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Oral Presentations—Methods and Materials of Cleaning,
Conservation, Repair and Maintenance; Logistics and
Planning

Session VIII: 8:00 – 10:00



CONSERVATION OF ARCHITECTURAL MARBLE AT THE NEW YORK PUBLIC LIBRARY

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Abstract

The contracted scopes of restorative work at the New York Public Library were established based on the results of laboratory and field evaluations and included cleaning, repointing of masonry joints, targeted protective surface treatments, systemic repairs, and localized repair or replacement of deteriorated elements. This paper will describe as-found conditions, selection of treatments, and the 'production level' execution of the work as it progressed across the four facades of the library (Figure 1).



Figure 1. The New York Public Library

Marble cleaning included overall, specialized, and localized treatments in different combinations depending on the substrate configuration and soiling patterns observed. Cleaning systems included an overall system utilizing soap and cycled steam for overall baseline cleaning supplemented with cycled water misting, micro-abrasives, and poultices.

Localized treatments with ammonium oxalate were applied to preferentially consolidate friable surfaces

in conjunction with lime-based shelter coat treatments to provide sacrificial protection to the stone surfaces. Hydrophobic and anti-microbial treatments were also applied at select areas.

Certain 'systemic' repairs were implemented throughout the entire facade. These repairs were preventative in nature, designed to assure long-term integrity and control deterioration. Systemic repairs to the marble included repointing of masonry joints, lead weather caps at skyward-facing joints, drips and ledge flashings, and bird controls.

Finally, many localized distress conditions required specific, localized repairs such as spalls, deteriorated ornamental features, cracks, and unsound or destabilized stone units. Repairs for these conditions varied depending on the type of architectural feature.

A detailed tracking and reconciliation process utilizing unit prices, estimated quantities, and reserve quantity allocations allowed the team the flexibility to adjust specific scopes of work as required in the field based on existing conditions and the evaluation and evolution of different repair techniques.

Keywords: marble, facade, restoration, preservation, hydraulic lime mortar, ammonium oxalate, lime shelter coat, zinc oxide patches, dutchman patches, drip edges, contracting, logistics, tracking, unit prices, allocations

1. Introduction

WJE Engineers & Architects, P.C. (WJE) was retained by the New York Public Library (NYPL) in April 2006 to investigate and make recommendations regarding the exterior of the main building, now known as the Stephen A. Schwarzman Building. Broadly, the scope of work under consideration includes cleaning and restoration of the masonry and sculpture, repair of the roofs, restoration of the historic bronze windows and doors, and restoration of the raised plazas or “approaches” upon which the structure is placed. This paper focuses on the marble restoration at the facades.

WJE assembled a broad team of in-house specialists and sub-consultants to execute the project. Senior staff participants and/or advisors in this effort included Kyle Normandin (Masonry Specialist), Matt Haberling (Project Architect), Remo Capolino (Roofing Specialist), Joshua Friedland (Conservator), and Tim Allanbrook (Project Manager). Sub-consultants that were part of the WJE team included Conservation Solutions, Inc. (fine art conservators), and A. Elena Charola (masonry conservation chemist).

The scope of restoration for the marble facades needed to address four primary evaluative factors: preservation and retention of historic fabric, cleanliness, safety, and cost. These evaluative factors influence the choices of restoration techniques in ways that are sometimes contradictory (Figure 2).

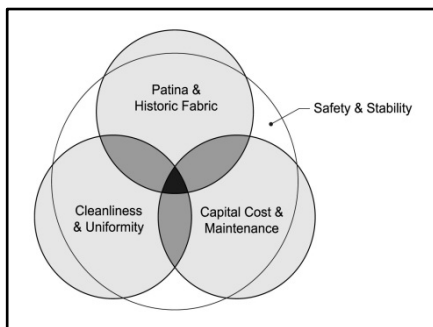


Figure 2. Venn diagram illustrating the sometimes contradictory restoration goals

For example, a delicate but eroded carved marble element can be carefully cleaned and the historic fabric preserved but it may present an unacceptable safety risk. Ironically, the retained patina of age, desirable from a philosophical standpoint, may not be particularly ‘clean’ from a practical perspective. Conversely, should the eroded element be replaced with a new piece of marble, the new material will, in many instances, stand out brightly and not blend into a monolithic whole. Finally, the costs of alternative restorative choices do not consistently favor one approach over another.

The specified scope of work sought a judicious balance of cleanliness along with the preservation of valuable historic fabric and patina. Balanced choices were required at all levels from the selection of overall restorative materials and techniques to the assignment of individual repairs at each stone unit. Safety of the restored facade was a baseline assumption and, when necessary, this factor overrode philosophical, aesthetic, and/or cost based considerations that could not be otherwise addressed.

2. History of Construction

The commission to design the New York Public Library was the apex of Carrère and Hastings’ work and the firm’s most famous project. Design and construction of the new Library took twelve years, and was completed at a cost of \$9 million. Before construction could begin, the Croton Reservoir had to be dismantled, a process which

involved 500 workers and took two years. The cornerstone of the library was finally laid in May 1902.¹

Relevant provisions from the original contract specifications dealing with stone procurement and quality provide a glimpse into the contracting conventions of the time:

“... the marble for all of the exterior work shall be white with a very slight amount of clouding of gray blue. The material shall be of such character that it will retain its white color under the action of the weather without discoloration from chemical changes or decomposition of the surface. No marble will be accepted which changes in color through any such decomposition of the surface, and the architects will not accept any material of which a sample cannot be shown which has been in a building and exposed to the weather for at least twenty years; the condition of such sample to be considered in the selection of the material for the Library building.

... the general color and character of material desired will be similar to the character and color of the so-called Drexel Building at the southwest corner of Broad and Wall Streets, in this city.

... the markings of the material shall be uniform so that the finished work will not show spots of color or marking, except in the courts where a greater amount of clouding and color will be permitted, but this shall not exceed the clouding and color on the south face of the bank building at the northwest corner of Fourteenth Street and Eighth Avenue, New York City.”²

The original stone ultimately selected to construct the facades was a commercial white marble quarried by the Norcross-West Marble Company in southwest Vermont. The marble had a uniform appearance that was regular and smooth, with light varied veining visible throughout the surface of many of the blocks. The completed library incorporated 530,000 cubic feet of marble, making it one of the largest all-marble building projects in the United States.



Figure 3. Exterior facade near completion in 1907 - note that no sculptures are yet in place

The construction of the building was photographically documented month by month.³ During the summer of 1905, the columns were put into place and work on the roof was begun. By the end of 1906, the roof was completed and five years of interior work began (Figure 3). In 1910, seventy-five miles of shelves were installed to house the collections, which included more than one million books set in place for the dedication.

