Environm e ntal degradation of cultural heritage in Portugal (1970-2001)

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1. Abstract

This paper presents a state-of-art of environmental degradation of cultural heritage in Portugal. Owing to time and space constrains, only some results are presented stemming from research and development in the last thirty years. Stress will be put into European Community Projects, which are representative of the work done within the scope of environmental degradation to cultural heritage in our country.

2. Introduction

In Portugal there are two national-wide agencies working on Cultural Heritage [1]:

1. Directorate General for National Buildings and Monuments - DGEMN

The Directorate General for National Buildings and Monuments - DGEMN - is a public body of the Ministry of Social Equipment. It was created in 1929 with specific functions such as responsibilities for the conception, planning, and co-ordination of activities leading to the following:

- construction, remodelling, and conservation of State public sector buildings;
- protection and enhancement of the architectural heritage in its care;
- evaluation and promotion of the quality of construction in conferences, seminars and congresses.

2. Portuguese Institute of Cultural Heritage - IPPAR [2]

Within the Ministry of Culture, the mission and tasks of IPPAR are to conserve, preserve safeguard and valuate the portuguese architectonic heritage. Included in this universe is the set of immobile goods of special historic architectonic, artistic, scientific, social or technical value existing within National territory. This is done through the emission of tied opinions with incidence on monuments or classified, or about to be classified sites, the realization of conservation works; rehabilitation and restoration in buildings and sites classified as state property, the classification of buildings and archaeological sites and the management of the main national monuments.

The main areas of action of IPPAR are:

- refurbishment and valuing of the heritage;
- safeguard of the built heritage and its contexts.

Nowadays, both areas are duly articulated. The first area includes a direct on monuments and cultural goods, through qualified surveyor interventions, refurbishment, repair, conservation, restoration and execution of several projects either in built heritage and respective involving, or in integrated and mobile heritage (painting, furniture, etc.), and the so called immobilized ”by destiny” such as wood carvings, wall painting, and tiling. Within the context of valuing, IPPAR proceeds to the managements of the national most important monuments (Palaces, Castles, and archaeological sites).

The second area of action, the safeguard, encompasses an action of technical administrative character through indirect intervention in diverse titular buildings, by means of promotion and instruction of classified processes of the heritage, setting up of special zones of protection or *non aedificandi* zones, which aim the legal protection of cultural goods and their contexts. Stemming from this protection, the IPPAR is called to issue tie opinions about projects or actions of other entities in classified or located buildings in their own protection zones, as well as to technically support the elaboration of several urban planning instruments, territory arrangement and environmental impact studies.

In Portugal there are three main research and development centres working on Cultural Heritage

1. Petrology and Geochemistry Centre - Instituto Superior Técnico (IST) (Technical University of Lisbon) where [3]:

CEPGIST (Petrology and Mineralogy Centre) was created in January of 1978 and it is located at Laboratory of Mineralogy and Petrology (Mining Department) of IST.

There are some facilities belonging to this Laboratory that can be used by CPGIST. So there are XRD and XFR laboratory and a laboratory of Chemical Analysis of Rocks and Waters as well as a FTIR unit. A unit of Image Analysis is also available. Petrophysical determinations like microporosity, ultrasonic measurements and rock ageing essays can also be performed. All common micropetrographic examinations (transmission and reflected light) are available. At CEPGIST 27 persons are working: 8 Doctors, 3 Masters, 7 Technicians, 4 Administratives and 5 Students with part-time grants. Two main lines of R&D are developing: Environmental Geochemistry; Mineral Resources. Within the framework of the 1st R&D line (Environmental Geochemistry) there are two main study areas:

i) one of them regards weathering and weatherability of rocks and its significance in geotechnics;

ii) The other one regards monuments stone decay phenomena and the study of their pathologies.

Special attention has been given to marine spray and polluted atmosphere as factors of damage to monuments as well as in modelling and simulating stone decay for different environment conditions.

In what concerns the study of weathering and weatherability of rocks and geotechnics a large amount of work has been made either in laboratory by means of ageing tests or in the field. Some work trying the establishment of weathering indexes should be mentioned. These studies have been made using in particular mathematical morphology based image analysis.

In deep articulation with the research projects, the Centre favours the development of post-graduation activities, which includes: Master and PhD thesis supervision; Actions of continuous formation through short duration courses; Advanced and Specialised Courses. The Centre maintains co-operation with several public and private research institutions (national and international) participating in scientific programmes and networks. It is also involved in projects of public services, especially in the field of geochemical and geohydrological risks associated with abandoned uranium mines should be referred (these studies have been carried out in liaison with the International Atomic Energy Agency-IAEA/Vienna) as well as physico-chemical analyses of water and geological materials. The Centre promotes and participates in the organisation of national and international congresses and in actions of diffusion of the scientific and technological culture for the community, particularly the school population. It maintains also, co-operation with several public and private research institutions (national and international) participating in scientific programmes and networks.

2. Centre of Environmental Sciences - University of Minho, where [4]:

The Centro de Ciências do Ambiente – CCA is one of the Research Centres of the University of Minho (UM). In accordance with the organization profile of the UM, the research and development activities of the Centre takes place in connection with the Biology and the Earth Sciences Departments and it is subjected to a specific scientific and administrative management.

The CCA combines research activities in the scope of the Biological Sciences (CCA-B) and Geology (CCA-CT), both as fundamental/applied research and environmental studies as the interface between the two domains. The main objectives of the R&D activities are as follows:

- develop teaching and research in the field of Life and Earth Sciences at the level of scientific quality compatible with progress achieved internationally;
- develop post-graduation activities and strengthen the capacity to attract foreign post-graduate students as well as to participate in national and international scientific research programmes and networks
- reinforce the relationship Research/Industries.
- According to these objectives the scientific activities are included in the following research domains:
- Biology (CCA/B): Microbial Physiology, Biochemistry and Molecular Genetics; Health Sciences; Plant Molecular Biology; Plant Biotechnology, Ecology; Conservation and Environmental Education.
- Earth Sciences (CCA/CT): Mineralogy; Petrology and Geochemistry; Isotope Geology; Sedimentology; Structural Geology; Geological Resources; Hydrogeology; Environmental Geology.

