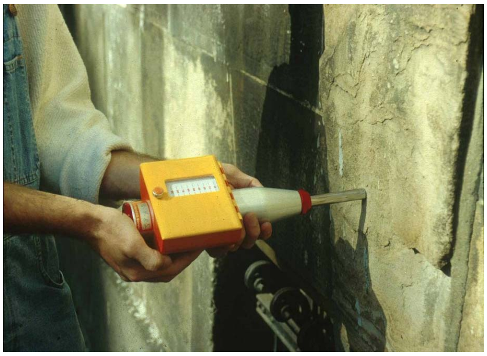


Figure 22. Rebound hardness measurements with the Schmidt hammer.

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

3.3. 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 due to weathering,
- 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 (Figure 23). Sampling of weathered or treated stone material at monuments, especially at historical monuments, must be performed most carefully so that any additional damage is minimized. Number and quantity of samples have to ensure that the defined 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.

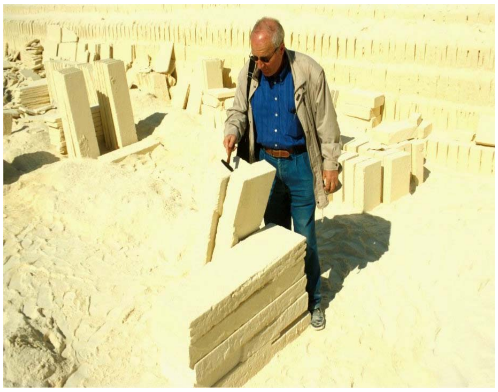
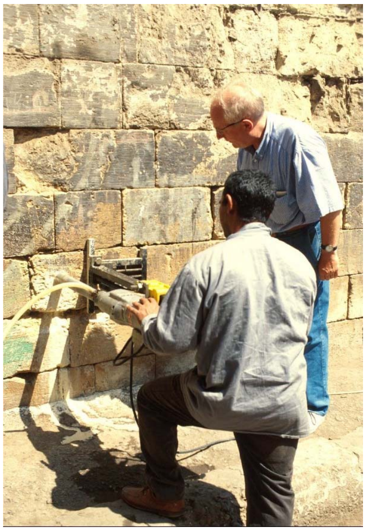


Figure 23. Sampling at the monument and in the quarry.



4. LABORATORY ANALYSIS

The long and complex geological history has resulted in a great variety of stone types and a remarkable variation of stone properties (Figure 24). All natural stones used as construction material are affected by natural or anthropogenically induced weathering processes. The weathering processes evoke again changes of the stone properties. Precise results on stone properties and their modifications due to weathering represent a very important part of comprehensive diagnosis and they are essential for effective monument preservation measures.

Sandstone *Granite* *Limestone*

Figure 24. Typical stone types at historical monuments in Upper Egypt.

The characteristical stone properties such as visual characteristics, mineral composition, geochemical composition, microtexture, porosity properties, hygric properties, mechanical properties and thermal properties are studied by means of modern analytical procedures (Figure 25). Composition and spatial-geometrical configuration of the components represent the basic stone characteristics, which condition further properties like hygric, mechanical or thermal properties. Many different methods have been developed for stone analysis. Therefore, it is very important, to select first the appropriate methods resp. suitable combinations of methods, which ensure the most efficient approach to solve the defined scientific and practical problems.