The official dedication of the Library occurred on 23 May 1911, sixteen years after the agreement was signed that created the Astor, Lenox, and Tilden Foundations and established the Library. The ceremony was presided over by President William Howard Taft and was attended by New York Governor John Alden Dix and Mayor

¹ www.nypl.org

² City of New York, Department of Parks, Boroughs of Manhattan and Richmond. Contract and Specifications, New York Public Library.

³ Photographs are in the collection of the New York Public Library, Building Archive.

William J. Gaynor. On the following morning, the Library opened to the public and between 30,000 and 50,000 people visited the building on the first day.⁴

3. Survey Methodology

The NYPL's digital scans of the original Carrère and Hastings architectural elevations and sections served as the starting point for development of CAD base drawings. These drawings, in due course, served as the basis for survey documentation, presentation drawings, and contract documents. Given the magnitude of the survey, a decision was made to conduct a tablet computer based survey of the masonry rather than to utilize hand annotation of base drawing sheets. The CAD elevation database was loaded into the tablet and provided a basis for linking photos and observations on a stone by stone basis.

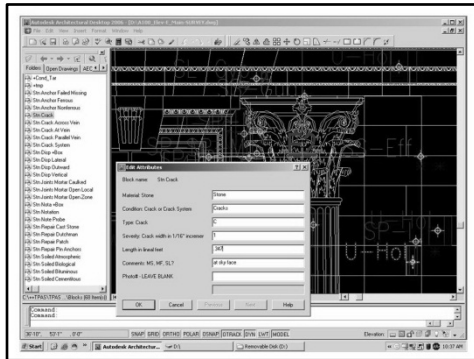


Figure 4. Screen capture from tablet software used to record existing conditions

An extremely detailed series of condition descriptions were developed to assure adequate flexibility in characterizing field observations. The conditions were categorized into broad types and sub-types. Finally, the quantity and severity of distress conditions observed, and comments relevant to the particular condition, were recorded through the course of the survey (Figure 4).

The team gained 100% hands-on access to the facades through the use of self-propelled boom trucks, suspended swing stage scaffolds, and industrial rope access techniques. The team's access contractor operated lifts, rigged and operated swing stages, made localized repairs, and provided ground support.

4. As-Found Conditions

Marble architectural features including highly decorative and ornate sculpted units varied in shape and size depending on the element and its building location. For example, the majority of the load bearing column units measure up to 36 inches in diameter while flat wall panels measure between 12 to 18 inches in width, 12 to 18 inches in height, and 4 to 8 inches in thickness.

The facades include a variety of stylistically integrated architectural elements such as entablatures, balustrades, columns, window and door surrounds, and corner quoins. Many of these marble elements were significantly deteriorated; however, their condition varied depending on the configuration, exposure, and characteristics of the specific stone units at each given location.

The marble was heavily soiled throughout with localized areas of black gypsum crust deposits and visible signs of sugaring. Generally, the most serious conditions had developed at the most delicately carved (and concomitantly more fully exposed) elements, such as the Corinthian column capitals, lion head keystones, and scroll modillions. In addition, the large, rusticated quoin units located at building corners and

⁴ www.nypl.org

used to set off the massive Reading Room window openings had suffered from significant localized failures.

Across the estimated 20,000 marble units used in the construction of the exterior walls of the building, approximately 7,000 individual occurrences of marble deterioration or distress were recorded in the course of the survey. Some twenty-five types of distress were identified and grouped into eight general categories. The categories of distress are noted below in Table 1 below and include cracks, spalls, erosion, displacement, surface loss, surface disintegration, unsound units, previous repairs, and deteriorated anchors.

The most prevalent type of distress observed during the survey was cracking, with 2,905 cracked units representing approximately 15 percent of the marble units on the building. The second most prevalent distress type was spalling, which numbered 1,621 or 8 percent of the marble units on the building. Other distress included surface loss, disintegration, and hollow (unsound) units of all types, with each condition represented in less than 6 percent of the marble units overall.

Table 1. Types and Distribution of Primary Marble Distress Symptoms Observed

Code / Distress Symptom		North 42nd	South 40th	East Fifth	West BP	Set backs	Court yards	All Facades
Appr. Quant. Marble Units		2,400	2,400	3,300	3,800	(*)	8,100	20,000
A	All Types of Anchors	27	7	45	32	6	24	141
		1.1%	0.3%	1.4%	0.9%	(*)	0.3%	0.7%
R	All Types of Prior Repairs	43	12	84	42	32	35	248
		1.8%	0.5%	2.5%	1.1%	(*)	0.4%	1.2%
D	All Types of Displacement	12	3	3	9	1	8	36
		0.5%	0.1%	0.1%	0.2%	(*)	0.1%	0.2%
C	All Types of Cracks	496	309	729	600	125	646	2,905
		20.7%	12.9%	22.1%	15.8%	(*)	8.0%	14.5%
U	All Types of Unsound Units	140	116	85	104	11	74	530
		5.8%	4.8%	2.6%	2.7%	(*)	0.9%	2.7%
SL	All Types of Surface Loss	56	123	542	241	15	53	1,030
		2.3%	5.1%	16.4%	6.3%	(*)	0.7%	5.2%
SD	All Types of Disintegration	155	58	123	129	31	223	719
		6.5%	2.4%	3.7%	3.4%	(*)	2.8%	3.6%
SP	All Types of Spalls	256	136	706	359	36	128	1,621
		10.7%	5.7%	21.4%	9.5%	(*)	1.6%	8.1%
Total Symptoms Recorded:		1,185	764	2,317	1,516	257	1,191	7,230
Percent of Units with Symptoms		49%	32%	70%	40%	(*)	15%	36%

(*) Areas of the setbacks are included in quantities of each major building elevation.



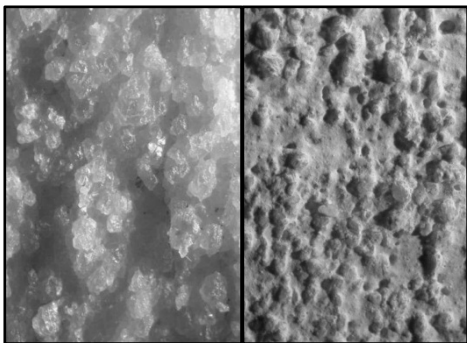
Figures 5a and 5b. Deteriorated modillions at main cornice without drip groove (left) and sound modillions at high cornice (right) with drip groove.

5a and 5b). A lead coated copper cornice ledge cover with a formed drip edge was specified to correct this problem for the future.

5. Selection of Conservation Treatments

The commercial white marble of the library was not highly metamorphosed, resulting in a heterogeneous structure wherein some areas had larger crystals and others smaller crystals. The main deterioration mechanisms were determined to include thermal cycling and acid dissolution leading to surface sugaring of the marble. Development of a conservation program to stabilize and protect these types of surfaces was of the highest priority but had to be balanced against minimum intervention principles.

As noted above, the marble of the library was found to be in a generally good state except for the more exposed and/or heavily washed elements. Preliminary tests were made with traditional consolidants, such as silicate esters. These did not perform well due to poor penetration into the sound substrate and so a more traditional approach using only inorganic materials was developed.