In deep articulation with the research projects, the Centre favours the development of post-graduation activities which include: Master and PhD thesis supervision; Post-Doc support and implementation of Master Courses; Actions of continuous formation through short duration courses; Advanced and Specialised Courses. The Centre maintains co-operation with several public and private research institutions (national and international) participating in scientific programmes and networks. It is also involved in projects of public services, especially in the field of microbial analyses of water, food and beverages, as well as physico-chemical analyses of water and geological materials. The Centre promotes and participates in the organisation of national and international congresses and in actions of diffusion of the scientific and technological culture for the community, particularly the school population.

3. National Laboratory of Civil Engineering (LNEC) where [5]:

Laboratório Nacional de Engenharia Civil (LNEC) is a science and technology institution of the State sector and it is controlled by Social Equipment Ministry. LNEC acts in several domains of Civil Engineering.

LNEC was created 19^{th} November 1946 from Materials Essay and Study of Public Works Ministry and from the Study Centre of Civil Engineering located at Instituto Superior Técnico.

There are three main action lines guiding LNEC activities: Innovation, depending largely from programmed research; Application of new acquired knowledge in the contract research programs aimed at the resolution of specific problems within the context of civil engineering and building industry; Diffusion of that know-how specially to the national scientific and technical community.

Considering the organization structure, within the Geotechnique Department the main fields of activity are: geotechnical works; foundations of structures; earth and rockfill dams;

road embankments; earth-retaining structures; stabilization of slopes; tunnels; and other underground works; decay and conservation of rocks in monuments problems. This field of activity is performed by different groups (Ornamental Rocks Group (GERO), Foundations Division (NF). Site Investigation Division (NP), Special Geotechnical Studies Division(NEGE), Rockfill and Environment Group (GEA)).

3. Stone Conservation In Portugal: Problems, Methods and Means (1972-1989)

For this period almost all research and development in the field of cultural heritage was done by CEPGIST-IST and LNEC. It can be said, quoting in full and largely Delgado Rodrigues [6] that Portugal has also a very rich cultural heritage, namely in stone monuments. Archaeological monuments dating from up to 6000 years before the present day, as well as Roman, Moslem, Romanesque, Gothic and baroque monuments are well represented styles in the Portuguese monumental art made of stone.

From the time of the Discoveries, a wealthy society emerged and religious as well as civil architecture developed in the principal cities of the Kingdom and mainly in the capital, Lisbon. Several architects and sculptors were contracted in the European countries where those arts had more tradition and support. The Gothic style acquired a splendorous decorative level with genuine local characteristics that made it the ex-libris of that golden period of Portuguese history.

The Manueline style, as it is called in homage to king Manuel, introduced a strong flavour of the sea into the decoration and it still remains a very impressive achievement of Portuguese art. Most of them being carved in limestone, our monuments underwent a disastrous abandonment during the centuries after the decline of the riches that used to reach Lisbon from the colonies, namely Brazil, and many of them suffered severe decay as a consequence of the lack of care and maintenance.

Before the nineties, our monuments were in very diversified states of conservation but, unfortunately, many masterpieces were in ruins or on the way to ruin. Conserving them only could be achieved at a national level by interesting all the community, a fact that was far from being understood in this way. Nowadays, this state of affairs is changing.

Scientific knowledge only began to be introduced in the conservation of stone monuments some thirty years ago, and up to the nineties with minor contribution from the State or its subsidiary entities. Research in stone conservation was being done in a few places, but no program of funding and sponsoring research in this matter had been defined at a national level. All that could be done was to apply general programs, at the same level as informatics, medicine or agriculture. European research programs contributed to a change in this state of abandonment and from the mid of eighties several research institutions have been funded in this way.

3.1 PROBLEMS

3.1.1 Stone materials and features of their decay

Limestones and granites are the two main types of stone used in Portuguese monuments. Marbles are mainly used in sculpture, although some complete buildings made of this material can be found near the principal centres of marble production.

Limestones are the dominant material in the west and south littoral bands coincidentally with the occurrence of the major sedimentary basins of the Portuguese territory. Granites predominate to the north of Oporto and in all the interior north and south regions.

Several varieties of limestone were locally used in monuments and tracing their origin back to the production quarries still needs to be done in most of them. However, a few types may be considered as typical construction materials where most of the research work dealing with Portuguese cases has been done.

In Lisbon and surroundings, "lioz" limestone is the dominant material. It is an excellent construction material and this quality is the main reason for our having such well preserved stone monuments from the fifteenth and sixteenth centuries. "Lioz" is a fossiliferous sub crystalline limestone with porosity of about one percent and with compressive strength higher than 120MPa.

Jerónimos Monastery, the masterpiece of the Manueline style, Belém Tower, several other monuments and all post-1755 earthquake Lisbon city centre were built using this variety of stone. This stone resists pollution very well and even in; marine environments its decay may be considered reasonably slow. Nevertheless, salt crystallization can be considered the main decay mechanism and solution by acid rain has also to be taken into account. Quite frequently, dirt is a very prominent feature and black and brown deposits are currently found in the more polluted areas. Crusts are also found in this lithotype, but honeycomb weathering is not a very common decay from.