DIAGNOSIS

LABORATORY ANALYSES

PARAMETERS	ANALYTICAL PROCEDURES
VISUAL CHARACTERISTICS ***Colour, gloss, macrotexture/-structure***	**Hand lens, binocular microscope, colour charts, colour measuring devices, reflectometer**
MINERAL COMPOSITION	**Optical microscopy, X-ray diffraction analysis (XDA)**
GEOCHEMICAL COMPOSITION ***Chemical compounds, elemental composition, trace elements, soluble salts, anions / cations, pH-value, organic compounds***	**Wet chemical analysis, scanning electron microscopy with energy dispersive X-ray analysis (SEM / EDX), X-ray fluorescence spectroscopy (XRF), microprobe, atomic absorption spectroscopy (AAS), atomic emission spectroscopy (AES), ion chromatography (IC), mass spectroscopy (MS), thermoanalytical procedures**
MICROTEXTURE ***Grain shape, grain size, grain size distribution, grain contacts, matrix / ground mass / cements recrystallization, intergrowth / overgrowth, arrangement / orientation of components, inhomogeneities, anisotropies, interfaces, microcracks, micromorphology, roughness***	**Optical microscopy with image analysis, scanning electron microscopy (SEM), microtomography, ultrasonic measurements, roughness measuring devices, perthometer, laser-optical measurements**
POROSITY PROPERTIES ***Densities, porosity, pore size, pore size distribution, pore surface***	**Pycnometer, optical microscopy with image analysis, scanning electron microscopy (SEM), mercury porosimetry, gas adsorption procedures, BET-method, X-ray microtomography**
HYGRIC PROPERTIES ***Water absorption / desorption, saturation coefficient, water permeability, hygroscopic capacity, isothermal water vapour absorption, water vapour permeability, hygric dilatation - shrinking / swelling***	**Weighing - mass change (immersion, capillary soaking, sorption / desorption, evaporation), dry cup / wet cup procedure, length variation measurements / dilatometer / extension gauge**
MECHANICAL PROPERTIES ***Compressive strength, tensile strength, flexural strength, shear strength, elastic modulus, stress-strain-relation, dry-to-wet strength ratio, static / dynamic hardness, abrasion / wear resistance***	**Various standardized strength testing procedures, pull-out test, ultrasonic measurements, scratch / indentation / rebound / impact hardness tests, (Schmidt Hammer, sclerometer), drilling resistance measurements, grinding wheel method**
THERMAL PROPERTIES ***Thermal conductivity, heat capacity, thermal resistance, thermal dilatation - shrinking / swelling***	**Hot plate procedure, hot box procedure, length variation measurements / dilatometer / extension gauge**

Figure 25. Laboratory analyses.

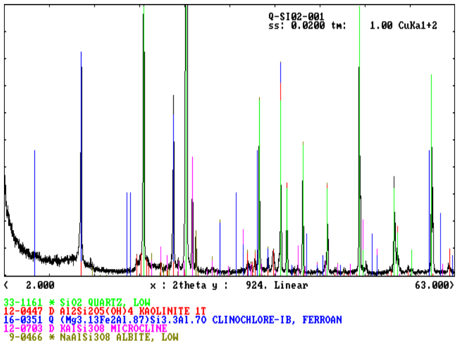
Visual characteristics

This first step of analysis comprises documentation and precise description of the stone material according to macroscopic criteria such as colour, gloss, discernible mineral components and macrotextural/-structural features. Colour charts (e.g. MUNSELL colour chart) are used very frequently for objective definition of stone colour. Detailed information on specification and measurement of colour is presented in URLAND (1999). Standard tools like hand lens or binocular microscope are used in order to describe macrotextural/-structural features. Based on their macroscopical characteristics, the stone materials can be assigned to superordinated stone groups.

Mineral composition

The X-ray diffraction analysis (XDA) represents the classical procedure for detection of mineral components and still is the most efficient method for identification of clay minerals and neogenic minerals due to weathering, especially salts (Figure 26). Low quantity of stone material needed for the analysis means another considerable advantage of this method.

X-ray diffractometer.



Diffractogramm, sandstone.

Figure 26. X-ray diffraction analysis (XDA).