Figures 6a and 6b. Photomicrograph of disaggregated marble crystals before (left) and after treatment (right).

One of the more straightforward lessons learned from the library was the importance of drip edges. The high Reading Room cornice with its bold block modillions was provided with a sizable drip groove that prevented water running off the ledge above to wash back under across the modillions. The main cornice below with its decorative scroll modillions had no drip groove. There were no significant repairs required at the upper cornice – on the other hand, almost all of the scroll modillions under the main cornice required appreciable repairs (Figures

Spray application of an ammonium oxalate solution was found to assist in the mitigation of intensive sugaring of the marble. Localized treatments using ammonium oxalate were evaluated both in the laboratory and later, through field trials on friable surfaces. To further protect the eroded surfaces, a lime based shelter coat was applied over the oxalate-protected surfaces. This method proved to be quite compatible with the marble substrate and in the end, provided a viable level of sacrificial protection to the material substrate (Figure 6a and 6b).

Three pre-blended proprietary patching materials were tested for repairs at small spalls. During field trials, a zinc oxide based composite patching mortar had the best workability and yielded the most aesthetically satisfactory results.



Figure 7. Marble dutchman patches were carved in place

Dutchman patch repairs are generally considered to be an appropriate restoration technique in the repair of distressed architectural stone work, particularly where stone elements are missing or are too severely deteriorated for other repairs to be effective. Some two thousand dutchman repairs were executed in the course of the work (Figure 7).

Dispersed hydrated lime injection mortar and hydraulic lime injection grouts were specified for crack fill repairs. Such repairs are designed to minimize water penetration into the stonework. Field and laboratory testing indicated limited depth of penetration and limited durability under freeze-thaw accelerated weathering. The DHL was specified as a sacrificial fill for non-structurally significant cracks.

Three mortar types were installed in sample trials, two lime based formulations and one portland-lime formulation similar to the original mortar. All three mortars could be further customized to meet desirable aesthetic results. There are advantages of workability and ease of installation with lime putty and hydraulic lime mortars. The high calcium carbonate lime based mortars can provide better material compatibility with the high calcium carbonate composition of marble masonry. The hydraulic lime based mortar was ultimately selected over the lime putty mortar due to cost advantages.

Field cleaning trials were conducted to evaluate a variety of cleaning products and systems. Cleaning trials included cold water misting, hot water & steam, detergent, laser, microabrasive, and poultices. During the field trials, gentle water misting and steam cleaning in combination with detergents were found to be practical and effective at smooth wall surfaces and decorative areas subjected to gypsum crust build-ups while microabrasive techniques were needed to effectively clean more heavily eroded areas such as the corner quoins.

6. Contracted Scope of Treatments

The scopes of restorative work to be contracted at the New York Public Library were established based on the results of the above noted evaluations and included cleaning, systemic repairs, targeted protective surface treatments, and localized repair or replacement of deteriorated elements.

Marble cleaning included overall, specialized, and localized treatments in different combinations depending on the substrate configuration and soiling patterns observed. Cleaning systems included an overall system utilizing soap and cycled steam for overall baseline cleaning supplemented with cycled water misting, micro-abrasives, and poultices.

Certain 'systemic' repairs were implemented throughout the entire facade. These repairs were preventative in nature, designed to assure long-term integrity and control ongoing deterioration. Systemic repairs to the marble included repointing of masonry

joints, lead weather caps at skyward-facing joints, drips and ledge flashings, and bird controls.

Localized treatments with ammonium oxalate were applied to preferentially consolidate friable surfaces in conjunction with lime-based shelter coat treatments to provide sacrificial protection to the stone surfaces. Hydrophobic and anti-microbial treatments were also applied at select areas.

Finally, many localized distress conditions such as spalls, deteriorated ornamental features, cracks, and unsound or destabilized stone units required specific, localized repairs. Repairs varied depending on the type of architectural feature.

7. Bidding

Four restoration companies were pre-qualified to bid on the Project. The Contract Documents included bid quantities for stone repairs but not for stone treatments or cleaning procedures. The bidders were responsible for determining the surface area of treatment and cleaning processes using scaled drawings provided, and tables showing the percentages of each zone of the facade anticipated to require application of any given treatment or cleaning procedure.

Due to the large size of the building facades the Contract Documents broke the Project into three separate Phases, each with a one-year duration, commencing on the west (rear) facade and finishing on the east (front) facade. This phasing sequence was specified so that initial work was performed on the simpler, rear facades and assuring that the work at the front would benefit from the project's learning curve. Reserving the most important facade for last also allowed for a 'big finish' and reduced the likelihood of having part of the last part of the project be deferred or cancelled should the funding falter.

The Bid Form required unit prices for all repairs, treatments and cleaning procedures, allowing for equitable modifications to the Contract amount to reflect actual work performed in the field. A detailed tracking and phase by phase reconciliation process based on the delineated quantities shown on the Contract Documents and specified reserve quantity allocations assured that the team would have the flexibility to adjust specific scopes of work as required in the field based on existing conditions and the evaluation and evolution of different repair techniques.

Despite the magnitude of the project, the complex nature of the work, and a variety of specialized treatments that were new to bidders, the four bids received were reasonably close in value with the highest bid being only 20% above the lowest bid.

8. Contractor's Means and Methods

Because of the constricted site that included Bryant Park and a restaurant immediately to the west, sidewalks on the north and south, and a public plaza on the east, the contractor was allowed virtually no staging areas at grade. Large protective sidewalk sheds were constructed in every phase to act as elevated staging areas and overcome this obstacle (Figure 8). Cable hoists from the street to the top of the sheds allowed materials to be hoisted directly from trucks up to the elevated staging area.

Modular pipe frame scaffolding was used to access the work at all locations. Prior to installation of the scaffolding, waterproofing membranes were installed on the sidewalk sheds to contain runoff from the cleaning procedures. The scaffolding system included hoist towers on all sides capable of lifting the largest replacement stones, the half-ton stones which capped the balustrades.



Figure 8. Scaffolds enclose west facade to avoid disruption to abutting restaurant

On the west elevation the scaffold was enclosed in a continuous substantially airtight white membrane to protect customers of the restaurant below whose business continued unabated throughout the work. On the other three facades the scaffold was enclosed in traditional debris netting.

Scaffolding was removed as each Phase finished allowing the site to return to normal in sequential order. Scaffold erection and removal was generally coincided with early spring and early winter respectively.

9. Execution of the Work

The stone restoration work during each phase generally followed a predetermined order. Scaffold erection was followed by a confirmatory survey by the consultants wherein exact types and quantities of localized repairs were adjusted.

Cutting & pointing of mortar joints preceded the cleaning work in order to minimize risk of water intrusion into the facades but a subsequent thirty-day cure period was then required prior to cleaning operations due to the slower strength development of the specified hydraulic lime based mortars.