In the centre of the country, a very porous limestone was for a long period a very common material both for common masonry and sculpture. The "Ançã" limestone, as it is called in the region, has between 14 and 30 percent porosity, is easily carved and its perfect white colour makes it a highly prized material. The Renaissance façade of Santa Cruz Church, most of the University buildings and several other monuments in Coimbra were built using this variety of limestone. Its very high porosity makes the stone very vulnerable to decay agents and some of the most illustrative examples of badly decayed stones may be found in these monuments. Plaques, plaquettes and honeycomb weathering are common decay: forms and salts are particularly harmful agents to this type of stone. Decay rates are very high and high pollution levels in some parts of that city have brought about very disastrous evolutions in some of the more exposed monuments.

Dolostones have also been used in this same region and some Romanesque and early Gothic monuments were buit using this type of stone. This is a yellowish stone with porosity around 14 percent and having a certain amount of illitic clays. The stone has frequent calcitic veinlets and its structure displays signs of cataclasis and other tectonic features. Heterogeneity is an important drawback that has visible influence in the distribution of the decay forms and on the degree of damage. The Romanesque façade of Santa Cruz Church, the Old Cathedral and Santa Clara Monastery, in Coimbra, are made of this stone.

Besides these typical varieties, clayey limestones can be found in monuments, commonly associated with a poor performance of the stonework.

Granites constitute another major type of stone used in Portuguese monuments. Several petrographic types displaying different textures and fabric may be found in the field and are used in monuments. Together with this large set of different varieties of stone, different weathering stages can be found, and these combined facts mean that an apparently simple designation such as granite becomes a broad term covering many individual cases.

Granite is a very hard rock and very frequently constructors tend to be slightly in favour of moderately weathered zones since the extraction and working is much easier. This gives a clear bias toward materials already weathered when applied to the monument and this is a very important issue that has to be taken into account when studying granite stones used in monuments. Plaque formation and sand desegregation are the two most common and devastating decay processes found in granite stonework. Weathering manifestations caused by hydrolysis and inherited from the *in situ* weathering process certainly are key-factors as decay inducers, but in itself hydrolysis can be considered almost irrelevant as a decay mechanism on a human timescale.

Gypsum is found in decayed zones and it is currently considered as decay. factor. Atmospheric SO_2 and rock sulphides are possible sources of sulphates and plagioclases and joint mortars may act as sources of calcium ions. Soluble salts are very devastating agents and sand disaggregation is sometimes clearly associated with their presence. A great deal of research work needs to be done in the study of weathering mechanisms, namely on those less commonly dealt with in monuments. Minute chemical and crystallographic changes, such as changes in the oxidation state of iron in biotites, cation extraction in feldspars, mineral corrosion by high concentration salt solutions are examples of possible underestimated weathering mechanisms of the granite stonework.

Portuguese examples of monuments made of granite are manifold, here, being included a large number of megalithic monuments, Cathedrals of Évora, Portalegre, Oporto, Braga, Bragança and a vast number of large and small churches, castles, fortresses and civil houses.

Azores and Madeira archipelagos end the series by adding the volcanic rocks to the set of stones used as construction materials in portuguese territory. Basalts, trachytes, ignimbrites and tuffs are some of the volcanic rocks that may be found in the monuments of those Atlantic islands. Quite often basalts are very durable, but tuffs and trachytes frequently exhibit high decay rates.

3.1.2 The environment

Within the scope of the present paper, only regional trends of the environment. parameters are justified; but it should be emphasised that stone behaviour in real cases may be governed preferentially or even exclusively by local conditions or it may have only subtle and concealed connections with the regional environment conditions. The climate in Portugal is temperate, oceanic with a dry hot season; in most of the territory, and as regards the influence on stone behaviour, it maybe considered a Mediterranean-type climate.

Precipitation is highly irregular in time and space. Mean annual values range from about 500 mm in the south up to 3000 mm in the north. Orography has marked influence on the spatial distribution and it introduces strong variation between low and high altitudes. Summer is the dry season, coincidentally with the occurrence of the highest temperatures. In the Azores and Madeira archipelagos the climate is temperate, with mean average temperatures at sea level of *17°* C and *16°* C, respectively. Precipitation is highly controlled by orography, and mean annual values of 360 mm and 2840 mm can be found on islands no more than 40 km apart.

The proximity to the sea introduces a relevant influence in the environment characteristics, and this is an additional factor of diversity dividing the territory into a littoral band and a hinterland region. Winds associated with moist period and precipitation blow preferentially from the sea side and an important amount of chlorides from this origin may be detected up to several dozen kilometers inland (The mild climatic conditions do not require intense domestic heating and consequently, this source of pollution is not very significant.

Heavy industries are relatively scarce at a national level, but important pollution levels have been characterized in some regions. To the early nineties, steel production and oil refineries in the Lisbon area, oil refineries, chemical production and thermal power plants in Sines and Oporto regions were the worst cases of industrial pollution. Some overcrowded urban areas presented traffic problems and pollution from vehicles reached very high levels. Lisbon, Coimbra, Oporto and Funchal have, even nowadays, good examples of monuments covered with dense layers of pollutant aerosols.

Insufficient maintenance care was responsible for local adverse conditions, namely seepage from roofs, platforms and other rain catchers or through joints and fractures. The exact extent of the harm caused by it is impossible to estimate but some masterpieces of the Portuguese heritage, such as Jerónimos and Batalha Monasteries, have been abandoned and exposed for some decades (in some cases up to two centuries) to weathering agents with total absence of maintenance. Some parts were ruined and others were repaired in the last century, not without leaving significant consequences in the remaining parts.