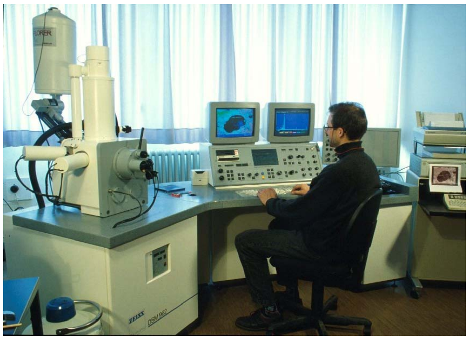
Analysis by means of thin section microscopy contributes additionally to identification of mineral components and especially is applied as standard method for quantification of mineral composition. By means of their modal composition the stone materials are petrographically classified according to well-established standard petrographical classification schemes. Furthermore, mineral alteration, dissolution or decomposition and neogenic mineral formation due to weathering are described.

Geochemical composition

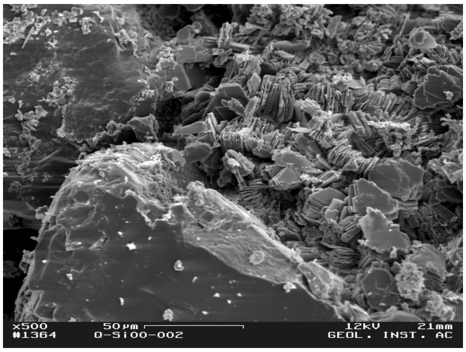
Information on geochemical composition contributes to characterization and classification of stone materials and to description and quantification of stone alteration. Geochemical data are very important for the elucidation of lithogenesis. Attempts have been made to use geochemical data as “fingerprints” for identification or verification of the provenance of natural stones. Furthermore, geochemical analysis is important for information on environmental influences on the stone material (pollutants, neogenic minerals / salt formation, organic components etc.). X-ray fluorescence spectroscopy (XRF), microprobe, atomic absorption spectroscopy (AAS) and atomic emission spectroscopy (AES) are important methods for exact determination of geochemical composition. Salts are analysed mainly by means of wet chemical analysis, ion chromatography (IC) and photometric methods.

Microtextural properties

Microtextural properties are very important in determining the weathering behaviour and durability of natural stones. Shape, sizes, contacts, arrangement / orientation and recrystallization, intergrowth / overgrowth of components as well as heterogeneities, anisotropies, interfaces or micromorphology are parameters characterizing the micotexture of natural stones. Stone genesis and susceptibility of the stone material to weathering can be inferred from these characteristics. Optical microscopy in combination with image analysing systems and scanning electron microscopy (Figure 27) represent the traditional methods for microtextural studies.



Scanning electron microscope.



SEM-micrograph. Sandstone. Stacks of authigenic kaolinite between quartz grains.

Figure 27. Scanning electron microscopy (SEM).

Microtomography, ultrasonic measurements, roughness measurements or laser-optical measurements can be applied as complementary procedures for assessment of microtexture.

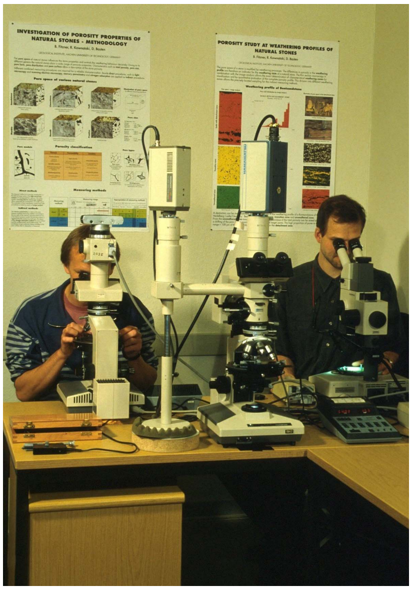
Porosity properties

Porosity properties decisively control the quality and the weathering behaviour of natural stones. Physical, chemical and biological weathering processes mainly proceed in the pore space and modify the porosity characteristics at the same time. Precise knowledge of porosity characteristics like total porosity, pore sizes, pore size distribution and pore surface is essential for:

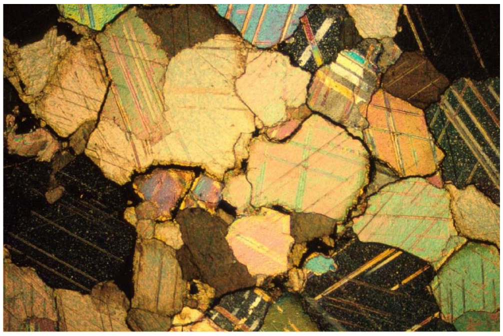
- stone characterization,
- modelling of transportation processes regarding gaseous and liquid phases,
- assessment of stone durability,
- interpretation and prediction of the weathering behaviour of natural stones,
- quantification and rating of stone deterioration,
- evaluation of effectiveness of stone treatments.

The Aachen working group “Natural stones and weathering” has long-term experience in assessment of realistic porosity characteristics, development of pore models and correlations between porosity characteristics and weathering behaviour of natural stones. Experience has shown that the very complex porosity properties cannot be determined satisfactory by one analytical procedure. Only the joint application of different optimized direct and indirect procedures can guarantee a reliable and quite realistic characterization of porosity properties (FITZNER 1994, BORELLI 1999).
Four complementary methods for joint assessment of porosity properties are briefly described in the following. Thin section microscopy and scanning electron microscopy represent methods, which allow direct documentation and measuring of pore space. Mercury porosimetry and nitrogen sorption method are indirect procedures. Most of the indirect methods measure the intrusion and extrusion behaviour of liquid phases in the pore space (e.g. mercury porosimetry) or the sorption of gases at the surface of pores (e.g. nitrogen sorption method). Porosity data then are calculated from the measuring results obtained.

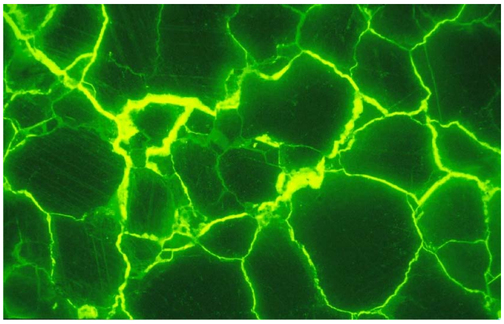
The microscopic analysis of thin sections represents the traditional direct method for porosity investigation (Figure 28). The lower measuring limit of this method depends upon the resolution limit of the microscope (commercial systems: appr. 4 µm). The additional use of image analysis has significantly improved statistical evaluation of porosity, pore sizes and pore shapes. With respect to measuring by means of image analysis, complete visibility of pore space is required. This can be achieved by impregnation of the stone material with coloured or UV-fluorescent resin.



Transmitted light microscope



Thin section Marble.



Impregnated thin section under UV-light,
pore space appears yellow.

Figure 28. Transmitted light microscopy with image analysis.

Porosity studies with a resolution limit up to 0.001 µm are possible by means of scanning electron microscopy. The geometry and spatial distribution of pores can be precisely described with this procedure, whereas statistical information on porosity is limited due to high magnification and correspondingly very small sections of the samples. A very large number of sections would have to be examined.

Mercury porosimetry represents the most frequently applied indirect measuring method for porosity studies (Figure 29). With this method - contrary to all other measuring procedures - almost the whole range of pore sizes occurring in natural stones can be studied. According to the principle of mercury intrusion in dependence upon pressure, pores with radii in the range of 0.0019 μm up to 200 μm can be measured. The smallest pore radius of 0.0019 μm corresponds to a pressure of 4000 bar, which represents the maximum pressure of commercial systems. Based on proportionality between pressure necessary for penetration and the dimension of the pores, the measuring results obtained from mercury porosimetry allow the calculation of total porosity, densities, median pore radius, pore size distribution (sizes of pore entries!) and pore surface.
Pore surface area, pore volume and pore radii distribution in the measuring range of 0.001 μm to 0.1 μm can be determined by means of the nitrogen-adsorption method (Figure 30). These porosity data are calculated from quantity of gas isothermally adsorbed by the porous material. This method has turned out to provide best results on micropores.