Figure 9. New turned marble balusters were installed at all balconies and parapets

Localized stone repair & replacement work was then conducted (Figure 9) along with the fine arts statuary conservation & cleaning work. Stone treatments such as the Ammonium Oxalate and Lime Shelter coats were then applied and a final wash-down performed. Final inspection, cleaning and/or treatment adjustments, and installation of bird netting in selected areas wrapped up the work in any given area. Due to the size of the building many of these procedures were being performed simultaneously at various areas.

Tracking the work was critical and entailed several distinct procedures. The Construction Manager typically accompanied the consultant during the initial confirmatory hands-on survey and marked up the elevation drawings showing minor modifications to the location or quantity of the repair work. Upon completion of the work in any given area, the consultant performed a punch-list inspection that verified the quality, quantity and location of the work.

Reconciliation spreadsheets were then created by the Construction Manager, and once the spreadsheets were agreed to by all parties, the Contract Amount was modified up or down via change orders, typically on a phase by phase basis. Despite many individual adjustments, both up and down, the overall project was completed on schedule and on budget. Finally the contractor issued detailed CAD As-Built elevation drawings that recorded final locations and quantities of all aspects of the work.

10. Unique Contractor Challenges

There were a number of challenges unique to this project. Ammonium oxalate, used to consolidate building stone, had not previously been used in the United States. The contractor had to arrange for importing large quantities of the material from Europe. There were no U.S. material safety data sheets or product data sheets. U.S. Customs required extensive information regarding the make-up and use of the material. Coverage rates for the material were unknown, and required broad assumptions during bidding.

The subcontractor used for laser cleaning was from Europe and brought crews over specifically for this project. Administrative issues such as insurance, workmen's compensation and contracts were difficult to sort out and required months of preparation before work could start.

Stone veining in the new replacement stones, while acceptable in ashlar units, became very prominent, and usually unsightly in the turned balusters. Unfortunately this was not detected during the submittal phase because the full size baluster samples submitted coincidentally did not have veins. This issue required replacement of many brand new balusters prior to installation.

Craftsmen capable of carving the detailed ornament found on the library's facades are not plentiful. The subcontractor performing the stone carving of the dutchmen started with three carvers and was only able to increase throughout the project to a maximum of six. Although they did an admirable job of keeping up with the schedule, falling behind on that portion of the work was a constant threat throughout the project.

11. Conclusion

The New York Public Library is considered a significant example of the Beaux-Arts style and the most important work of the firm of Carrère and Hastings. The New York City Landmark designation report notes:



Figure 10. Detail of completed front facade

"This majestic marble building ... is a magnificent civic monument and fully justifies the pride of its generation and of ours. It sits regally enthroned on a terraced plateau, displaying urns, fountains, flagpoles, sculpture and ornament. Replete with sparkle and delicacy, it is by night or day a joyous creation."⁵

The restoration of this acclaimed building was executed with the highest quality and minimal compromise. The work sought a judicious balance of cleanliness with preservation of valuable historic fabric and patina. Thousands of instances of deterioration were recorded during the initial survey. These 'as-found' conditions were subjected to laboratory evaluation and field-testing of alternative conservation methodologies to establish the most appropriate and least invasive treatments. Then, during the three-year construction period, members of the preservation team made repair and treatment decisions on a stone by stone basis ranging from crack fills to more than 2,000 carved dutchman patches (Figure 10). This was truly a career topping project for all parties involved.

⁵ New York City Landmarks Preservation Commission, Designation Report, January 11, 1967

The New York Public Library Statuary– Marble Deterioration & Conservation

Mark Rabinowitz¹, John Carr²

Abstract

Created by 4 different sculptors, the marble sculptures at the New York Public Library's east façade demonstrate how a variety of styles (Classical, Impressionist, Baroque, and idiosyncratic) and diversity of marbles (Vermont, Georgia, Tennessee and Carrara) could unify within the program of a well-designed Beaux Arts building. The different stones and exposures lead to different degrees of deterioration and, ultimately divergent treatment goals.

While initially the most deferential conservation plan targeted to maximum preservation of existing materials and minimal intervention was planned, the dramatically different conditions, ranging from modest weathering to catastrophic loss, led to introducing a more restoration oriented approach for some of the treatments. These variations in treatment goals were accomplished using high standards in collaborations between several conservators and cleaning specialists. The session will present some history of the sculptures and their creators, the initial survey and study methods, implementation of the laser and other specialized cleaning methods, innovative stone repairs, and how the conditions of the pediment statuary lead to the choice for substantial reconstruction over the more modest stabilization of the statuary applied elsewhere.

Ultimately, theoretical questions of where and how these choices should be made, and why they may differ dramatically even at the same site, will be discussed.

Keywords: Marble cleaning, biocide, consolidation, sculpture conservation, stabilization

1. Introduction

The marble sculptures at the New York Public Library's east façade were treated during a major restoration campaign on the building envelop. The different stones from which they were carved and variations in exposures lead to different degrees of deterioration and,

ultimately divergent treatment goals. Work was accomplished in a fruitful collaboration between conservators, contractors, conservation scientists and the project architects. While initially the most deferential conservation plan targeted at maximum preservation

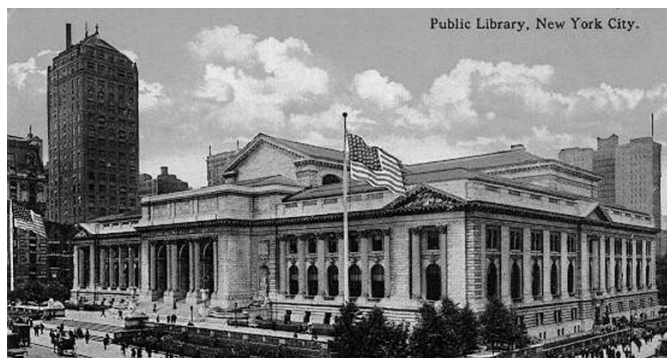


Figure1. Historic postcard showing statuary on NYPL 5th Ave. façade.

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of existing materials and minimal intervention was planned, the dramatically different conditions, ranging from modest weathering to catastrophic loss, led to introducing a more restoration oriented approach for some of the treatments.. Ultimately, theoretical questions of where and how these choices should be made, and why they may differ dramatically even at the same site became an interesting aspect of the collection of treatments.

2. History

The stone sculptures at the New York Public Library were conceived and created as integral elements of the overall design of the Beaux Arts building by the firm of Carrère and Hastings. The architects considered the sculptural program so essential to the design integrity of the building that they tried to have the sculpture contracts assigned under the sidewalk contractor in an attempt to avoid the constraints of the City's competitive bidding process and better control the selection and design. They intended that the creation of each should be assigned to the best younger American sculptors and created in overall harmony with their classic design. The main 5th Avenue elevation clearly is incomplete without these works.