3.2 METHODS AND MEANS

3.2.1 General approach

Research in stone conservation started around 30 years ago in a few centres that were successful in establishing scientific and technical communication channels with other European research centres. A group called COPE/GTP (working Group for the Study of

Stone Conservation) obtained legal recognition in 1977 and since then it has promoted dialogue among the participants and contact with the authorities responsible for the conservation of the Cultural Heritage. Research teams on stone weathering, decay mechanisms and stone treatment are located in the national Laboratory of Civil Engineering, at LAMPIST/CEPGIST (Technical University of Lisbon) and José de Figueiredo Institute (IJF). A few, stone conservation practitioners could be found in this Institute and at the Museum of Conímbriga, although their experience is mainly concerned with sculptures and other mobile objects.

3.2.2 Highlights of Portuguese experience

Until the late eighties, in spite of being done by a very limited number of researchers it would be too lengthy and inappropriate to summarize all the research work published since 1970, on stone conservation in Portugal. In the following paragraphs some points will be highlighted aiming at giving an idea of the path followed and the way problems have been tackled and solved.

LAMPIST team developed some original ageing tests and produced some references on the mobilization of rock ions by percolating solutions and on the effect of heat and moisture on the properties of rocks [7]. Dry and wet field and laboratory ageing tests to the quantitative estimation of building stone weathering and weatherability by means of geochemical, petrophysical were also performed using climatic chamber and thermal fatigue tests to predicting the behaviour of rocks as applied to geotechnics, buildings or monuments has been a major concern, since pioneering woks on rock weathering and weatherability. In the search to quantify the weathering state of a rock under simulated environmental conditions, a weatherability index was postulated as a function of the simulated environmental conditions and of intrinsic rock characteristics (e.g. mineralogy, texture and petrophysic properties). This alterability index has been used to study mainly thermal fatigue of igneous rocks (granites and nepheline syenites) as well as non-igneous rocks (limestones, marbles, shales, etc.). For the purpose of thermal fatigue study, even an ageing experimental device was developed. Taking into account the data obtained from these ageing laboratory tests the weatherability index proposed is then calculated. By looking closely at its values, the rocks under study can be classified according to their susceptibility to weathering (weatherability seriation). The evolution of such an index along time can also be discussed. This index being essentially based on stones geochemistry can then be correlated with other physical and mechanical properties of stones. Statistical model could also be fitted to the values derived from thermal fatigue tests to obtain "empirical" geochemicaly based weatherability results for the studied stones. This way stone behaviour under comparable environmental conditions can be quantitatively predicted [8].

Stones having clay minerals have been studied and appropriate tests investigated. An original method for determining swelling strain was found [9] and some complementary methods were later developed [10]. As research and experience progressed, swelling strain acquired a very important place in the methodologies of durability assessment and some original uses of it have been proposed. Swelling strain and porosity were used for classifying carbonate rocks mainly for geotechnical purposes and the abacus that has been elaborated has proved suitable according to existing experience and available data [6].

Environment studies carried out at Jerónimos Monastery within the framework of a EEC research project constituted a starting point for this type of research [9]. Research on conservation problems has been tackled using low technology methods since funding hardly allowed enough for current expenses.

Studies on real cases have made it possible to start the approach to conservation problems but up to the nineties only cleaning is mastered in a reasonable degree. Consolidation and protection have been studied and products tested in laboratory, but application to in situ treatments is virtually absent in the last two decades. Cleaning of compact limestone was successfully carried out with water spray and soft brushing [6], but a monument made of granite required a low concentration hydrofluoric acid and a very skilled and careful application for cleaning it [6].

The study of some monuments in Coimbra made of very porous limestone has faced us with ancient treatments that have brought about poor and sometimes highly devastating results. The low penetration capacity of the products is the reason for these unfortunate conservation actions.

Archaeological heritage, mainly from the Roman age has merited attention and some ensembles may be pointed out as examples of good conservation practice. On the other hand, megalithic monuments have been relegated to a state of abandonment that is threatening many of the best examples of this prehistoric architecture. Agriculture practices, extensive forestry and vandalism have brought about the destruction of many of them and substantially reduced the high number of the once existing monuments.

4. Stone Conservation In Portugal Problems, Methods and Means (1989-2001)

In the last fifteen years, the possibility of getting funding from European programs to international research projects coupled with national research projects and projects of public services funded by the Portuguese State has dramatically and irreversibly (I hope) changed the expectations of research centres compared to the previous context, where it was very difficult to apply research results owing to a dramatic shortage of conservation and skilled workers. An important increase in the quality and quantity of research as well as its application to case studies can be measured by the number and quality of scientific publications associated with those projects. In particular, it should be stressed that, within the university context, LAMPIST, CCA-CT and more recently other new research and/or University Centres (see below other Portuguese partners of Granitix project), a deeper articulation between those projects and the development of graduation, post-graduation and specialised courses have been made.

Since it is impossible to summarize all the work published in the literature, only some of the results, particularly those connected to European projects, will be more or less briefly highlighted chronologically. The details of research results performed by each Portuguese participating work group are published in the project reports, in national and international congress proceedings and also in scientific journals addressing these issues.

Within the context of the European program on “Environment", the teams from LAMPIST and IJF developed a research project (EV4V-0063-P), based on the monitoring of the microclimatic parameters and on their connection of lichen growth as well as on the formation of black crusts in particular in some Portuguese monuments (e.g. Jerónimos Monastery). The results were presented and published in the project reports and in national and international congress proceedings, for example [11,12] and scientific journals. It is not possible for the moment to present more details about the research results of the project.

A research project lead by Delgado Rodrigues from LNEC, on conservation of granitic rocks, taking the megalithic monuments as case studies was launched in 1989 in the framework of the EEC STEP Programme. Project STEP CT90-110: Conservation of Granitic Rocks with Application to the Megalithic Monuments (Granitix). The results constituted a turning point in the conservation of this rock type so widely used as construction material in Portugal. Ten research Institutions from Portugal, Spain, France and U.K. participated in this EEC project and a few more have joined the group through the EUROCARE/EUREKA initiative [14].