Figure 29. Mercury porosimeter.

Figure 30. Nitrogen adsorption analyser.

Measuring ranges of thin section microscopy / image analysis, scanning electron microscopy, mercury porosimetry and nitrogen sorption method partly overlap. This is very important for comparison and joint evaluation of results in order to derive realistic porosity data!

Hygric properties

Weathering processes are associated with water. The hygric properties of natural stones are conditioned by their porosity characteristics. Water absorption and desorption, water transport and migration and hygric dilatation of natural stones are important hygric processes. Knowledge of hygric properties is important for characterization of stone materials and their state of weathering as well as for stone treatment and the design of effective protective agents.

National and international norms are well-established for studies on hygric properties such as water absorption/desorption, saturation coefficient, water permeability, hygroscopic capacity, isothermal water vapour absorption or water vapour permeability. Hygric shrinking/swelling of natural stones is measured by means of dilatometer, extension gauge or other length variation measuring devices. High proportions of swelling clay minerals and certain salt minerals can evoke high hygric dilatation as stone deterioration mechanism.

Mechanical properties

Stone weathering is associated with decrease of strength / hardness (granular disintegration, loss of cohesion, cracks etc.). Information on strength / hardness and deformation properties additionally facilitates stone characterization and quantification of stone deterioration. The integration of results on mechanical properties enhances stone life cycle analysis and the appraisal of stone durability as well as the deduction of models regarding the weathering behaviour of natural stones.

It has to be taken into account that most of the standardized strength testing procedures are destructive. They require larger amounts of stone material and larger-sized samples. Alternatively, non-destructive or only slightly destructive procedures (ultrasonic measurements, various types of hardness measurements, drilling resistance measurements) can provide results on ultrasonic velocities or hardness as indicators of strength. These alternative procedures are suited better for investigation of historical construction materials and they allow the re-use of the stone material for further studies.

Thermal properties

The responses and proneness of the stone material to temperature variation are characterized by thermal analysis. The rating of temperature as weathering factor is important.
The hot plate and hot box procedure, dilatometer, extension gauge or other length variation measuring devices are used to determine the thermal properties such as thermal conductivity, heat capacity, thermal resistance or thermal dilatation.

5. WEATHERING SIMULATION AND OUTDOOR EXPOSURE

The priority aim of accelerated weathering simulation tests and outdoor exposure studies is the elucidation of deterioration mechanisms and processes (MIRWALD & BRÜGGERHOFF 1997). They contribute to:

- development of weathering models,
- characterization and quantification of weathering progression,
- appraisal of stone quality / durability,
- selection of appropriate natural stones for stone replacement measures,
- rating of effectiveness of stone treatment.

In Figure 31 weathering simulation and outdoor exposure procedures are listed according to type of test, test parameters and evaluation criteria. The great advantage of weathering simulation tests and outdoor exposure studies is the possibility of comparing various materials under identical conditions (e.g. FITZNER & KALDE 1991). In all types of experiments thorough characterization of initial stone properties, quantification of the external factors and monitoring of any changes of the stone material are required as basis for reliable interpretation of results.

Compared to outdoor exposure studies, weathering simulation tests in chambers have the advantage of time reduction and control of factors. Several norms for standardized simulation tests in have been elaborated by national and international institutions (RILEM, ASTM, DIN, ASTM, VDI, NORMAL etc.).