To that end, they turned to sculptors who shared two crucial defining aspects of their own training and esthetics. All of the sculptors attended the *École des Beaux-Arts* (or the related art studio, the *Académie Julian*) before contributing to the *World's Columbian Exposition* in Chicago in 1893 just as the architects themselves had. Following Beaux Arts dictates, the sculptor's work at the *White City* were integrated into the architecture and site planning in the same manner that they do at the New York Public Library. The success of this contextualization is clear as the image of Library is defined now by its signature Lions; Patience (south) and Fortitude (north), which have become emblematic of the Library building and, in fact, the institution, who use them in its logo.

Figures 2,3: Half scale plaster mock-ups of proposed sculptures by Barnard (above) and Bartlett (right) from New York City Art Commission archives.



The sculptures were created by four different sculptors; Paul Wayland Bartlett, George Grey Barnard, Edward Clark Potter, and Frederick MacMonnies, in a variety of styles; Classical, Impressionist, Baroque, and Idiosyncratic, and diversity of marbles (Vermont, Georgia, Tennessee and Carrara). Despite this, the sculptures at the New York Public Library's 5th Avenue façade demonstrate how such variety could be unified within the program of a well-designed Beaux Arts building.

By the time of the commission for the Library, each of these sculptors had already completed or was engaged in implementing works like those required at the Library for other great public buildings, particularly in the nation's or state's capitals. The sculptures themselves took years to create and several were not installed until a decade after the completion of the building. Only the Barnard pediment groups were carved on site of the same Vermont Danby marble used elsewhere on the building, to unhappy results then as

now. A miscommunication with the builders, who did not leave adequate rough stone on the building to fit the sculptor's designs, resulted in the carvers truncating the upper parts of the figures to fit the blocks, leaving an anguished sculptor to sue unsuccessfully for damages over his distorted figures. The stone also proved inadequate to the challenges of the exposure and were the most deteriorated of any of the works at the building.

At the commencement of the project to restore the building in preparation for its centennial, Conservation Solutions, Inc. (CSI) was contracted by Wiss Janney Elstner, to assess the sculptures, document the conditions, and make recommendations for treatment. After contract award, CSI collaborated with the Milner + Carr Conservation, LCC, now Materials + Conservation Co. (MCC) the conservators who implemented the work. The assessments commenced in 2008 and work was substantially completed in 2010.

3. Condition Assessment

A condition assessment was performed from the ground and man lifts. A glossary of condition was developed which was consistent with the terminology of the ICROM stone condition glossary. CAD drawings were prepared and the observed conditions noted on them in detailed colored overlays that were transferred from field annotations on photographs. As no preliminary cleaning had occurred some conditions were difficult to discern in the muddle of soiling, gypsum crusts, extensive losses, failed previous repairs overlaid with bird dropping, particularly on the Barnard pediments, leading to the need for some modifications in scope that became apparent as work progressed. This was one of the factors that influenced a later modification of the treatment goal regarding these pieces that will be expanded on later.



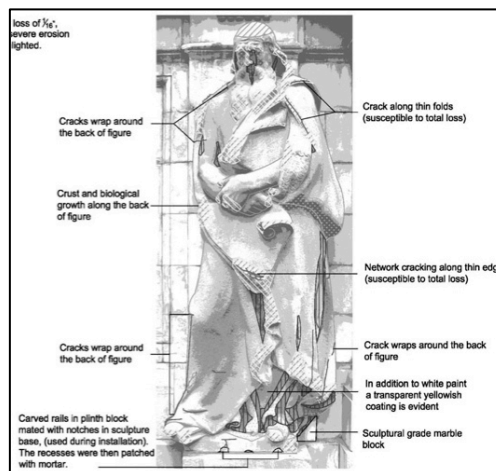
Figure 4 (above): Barnard pediment group detail showing extent of deterioration prior to treatment.

Figure 5 (below): Condition were noted on assessment drawings prior to treatment implementation.

Potter's lions, carved by the Piccirilli Brothers firm

from Tennessee marble, have survived relatively well even with the full exposure and regular climbing and other regular use. A conversion treatment may have contributed to their preservation however the Tennessee stone is very dense and not subject to crystalline disaggregation like a true marble. They received only gentle maintenance treatments to clean them and preserve existing fills.

The MacMonnies Carrara works also remained generally intact, possibly helped by having had an undocumented conversion treatment that may have



occurred and resisted erosion of the marble. The pieces have the pasty look of the converted surface although no records of any treatment have been found. They too only required modest cleaning and repairs.

Losses were more evident on the Bartlett attic figures, which are fully exposed to weathering and suffered modest loss from erosion and crystal disaggregation at vulnerable water run off areas. However, the durable large-grained calcitic Georgia Cherokee White remained generally sound and losses were concentrated on exposed elements. The exposure limited the dry deposition and bird infestations were not an issue.

The Barnard groups were the most severely compromised. Caked bird guano, black gypsum crusts, friable fissured stone, and major and minor losses were endemic. A substantial amount of detailed carved surfaces had been lost, leaving the complex compositions disfigured and illegible. Due to the extreme vulnerability of these surfaces it was decided to clean them with lasers, which was carried out by Giancarlo Calcagno using Nd:Yag Q-switched *Michelangelo* units by Quanta after an initial removal of loose soiling.

4. Conservation Treatment

As a subcontractor to Nicholson and Galloway, Inc., Milner + Carr Conservation, LLC (MCC) implemented the following treatments on the façade sculptures of the New York Public Library. These treatments were largely established by Wiss Janney Elstner Associates, Inc., sub-consultants CSI and A. Elena Charola, Conservation Chemist and based on extensive investigation, analysis and testing. Once work began, some unanticipated conditions required modification of proposed treatments and/or establishment of new treatment methods and materials. In such cases, proposals for new or revised treatments were submitted to the design team, client and review agencies for approval. In addition to the statuary, the fountain basins and monumental urns were treated during this campaign.

4.1 Bartlett Attic Figures

Six colossal attic figures are situated within the central frieze above the main entrance on the east elevation of the Library. The figures, each carved from a single block of coarse-grained Georgia white marble, were found to be in more stable condition than other façade sculptures. All exhibited moderate atmospheric soiling and localized areas of biological growth. Areas of the figures that face skyward and are exposed to direct weathering had suffered erosion and granular loss. Recessed areas which had remained protected such as folds in the drapery are more heavily soiled and developed gypsum crusts that had been subsequently coated with white paint. At some locations, this white paint was associated with a transparent yellowish coating. Other conditions included various size cracks, minor incipient and actual losses, previous repairs, minor blistering, and open joints.