Considering a brief description or the Portuguese participants activities:

Participant 01 - Laboratório Nacional de Engenharia Civil (LNEC)

LNEC took the responsibility for the coordination work and assumed all external official contacts. Besides administrative tasks, the project coordinator also acted as the pivot of the research work by receiving/distributing the information, data and other relevant matters from/to the participants. LNEC team carried out the survey of the two Portuguese study cases - Anta do Tapadão and Anta Grande do Zambujeiro - and participated in the definition of the sampling strategies. Extraction of samples was also made by LNEC. In collaboration with University of Santiago de Compostela (USC) some lab tests were carried out aiming at studying the decay mechanisms of plaque formation and sand disaggregation, and in collaboration with INETI and IICT a study of core samples was made aiming at comparing the decay processes in the dolmens and in the outcrops. An extensive programme of tests on stone treatments was carried out. Several water repellents and stone consolidants were tested. Efficacy, harmfulness and durability were systematically assessed. Several improvements in the test procedures were introduced in order to cope with the difficulties of testing very low porosity rocks.

Participant 02 - Instituto Português do Património Arquitectónico e Arqueológico (IPPAR)

IPPAR was in charge of the research on the methods of dolmen construction and on the interpretation of the dynamics of land occupation related to this type of settlement. Complementary archaeologic excavations were carried out in Zambujeiro and Monte Canelas dolmens and topographic drawings of the upright stones from Zambujeiro and Tapadão were made. IPPAR took the responsibility for the field interventions and supervised the different partners in their work carried out directly on the monuments.

Participant 03 - Instituto Nacional de Engenharia e Tecnologia Industrial (INETI)

INETI's activity, in collaboration with IICT, included chemical and mineralogical characterisation of samples taken from dolmens (Zambujeiro and Tapadão) and surrounding outcrops and quarries in order to determine the origin of the granitic stones used as building materials in the monuments. The study of the weathering mechanisms in those rocks (including sand disaggregation and Plaque formation) and the evaluation of the differences in the weathering rate of the monument stones and natural outcrops, as well as the role of biogeochemical processes in rock alteration were undertaken. A detailed study on chemical and structural transformations of biotites and feldspars was carried out. A special attention was paid to trace element geochemistry, specially the rare earth elements (REE).

Participant 04 - Instituto de Investigação Científica Tropical (IICT)

IICT activity, in collaboration with INETI, included the chemical, mineralogical and petrographic characterisation of granitic stones from Zambujeiro and Tapadão dolmens as well as samples from surrounding outerops and quarries to assert a possible origin of the former. A study of weathering mechanisms (plaque formation and sand disaggregation) and process rates (megalith vs outcrops) was carried out. Laboratory experiments were performed to simulate the bio attack by lichens with incidence on biotites and feldspars. A chemical study was carried out to check a possible chemical fingerprint in biogeochemical processes.

Participant 05 - Instituto de Investigação Científica Bento da Rocha Cabral (IRC)

The activity of IRC pointed towards the biodeterioration processes in order to evaluate their contribution to the weathering phenomena of granitic rocks. An extensive survey of the organisms that colonise Zambujeiro and Tapadão dolmens was carried out. Lichens were recognised as the main contributors to biodeterioration in these two places. In collaboration with USC and the Cesare Gnudi Foundation (external to the project) all the lichen species colonising both monuments were identified. IRC drew their distribution maps and related them with the prevailing environment conditions of each site. IRC studied the typical degradation phenomena caused by lichens in the granitic substrata and stressed the significance of those mechanisms in the whole degradation process. For comparative purposes with the USC research on biocides, IRC performed some tests with some available products.

Participant 06 - Universidade de Évora (UE)

The work carried out aimed at determining a number of relevant physical properties of granite samples obtained at the Zambujeiro quarry. The experimental work comprised the measurement of hydric, electrical and thermal properties. Some new test procedures were also developed or applied to granitic rocks by the first time. The pore space was characterised on the basis of physico-mathematical models for the equilibrium and transport processes in the fissure network and of the measured physical properties. Lichen species colonizing the Zambujeiro and Tapadão dolmens and nearby outcrops were identified with the collaboration of Universidade de Santiago de Compostela and with the external assistance provided by Cesare Gnudi Foundation, Italy.

As final remarks regarding this project, it can be said that at the starting date of the project, the GRANITIX team was aware of the difficulties expected from the research programme and the scarcity of references on the subject was taken more as a challenge than as a threatening obstacle. At the time of its conclusion, the team considered that a great deal of interesting results was produced, but it was also aware that the problems solved is surmounted by the new unsolved questions and doubts raised in the course of the work. Future research work would certainly be developed on the topics addressed by the project, namely on the interaction between living organisms and granites, on the study of fingerprints of buried and urban environments on the decay behaviour of granitic stones, on experimental decay studies, on the novel methods for non-destructive testing, on the petrophysical interpretation of granite decay behaviour and on the assessment of treatments performance. The comprehensive approach followed in the project has certainly helped in the recording of some interesting results, but above all it enables the scientific community to proceed towards future research work supported in a much more solid basis. The number of researchers involved in the three-year project, particularly of young scientists, and the number and quality of the documents produced were the best guaranty for continuing progress in the important subject of monuments conservation.