DIAGNOSIS

WEATHERING SIMULATION AND OUTDOOR EXPOSURE

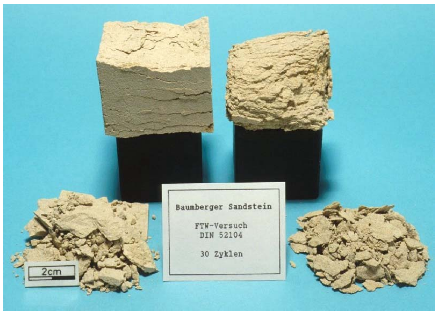
Type of simulation test	Test parameter	Evaluation criterion
Simulation of physical weathering		
Temperature variation test	Temperature gradient,number of cycles	Visual inspection,mass change,structural change
Salt crystallisation test	Salt, concentration, saturation period, number of cycles	
Freeze-thaw-cycling-test	Water saturation, freeze period, number of cycles	
Combined salt / freeze-thaw cycling-test	Salt sort, concentration, salt supply, saturation peroid, freezing peroid, number of cycles	
Simulation of chemical weathering		
Air pollutant test	Gas (SO_2, NO_x, CO_2), concentration, number of cycles	Visual inspection, mass change, alteration products
Light test	UV-wavelength, luminous intensity, number of cycles	Visual inspection, light stability
Simulation of biological weathering		
Bioreceptivity tests	Climatic conditions, association of organisms	Visual inspection, biofilm, dissolutions/neoformations
Combinations between physical, chemical and biological weathering		
Nature adapted tests		
Combined test	Salt, concentration, saturation period, temperature, gradient, rel.humidity, fog, rain, wind, irradiation, number of cycles	Visual inspection, mass change, structural change, alteration products
Outdoor exposure		
Test fields in different environment	Natural environment	Visual inspection, mass change, structural change,alteration products

Figure 31. Weathering simulation and outdoor exposure.

Although the natural complex interaction and all synergistic effects of different weathering factors can rarely be considered by means of accelerated weathering simulation tests in chambers, the correlation of experimental results and weathering phenomena observed at monuments allow to identify and characterize the predominant factors and processes controlling the stone deterioration. Accelerated weathering simulation tests represent an important tool for research on weathering processes (Figure 32). They are also very suitable for rating of stone durability and effectiveness of stone treatment.

Weathering simulation chambers.

Weathering simulation test.



Sandstone samples before and after 30 freeze-thaw cycles.

Figure 32. Accelerated weathering simulation.

Outdoor exposure tests represent long-term studies. Stone samples are exposed to the natural climatic and environmental factors (Figure 33). Outdoor exposure tests contribute to following scientific and practical aims:

differentiated and quantitative assessment of weathering mechanisms and processes, weathering phenomena and state of stone deterioration in dependence upon stone types, weathering factors and time,

- identification of critical threshold levels with respect to stone properties and environmental influences,
- quantification and explanation of initial, pre-macroscopic and early phases of stone deterioration,
- rating of effectiveness of stone treatment,
- elaboration of monument preservation strategies.

Test field in Duisburg, Germany. Sample shape (“ Asterix”) imitates different exposition characteristics like occurring at monuments.

Test field in Aachen, Germany.

Figure 33. Outdoor exposure tests.

6. 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 an important 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 an important 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 damages. 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 an important 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 important 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.

Characteristical stone properties such as visual characteristics, mineral composition, geochemical composition, microtexture, porosity properties, hygric properties, mechanical properties and thermal properties are studied by means of modern analytical procedures. Many different methods have been developed for these stone analyses. Therefore, it is very important to select first the appropriate methods, respectively the suitable combinations of methods, which ensure the most efficient approach to solve the defined scientific and practical problems.

Porosity properties decisively control the quality and the weathering behaviour of natural stones. Therefore, precise knowledge of porosity characteristics such as total porosity, pore sizes, pore size distribution and pore surface is very important. Experience has shown that the very complex porosity properties of natural stones cannot be determined satisfactory by only one analytical procedure. Only the joint application of different optimized direct and indirect procedures can guarantee a reliable and quite realistic characterization of porosity properties.

Weathering simulation tests and outdoor exposure studies contribute to the development of weathering models, the characterization and quantification of weathering progression, the appraisal of stone quality / durability, the selection of appropriate natural stones for stone replacement and the rating of effectiveness of stone treatments.

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.

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