Removal of generalized atmospheric soiling was accomplished by a combination of steam and detergent cleaning using a Goodway Backpack Vapor Steam Cleaner. A 25% solution of Vulpex Liquid Soap and water was then spray applied and allowed to dwell for approximately 20 minutes. Soft bristle nylon brushes were used to agitate the detergent during the dwell period. The masonry surface was then steam cleaned at 72 psi. All statues were then thoroughly rinsed with warm water at low pressure (approximately 20 psi). Biological were treated with D/2 Biological Solution, 50% solution spray applied to the masonry surface in conjunction with the Vulpex Liquid Soap as part of the generalized cleaning procedure. The D/2 was allowed to dwell for approximately 20

minutes and then gently scrubbed using a soft bristle nylon brush. The masonry surface was then thoroughly rinsed with warm water at low pressure (approximately 20 psi).

Gypsum encrustations proved to be multi-layered and extremely tenacious. Removal required a multi-step process which included water misting, application of a carbonate gel and mechanical removal. Affected areas were first treated with cycled water mist. The cycle for misting was established as a sequence of spraying at intervals of two hours on and one hour off for a total duration of eight hours. The water misting helped to soften the crusts and caused them to blister away from the surface of the stone, allowing for gentle mechanical removal between cycles. Due to the tenacity of the gypsum crusts, it was necessary to repeat water misting over the course of two months. During this time, misting cycles were interspersed with the application of Ammonium (Bi)Carbonate Gel Poultice manufactured by FTB Remmers. The gel was mixed into finely shredded paper pulp which was applied to affected areas, covered with plastic to prevent drying out and allowed to dwell for approximately 24 hours. Poultices were reapplied as necessary to help soften the crusts. The combination of water misting, carbonate gel poultice and mechanical removal eventually resulted in complete removal of the gypsum crusts.

All existing mortar surrounding each figure block was removed using a combination of an angle grinder with a fine diamond blade and small masonry chisels. These voids were backfilled using backer rod and NHL 3.5 pointing mortar as manufactured by Virginia Lime Works under the name Mix&Go Pre-Mixed Natural Hydraulic Lime Mortar. All joints were then pointed with the same mortar.

All surfaces of the Attic figures were treated with ammonium oxalate. A significant amount of deterioration on the marble statuary has been caused by weathering and the effects of acid rain. When applied to marble, ammonium oxalate chemically reacts with the calcium carbonate of the stone and produces a protective layer of calcium oxalate. This calcium oxalate layer consolidates deteriorated stone and is more resistant to acid attack than calcium carbonate. Being a sacrificial coating, the treatment will offer protection from exposure to the elements but will weather over time. The ammonium oxalate – as manufactured by FTB Remmers in a pre-diluted 5% solution – was applied to all surfaces of the clean Attic figures. The ammonium oxalate was applied using a natural-bristle brush until surface saturation and then allowed to dry for 24 hours before any further treatments were performed. Finally, lead “T” caps (as manufactured by Weathercap) were installed on all upward facing perimeter mortar joints bedded in Sikaflex® - 1a elastomeric sealant.



Figure 6 (above): Barnard Pediment Group Art in historic photo detail

Figure 7 (below): Conditions of same figure after laser cleaning showing extent of erosion and loss.



Incipient spalls were pinned using alumina ceramic pins with B-72 adhesive. To increase viscosity the dissolved adhesive solution was bulked with ultra-fine precipitated calcium carbonate at 40% by weight of the dissolved adhesive solution. Once the adhesive was set, the holes were patched using Lithos Arte composite patching material. Small cracks were filled with DHL-IM Injection Grout as distributed by US Heritage Group. The injection grout was delivered through a syringe.

More extensive cracking was observed on both the *History* and *Philosophy* figures. WJE carried out NDT (nondestructive testing) to confirm the depth of cracks and determine whether the cracks needed local stabilization. Test results determined that three cracks in *Philosophy* and one crack in *History* needed to be stabilized. Stabilization was carried out by MCC by installing stainless steel threaded rod set in Cintec Presstec Standard Micro Injection Grout at specified locations.

Areas of loss or existing previous repairs were re-sculpted using Lithos Arte, a zinc oxide patching mortar manufactured by FTB Remmers. The Lithos Arte was custom matched and formulated for the project. Only one area on the actual Attic figures (the right cheek of *Romance*) required patching. The remaining patching was done at the base of each sculpture where holes – originally created to aid in the installation of the sculptures – had had previously been patched with mortar. This mortar was removed and Lithos Arte patches were installed.

A custom matched lime shelter coat by Virginia Lime Works (a modified NHL 3.5 formulation) was applied to all areas of grain loss and erosion including local fissures. The concept of a “sacrificial layer” is well known in the field of conservation and is primarily based on the application of a surface finish that will protect the existing substrate while giving the surface a more uniform appearance. Lime shelter coats help smooth and fill irregular surfaces and open pore structures thereby improving water shedding abilities of the marble and reducing the surface area of the stone. The lime shelter coat was also used to cosmetically treat localized stains that could not be removed during cleaning procedures. The lime shelter coat was applied wholesale to each of the Attic figure at a ratio of 1:10 (shelter coat: water). The lime shelter coat was also applied locally to heavily disaggregated areas at a ratio of 1:5 (shelter coat: water). The shelter coat was applied using a natural-bristle brush and allowed to dry for a minimum of 72 hours.

4.2 Barnard Pediment Groups

The north and south pediment groups are carved in-situ from coursed Vermont marble ashlar. The pediments sculptures were found to be in extremely poor condition with heavy soiling, severe disintegration of the stone and significant loss of carved features. In contrast to the Attic figures, the shelter provided by the pediments had exacerbated deterioration of these sculptures. The overhanging cornices interfered with regular rainwater washing, which both allows for dry deposition of pollutants and provides protected surfaces for birds to roost. The guano and retained pollutants resulted in gypsum crusts on the underlying disintegrated stone that were measured to depths of an inch in places. The pediment groups exhibited the most severely deteriorated conditions of all the façade sculptures. Other conditions included displaced stones, blistering, cracks, open joints, previous repairs, caulked joints, and isolated cement parging, failed previous repairs including pinning and patching and isolated areas of heavy biological growth.

Prior to laser cleaning, all existing mortar and caulk were removed from the joints using an angle grinder with a fine diamond blade along with small masonry chisels. After completion of laser cleaning, all joints were repointed as noted above.

Although laser cleaning removed all of the black gypsum crusts on the surface of the pediment sculptures, removal of the crusts revealed areas of yellowish-orange staining. In many areas, the staining extended beneath the surface of the stone, sometimes reaching depths of 6 or more inches. Attempts were made to mobilize and draw out this staining using various techniques including water poultice and Arte Mudit, a latex based poultice. Ultimately, Ammonium (Bi)Carbonate Gel Poultice manufactured by FTB Remmers applied repeatedly for 24 hour dwell periods was successful at removing the majority of the staining. Removal of biological growth, consolidation, and the application of the lime shelter coat were similar to those implemented for the Attic Figures. However, the condition of the pediment sculptures required additional treatments and a reexamination of the expectations of this project.