Based on [13], it can be said that in the research project STEP-CT900101 - Granitic materials and historical monuments: study of the factors and mechanisms of weathering and application to historical heritage conservation, the team from CCA-CT from Minho University cooperated as partner. The objective of the project was the knowledge of the behaviour of granitic and similar rocks under different environments in order to improve a scientific basis for decisions on restoration and maintenance procedures for granitic monuments in Europe. The broad scientific content of the project was as follows: Characterization of granite materials used in the areas to be studied, using appropriate experimental techniques. A comparative study was performed of fresh stones (from quarries) and corresponding weathered stones from different parts of monuments. Studies of the behaviour and response of the different materials under selected environmental conditions and in chambers under controlled conditions, as well as their response to different types of treatment for cleaning and for maintenance. Knowledge acquisition of the factors governing degradation processes and the main mechanisms involved. The effect of different factors (physical, chemical and biological) on every component of the rocks and on their texture and structure were identified.

The result of the contribution of the Portuguese team can be summarised as follows:

Given the study area, with characteristic environmental conditions representative of Oporto and Braga area (Portugal), under Atlantic influence and under a temperate and perhumid climate but with significant levels of industrial air pollution (Oporto) or no significant air pollution (Braga). In this area of study, "pilot monuments" were selected, investigating the quarries that had been the sources of the materials used in the construction and successive restorations of the monuments. In Braga (Portugal) the Edifício do Largo do Paço was selected. It is currently the Reitoria da Universidade do Minho and one of the most important buildings in the "Centro Cívico" of Braga. This monument from three different periods medieval, renaissance and baroque dates from the XIII and XIV, XVI and XVII centuries, respectively. In Oporto, the Hospital de Santo António, built for this purpose in the English neoclassic style in the late XVIII century, beginning of the XIX century was chosen. The working group performed the work following the above-specified general objectives, in a coordinated fashion with the other groups, attending to the specific problems arising in their study area. As general conclusions, specific disaggregation problems with either grain (granular) or scale formation were observed. These phenomena occur under the influence of endogeneous and/or exogeneous factors. Among the latter the general role of salts in the disintegration of granitic rocks were mentioned. Other phenomena could be important if the climatic conditions (strong thermal changes, high degree of humidity, marine sprays, etc.) or different kinds of pollution act against these materiais.

In view of the results obtained in assays addressing the materiais from quarries and pilot monuments, subjected to artificial ageing, in a simulation chamber and/or subjected to different treatments, together with the environmental data on the different areas studied, the following conclusions were drawn:

The endogenous factors of granitic rocks governing their behaviour, such as the materials used in construction and their resistance to the processes of stone decay, are related to the pore network and mineralogical composition. These characteristics were related to previous processes of natural weathering of the materials in quarries, " sub-actual " weathering processes (Braga and Oporto granites). The presence in rocks of mineralogical species of high solubility and/or reactivity in some cases increases degradation: stress produced by changes in volume, inherent to changes in humidity occurring in the swelling clays present in some granite facies ("ochre" granite), etc. The exogenous factors were related to environmental (climatic and pollution) conditions or human activities. The crystallization of salts was the most degradative and generalized weathering process and its intensity increased as a function of capillary transfer in the stone and of the pollution of waters. Salts crystallized in the parts of buildings affected by humidity (from capillary ascent or filtrations) in all of studied areas and this phenomenon was generalized in the buildings of areas affected by sea sprays (Oceanic influence). Black crusts were related to atmospheric pollution and appeared in sheltered areas affected by this phenomenon. Biological degradation was important in zones with a high degree of humidity (Braga). In Oporto the effect of industrial pollution could be a limiting factor for their growth. Further studies should be carried out to gain insight into bacterial growth with respect to air pollution. The influence of human activity was related to unsuitable management of the stone, the use of certain mortars and cements and products used for washing or conservation or to human activity affecting the environment.

A research project on environmental protection and conservation of cultural heritage has been launched in 1991 the framework of the EEC ENVIRONMENT Programme [15-16]. The aim of the project is to make a scientific study of the processes of weathering on monuments with particular reference to the Mediterranean coastal areas of southern Europe. In the project Marine Spray and Polluted Atmosphere as Factors of Damage to Monuments in the Mediterranean Coastal Environment - EV5V-CT92-0102, its objective was to make a scientific study of the processes of weathering on monuments with particular reference to the Mediterranean coastal areas of Southern Europe where two factors act together in causing stone decay: the marine aerosol and pollution. The complexity of the phenomenon of weathering - as it develops in that area is due to variable climatic and micro-climatic conditions, to the state of environmental pollution and to the different chemical and physical characteristics of the stone employed in construction - requires a selection of analytic techniques and the application of appropriate methods of investigation.

In the context of the methodologies and experiments undertaken, the project proceeded following two lines of scientific investigation:

1. Research in-situ and monitoring; laboratory analysis of samples taken from the internal and external walls of monuments in areas where - owing to their nature and composition - the marine spray and airborne pollutants can determine phenomena of stone decay.
2. Improvement of the methodology for monument studies, which, based on appropriate and interdisciplinary analytical techniques, would identify in qualitative and quantitative terms the effects of the weathering; could assist the understanding of the phenomena and consequently would suggest the most appropriate techniques of study applied to conservative interventions to adopt.

Four pilot monuments located along the east-west axis of the Mediterranean were examined. The different positions of the pilot monuments in the Mediterranean Basin, determined by the different physiographical aspects of the areas in which they are situated, reflect also different conditions of salinity and state of marine and atmospheric pollution which must be understood in order to establish the influence of marine spray on monuments and to evaluate the effects of pollution on the stones (marbles, limestones, calcarenites) which are common to the four monuments. The four pilot monuments which were selected are: (i) the Cathedral of Cadiz (Spain), located at the furthest limits of mediterranean Spain near Gibraltar, significantly affected by the Atlantic climatic conditions to which the most westerly part of the Mediterranean is also geographically close; (ii) the Cathedral of Bari (Italy), located in the central part of the southern coast of Europe where it is exposed to a marine environment influenced by anthropic activity; iii) the Archaeological Site of Eleusis near Athens (Greece), located on the sea in a typical urban centre of intense and diversified industrial activity; (iv) the Church of Sta. Marija Ta' Cwerra, Siggiewi, on the island of Malta in the centre of the Mediterranean.