Areas of loss or existing previous repairs were re-sculpted using Lithos Arte, a zinc oxide patching mortar manufactured by FTB Remmers. The Lithos Arte was custom matched and formulated for the project.

Project specifications originally called for minimally sculpting patching mortar repairs to re-establish essential sculptural legibility. As it turned out, the overall level of deterioration was far more extensive than originally anticipated and many areas could not be stabilized through application of the consolidant, which did not penetrate more than 2 inches beyond the stone surface. It was therefore determined that more extensive patching was required for structural stabilization. After much deliberation, it was further decided that the “readability” of these allegorical figures (especially from street

level) would be optimized if all losses were fully recreated to their original appearance. To ensure accuracy of the newly sculpted elements, historic photographs were referenced, remaining physical features and detailing was carefully examined, and comparable works by Barnard were scrutinized. In order to ensure a sufficient bond between patching material and the stone substrate, it was often necessary to remove a portion of deteriorated stone before installation of the patching material. It should be noted that in many cases, the extent of deterioration was far more extensive than originally understood. Oftentimes, areas of stone which appeared to be sound on the surface were actually completely sugared just below the stone’s outermost layer. This



Figure 8 (above): Fitting replica casting at Barnard Pediment Group

Figure 9 (below): Same figure after treatment.



condition required removal of significantly more material than originally anticipated. Where necessary, stainless steel threaded rods and/or fiberglass rod set in Sikadur® 31 Hi Mod Gel epoxy were installed before the application of the patching material to provide structural support.

For large areas of loss – either elements missing at the start of the project or areas where extreme deterioration require removal of extensive material – it was decided that new elements would be cast out of Lithos Arte. Dutchman repairs were ruled out largely because the weight of stone compared with Lithos Arte and because installation of new stone would require even more removal of original material. Casting of new elements was accomplished through a specially designed mold making and installation process based on the principle that cured or partially cured Lithos Arte successfully bonds to wet Lithos Arte.

Before casting, all stone adjacent to treatment areas was protected with 3 mil plastic sheeting. Additionally, cyclododecane (dissolved to a 30% solution in Naphtha) was brush applied to all treatment surfaces. Once re-crystallized, cyclododecane provides a protective barrier which lasts for several months until eventually sublimating into gas form. For elements which required removal due to instability beyond repair, molds were then taken using Resilpox putty followed by a burlap and plaster mother-mold. Missing elements were first sculpted *in situ* out of oil-based clay; the mold was then taken of the newly created element. Where necessary, molds were created in sections to allow for ease of installation of the cast elements. Once cured, molds were removed and used to cast the elements out of Lithos Arte at an average of 1” thickness. Fiberglass armatures were textured with epoxy and installed at areas to receive cast elements; in some cases, preliminary forms were created on the armatures using Lithos Arte. Cast elements were then installed, using wet Lithos Arte to fill any voids and secure the cast pieces to the armatures.

A number of extremely deteriorated or else entirely missing elements were re-carved out of Vermont marble which matched the color and texture of the surrounding stone. Historic photographs were referenced to ensure accuracy of the newly carved element. Dutchman repairs were secured in place with threaded stainless steel rod set in Sikadur® 31 Hi Mod Gel epoxy.

4.3 McMonnies Fountain Figures

Flanking the main entrance steps are large fountain statues situated within niches in the building façade are two figures carved from monolithic blocks of Carrara marble by Frederick William MacMonnies between 1914 and 1920. Both statues were in good condition with only minor erosion, localized deterioration of features, minor cracks, and light atmospheric soiling. Thin gypsum crusts had formed in protected areas and it appeared that a white coating had possibly been applied in an attempt to mask staining on the backs of the figures.

Portions of the both fountain figures exhibited a “chalky” white appearance, suggesting that an inorganic consolidant or other coating may have been applied to the surface of the masonry at some point. MCC submitted two samples of stone to a laboratory for analysis. Samples were analyzed by FTIR (Fourier-transform infrared) microspectroscopy and X-ray fluorescence (XRF) spectrometry. Neither analytic technique detected the presence of an organic or inorganic coating on the surface of the fountain statue stone.

Treatment procedures for removal of soiling, biological growth, and fills for losses were similar to those applied elsewhere. Several missing elements such as the turtle’s heads

were re-carved out of Vermont marble which matched the color and texture of the surrounding stone. Historic photographs were referenced to ensure accuracy of the newly carved element. When appropriate, new stone elements were carved to match the level of erosion of detail which was exhibited by adjacent elements. Dutchman repairs were secured in place with threaded stainless steel rod set in Sikadur® 31 Hi Mod Gel epoxy.

4.4 Potter Lions

At the completion of the main restoration scope, maintenance of the two iconic Tennessee marble lions was performed by CSI. They had been treated and maintained several times over the last decade and were in generally good condition. Nevertheless, localized areas of gypsum crust in areas protected from water run off,

overall soiling and biological growth existed. Work, including detergent washing, water misting, steam cleaning, biocidal treatments and injection fills generally followed that detailed above with the following modifications. Triton X-100 3% solution was used for detergent cleaning and Presto gel was selectively used to reduce tenacious black biota found on skyward facing areas after treatment with D/2.



Figure 10; One of the Edward Clark Potter Lions.

5. Conclusion

Within the overall context of the building restoration, the statuary conservation was a small item which nevertheless had an outsized effect on the visual impact of the project. Treated as individual works of arts, with appropriate caution and goals of minimal intervention, the treatments were consistent with the overarching project goals of bringing best practices on marble treatment to the preservation of the building at its centenary. While treatment of most of the statuary could be achieved within these goals, it became clear that a higher level of intervention was required on the Barnard pediment groups. This was warranted by their advanced degree of deterioration and feasible because of the availability of adequate historical documentation. The collaborative nature of the project, which entailed on-going review and discussions amongst the parties over a multi-year effort, ensured that goals could evolve and be refined as new and different conditions

were revealed while retaining a consistent standard throughout.



Figure 11; Barnard pediment group *Life* after treatment

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INTERIOR CLEANING AT SAINT JOHN THE DIVINE: PRACTICAL AND LOGISTICAL CONSIDERATIONS

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Abstract

One of the primary tasks following a major fire at the Cathedral Church of Saint John the Divine was the cleaning of all of the interior masonry. A number of tests were performed to determine appropriate options for cleaning the various types of masonry and tile that clad the building's interior. In addition to considering the effect of each cleaning method on the masonry substrates and the level of cleaning achieved, the review process also had to include the enormous scale of the undertaking, the desire to use a single method to clean multiple substrates, and the fact that portions of the building were to remain open while work was on-going. Ultimately, Arte Mundit® was selected for cleaning the two primary interior cladding materials: limestone and Akoustilith tile. The many construction-related issues that had to be addressed during the course of the project included procurement, containment, health and safety, and waste disposal. Additionally, a great deal was learned about the relatively new cleaning method during the course of the work and the technique was modified in response to specific issues that were encountered. Issues included appropriate conditions for cure, amount of scrubbing of the substrate following product removal, and the need to inspect for chemical and latex residues at the conclusion of the cleaning. The cleaning was successful and the lessons learned during the course of the work may benefit future projects.