The cooperation partners were:

1. National Technical University of Athens, Department of Chernical Engineering, Greece. Leading investigator: T. Skoulikidis.
2. Universidad de Sevilla, Facultad de Quimica, Departamento de Cristalografia, Mineralogia y Quimica Agricola, Spain. Leading investigator: E. Galan.
3. National Museum of Archaeology of Malta and Institute for Masonry and Construction Research of University of Malta. Leading investigator: J. Cassar.
4. University of Antwerp, Dept. of Chemistry, Belgium. Leading investigator: R. Van Grieken
5. Aristotle University of Thessaloniki, Lab. Engineering Geology-Hydrogeology, Dept of Geology & Physical Geology, School of Geology, Greece. Leading investigator: B. Christaras
6. Rheinisch-Westfãlische Technische Hochschule - Aachen, Geologisches Institut, Germany. Leading investigator: B. Fitzner
7. Instituto Superior Técnico, LAMPIST (Laboratório de Mineralogia e Petrologia), Lisbon, Portugal Leading investigator: L. Aires-Barros
8. Laboratorio Scientifico della Soprintendenza ai Beni Artistici e Storici di Venezia, Italy and Dipartimento di Chimica-Fisica, Facoltà di Scienze, Università di Venezia, Italy. Leading investigator: V. Fassina

Regarding the distribution of the tasks among the different partners, in addition to the administrative and scientific coordination of the project, the School of Monument Conservation of the Community of Mediterranean Universities (Istituto di Geologia Applicata e Geotecnica del Politecnico di Bari) will contributed essentially to the studies outlined in points 3 and 5.

The National Technical University of Athens contributed to the research described in points 1, 2 and 6.

The Universidad de Sevilla as well as the National Museum of Archaeology and the Institute for Masonry and Construction Research of the University of Malta will contributed to points 1, 2, 4 and 6.

The University of Antwerp contributed to points 1 and 2.

The Aristotle University of Thessaloniki contributed to points 2 and 4.

The Rheinisch- Westfàlische Technischule Hochschule, Aachen will contributed to the researches indicated in topics 4 and 5.

The Instituto Superior Técnico of Lisbon contributed to topics 1, 2 and 4.

The Laboratorio Scientifico della Soprintendenza ai Beni Artistici e Storici di Venezia and the Departimento di Chimica-Fisica, Facoltà di Scienze of the University of Venice will contibuted to the researches in topic 2.

The research programme included the following principal functional parts:

- Monitoring of environmental and micro-environmental parameters;
- Systematic mineralogical, petrographical and chemical examination of weathered stones and crusts;
- Relative non-destructive dating techniques for chronological information on organic elements contaminating stone;
- Analysis of the physical and mechanical characteristics of the weathered surfaces and walls;
- Mapping of weathered monuments: non-destructive techniques in situ damage evaluation;
- Study of macroclimate around the buildings; rainwater action; influence of marine spray, etc;
- Air sampling for suspended particles measurement, their size classification and chemical analysis;
- Use of liquid crystals, as surface air pollution indicator;
- Kinetic studies on photochemical conversion of particles involving nitrogen oxides at the marble/air interface;
- Data treatment of monitoring parameters applying signal analysis and processing theory;
- Mineralogic-petrographic studies of stone materials;
- Wet chemical analysis (soluble salts) of stone samples;
- Systematic chemical examination of marble surface crusts (IR Spectroscopy, SEM, X-ray diffraction analy- sis, X-ray maps .on thin section);
- Study of black crusts and other decay products using XRD, XRF, AAS, Infrared spectroscopy and liquid ion chromatology.
- Application of various-trace and micro analysis techniques;
- Mõssbauer spectroscopy for the detection of iron oxides;
- Analysis of the ecological succession in relation to the time of populating by organisms that live on the monuments;
- Geomechanical studies on sound rocks taken from quarries used in the past and at present for repairs to monuments;
- Physical and mechanical analysis;
- Micro-structure analysis of the porous stone system of different types of stones used in the monuments;
- Effects of the characteristics of the subsoil and the structure of the building on the weathering;
- Identification and distribution of the different forms of stone decay on the pilot monuments by means of computerized analysis.
- Working methodology of building mapping in combination with measurements on the building of the weathering forms;
- Processing of data.

- Elaboration of a methodology for the evaluation of the state of conservation and recommendations for conservative interventions on monuments exposed to marine spray and pollution.

The results of the project allowed the publication of forty works in the course of symposia, congresses, meetings and workshops. LAMPIST team contributed to the productive effort of the project at least with the following scientific papers:

- MOROPOULOU A., ZEZZA F., AIRES BARROS L, CHRISTARAS B., FASSINA V, FITZNER B., GALAN E., VAN GRIEKEN R., & KASSOLI - FOURNARAKI A. "Marine spray and polluted atmosphere as factors of damage to monuments in the Mediterranean coastal environment - a preliminary approach to the case of Demeter Sanctuary in Eleusis" *Proceedings of the 3rd International Symposium on the Conservation of Monuments in the Mediterranean Basin,* Venice, 22-25 June 1994, pp. 275-285, (1994).
- AIRES BARROS L., & MAURICIO A., "Forecast of spatio-temporal probability of salt efflorescence occurences on monuments stone". *Memorias* n.4 161-167. Univ.do Porto, Porto, (1995).
- AIRES BARROS L. "Monitoring of some *meteorological variables related with hygroscopic products occurring at monuments of the Mediterranean Basin". E.C. Workshop Origin, Mechanisms and Effects of Salts on Degradation of Monuments in Marine and Continental Environments,* 25-27 March 1996, Bari (1996).
- GALAN E., AIRES BARROS L., CHRISTARAS B., KASSOLI-FOURNARAKI A., FITZNER B., ZEZZA F. "Representative stones from the Sanctuary of Demeter in Eleusis (Greece), Sta.Marija Ta´Cwerra of Siggiewi (Malta) and Bari (Italy) and Cadiz (Spain) Cathedrals: petrographic characteristics, physical properties and alteration products". E.C. Workshop *Origin, Mechanisms and Effects of Salts on Degradation of Monuments in Marine and Continental Environments,* 25-27 March 1996, Bari (1996).
- CHRISTARAS B., KASSOLI - FOURNARAKI A., GALAN E., AIRES BARROS L. " Origin and stone material characteristics in the protection of monuments. The case of the archaeological site of Eleusis, in Athens". E.C.Workshop *Origin, Mechanisms and Effects of Salts on Degradation of Monuments in Marine and Continental Environments,* 25-27 March 1996, Bari (1996).
- MAURICIO A., AIRES BARROS L., FASSINA V, CASSAR J., TORPIANO A. "Multivariate data analysis applied to salt efflorescences occurring at Sta. Marija Ta´Cwerra Church (Malta). E.C. Work- shop *Origin, Mechanisms and Effects of Salts on Degradation of Monuments in Marine and Continental Environments,* 25-27 March 1996, Bari (1996).

The European Commission REACH project (Rationalised Economic Appraisal Of Cultural Heritage - ENV 4-CT98-0708) was established in May 1998 to consider how economic analysis has been applied to Cultural Heritage and how this analysis might be improved. The project focused on culturally important materials and objects exposed or potentially exposed to damage from air pollution, which included cities, districts, buildings, monuments individual pieces of art and other historical objects [17],

The REACH programme had three main objectives:

- The development of a method to integrate the different aspects of cost/benefit analysis that can be applied to cultural heritage.
- The development of a working prototype management tool with a modular design that can be used to evaluate cost/benefit scenarios at different scales.
- The development and validation of the model and management tool by use of practical case studies.

The Partnerships were:

- Middlesex University. UK. Coordinator Prof. R. Hamilton
- Building Research Establishment. UK
- Norwegian Institute for Air Research. NO
- Swedish Corrosion Institute. SE
- LAMPIST - Instituto Superior Técnico. PT
- Norwegian Agricultural University .NO
- Associated Partners and Sub-Contractors
- Norgit Senteret A.S. NO
- Ecotec Research and Consulting Ltd. UK
- SVOUM, Praha A.S. CZ

The project was developed through the following topics (work packages): Air Pollution and Material Damage Functions, Indirect Costs, Direct Costs, Policy Effects, Management Tool.

It has produced the following deliverables:

- D 1 Maps of air pollution distribution of selected degradation agents
- D2 Maps of corrosion rates or lifetimes of materials
- D3 Maps of the above w.r.t. historic data
- D4 List of selected materials
- D5 Dose response/ damage functions for selected materials
- D6 Limits and ranges of applicability of each equation
- D7 Review of techniques available for calculating indirect costs
- D8 Benchmark information for proto-type cost/benefit model
- D9 Cost model for assessing indirect costs
- D1O Assessment framework for environmental degradation of historic buildings + assoc costs
- D11 Information on the effects of policy issues on care of historic buildings
- D12 Report on influence of environment management policy on care of historic buildings
- D13 Estimate of cost of economic worth of policy
- D 14 Framework for full cost/benefit analysis model
- D15 Software (management tool)
- D 16 Integrated information retrieval package

In this project LAMPIST team was involved in the Policy effects workpackage and was involved in the production of deliverables D12 and D13 and in Jerónimos Monastery case study. Details cannot be developed in this paper.

Synopsis of the Project

The REACH project was established in May 1998 to consider the use of economic analysis applied to Cultural Heritage and how this might be developed further. It has taken a cost/benefit approach to the subject, which for reasons of operational efficiency, was limited to the economic impact of air quality (pollution) on the built heritage. Thorough reviews of the state of the art undertaken in the early period of the project showed that very little coherent work had been undertaken in this field, although there were a number of promising avenues of research and some potentially useful techniques. The field of environmental economics that had developed over the previous twenty years or so had given rise to a number of useful techniques for valuation of public goods and a few economists were beginning to explore the possibilities of applying them to cultural heritage goods. At the same time scientists working on the estimation of the amount of damage caused to sensitive materials in the built heritage were starting to add in cost calculations to their methods. National and European policy in the areas of air quality and heritage were also reviewed.

A principal aim of the REACH project was to design and build a prototype management software tool to undertake cost benefit analysis within the areas studied.

The reviews clearly demonstrated that there was insufficient data to provide a decision making tool for all situations -the necessary research to achieve this end will take many years to complete. What the software does is to provide a first demonstration of the type of calculation that is possible. A presentation of the existing material reviewed by REACH has been incorporated into the software in order that the user will benefit directly from the work undertaken.

The model that REACH has developed in the course of its three years of research has reflected the state of the art of air quality science and economic analysis in the field of damage to cultural heritage. The project did not set out to (or have the resources to) undertake major new studies in areas where gaps in the knowledge were identified. The REACH model is described in detail in the final report, and is provided for evaluation on the accompanying CD-ROM. It is made up of a number of modules, each of which relates to an area of cost (or benefit) calculation. The level of sophistication of the models available to undertake each type of calculation varies and the report includes a critical evaluation of their suitability.

Even allowing for the lack of sophistication of some of the components, there is considerable benefit to the development of an integrated mode, without which it will remain difficult to make comparisons between different costs. Now that a preliminary model has been developed, it can be adapted in response to further developments in the field. It has been designed in such a way that each component can be improved and substituted without the necessity to rebuild the entire framework.

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