Keywords: Arte Mundit, latex, interior masonry cleaning

1. Introduction

Following a major fire at the Cathedral Church of Saint John the Divine in the Morningside Heights neighborhood of New York City in December of 2001, the decision was made to clean the massive interiors. All cleaning projects on buildings of historic significance require a thoughtful study of appropriate techniques. Cleaning a very large scale historic interior such as Saint John added an additional layer of complexity, both in selection of an appropriate cleaning technique and in the logistical issues associated with achieving optimal results and ensuring timely completion of a project. The chosen technique, the proprietary Arte Mundit cleaning systemⁱ, was new in the United States at the time it was selected and therefore the project had an additional issue of learning how best to use the product as the work progressed. This paper catalogues the practical and logistical issues related to the use of the proprietary Arte Mundit system for cleaning interior masonry at the Cathedral, and describes the lessons learned, which may benefit future projects using this same cleaning system.

A description of the Cathedral and its historyⁱⁱ, a characterization of the interior fire soil prior to deciding to clean the interiors and a description of the comprehensive cleaning test program conducted to assess appropriate methods for cleaning the interiorⁱⁱⁱ, and a study of the associated repairs undertaken as a part of the post-fire restoration^{iv} are detailed in other publications.

2. Summary: Arte Mundit

The proprietary Arte Mundit, manufactured and distributed by FTB-Remmers, is a two-component system based on natural latex rubber. The thick white paste cures to form a film that can be peeled from the substrate. Four variations of the product are currently marketed: Type 1 contains no chemical additives specifically included to facilitate cleaning; Types II, III, and V contain differing concentrations of EDTA. Other components of the product are not released by the manufacturer but have been studied by others.^v

3. Summary: Saint John's Materials of Construction

Construction of the Cathedral began in the 1890s and continued, with some interruptions, until the start of World War II. Additional progress was made on the west elevation towers in the last quarter of the twentieth century; however, the building's exterior and interior remain unfinished. The interior walls of the Cathedral are clad primarily in smooth

sawn Indiana limestone. The regular coursed ashlar walls comprise the minority of overall surface area; bundled columns with ornate capitals, various large moldings, and carved ornament interrupt the flat surfaces frequently. In some areas of the interior the cladding is not yet installed; in these locations, brick and large units of rough-cut granite back-up masonry remain exposed. The vaulted ceilings have cast stone ribs and Akoustilith tile vaults^{vi}. Flooring materials include finished surfaces of limestone, argillite, and tile; there are also large expanses of concrete, where the finish floor was never installed. The interiors of the Ambulatory chapels comprise a greater range of unique decorative stones and tiles.

4. Evaluation of Cleaning Method

Evaluation of cleaning methods can generally be divided into two categories: *material issues* related specifically to the substrate to be cleaned and *constructability issues* related to the logistics of completing a project on a schedule and within a proscribed budget.

Material Issues

- Potential effects of the cleaning system on each substrate
- Degree and uniformity desired and achieved
- Potential for cleaning product to leave residues in substrate

Constructability Issues

- Cost associated with cleaning system
- Product availability and quality control
- Availability of manufacturer support
- Shelf life of cleaning product
- Access of materials to work area
- Ease of product application and removal
- Control and containment of cleaning products and waste products
- Disposal of waste products
- Noise and odor issues
- Schedule impact
- Ability of one product/system to clean multiple substrates
- Dependence of successful results on operator skill
- Worker health and safety

The relative value assigned to the various items within each category necessarily varies on a project-by-project basis. On a very large-scale project with limited funds, compromises are sometimes made, but all items should be considered.

When work began at Saint John, the use of Arte Mundit as an interior masonry cleaning system was new to the United States although it had been in use in Europe for some years. In order to reduce risk and establish an estimate of schedule and cost with some degree of confidence, a large-scale mock-up was produced prior to commencing with full-scale work. The mock-up was performed on two entire walls of a chapel that occupies one bay of the nave. The mock-up allowed the team to assess application rates, containment and ventilation needs, and noise and odor issues, and permitted the project team's conservators to assess results of the various types of Arte Mundit in large areas in terms of appearance and of material impact on substrate.

5. Access Considerations

The Cathedral is approximately 183 m in length. The nave is approximately 75 m long. The highest point at the center of each nave vault reaches nearly 38 m. Thus, access to work areas, and the associated cost, was necessarily an important consideration at the planning stages of the project. The decision was made early on to keep portions of the building open to the public at all times and this decision impacted access options. There was also a desire to have visitors walk the length of the nave even when the construction work was in progress in that space so that they could experience the enormity of the building despite the restricted access.

Use of aerial lift equipment suitable for use on interiors was considered but rejected for several reasons. First, it would not be possible to fit all the personnel and equipment required for cleaning operations on the lift's platform. Second, the amount of time for the lift to repeatedly raise and lower in order to access supplies at least partially negated the estimated cost savings of this type of equipment. And third, although it was believed (based on the mock-ups performed) that Arte

Mundit would require far less rinse water and containment than other types of cleaning systems, issues of containment during application and removal still existed and would be extremely difficult to address using lift equipment.

During the restoration, surfaces were accessed primarily using stationary pipe frame scaffolding. The pipe frame enabled containment of discreet work areas and permitted the contractor to access many areas simultaneously. It also facilitated design team review of completed areas while work was progressing in new locations. At the perimeter, pipe frame was erected to the full height of the nave, crossing, and great choir/high altar walls. A rolling platform, sized to fit within two bays of the nave and set at approximately 30 m – near the spring point of the nave vaults -, allowed for access to the nave ceiling while keeping the nave's center aisle free for pedestrian traffic (figure 1). Stationary pipe frame was also erected across the full width of the building at the juncture of the Nave and the Crossing. This portion of the pipe frame was necessary to reach certain otherwise inaccessible surfaces. It was also used as a physical separation between work areas and areas open to the public. Sheets of plywood were secured to the pipe frame, forming a solid wall; when work shifted from the crossing to the nave, the plywood was moved from one face of the pipe frame to the other.

6. Procurement Considerations

Arte Mundit is manufactured in Europe. Although currently available for purchase within the United States, at the start of the project it could only be obtained from Europe. Thus, it had to go through Customs upon arrival in the United States. United States Customs, when questioned in advance, would not give an estimate for the amount of time it would take to approve the shipment. The contractor allowed for a two-week delay at Customs, which turned out to be an accurate estimate. Because of the unknown factor and risk of delaying the work, in order to maintain a constant supply of product at the site very large quantities were ordered four months in advance of anticipated need date. To accommodate project requirements, full shipping containers were purchased. Ordering such large quantities at one time carried the risk that the product would not be used within the presumed shelf life. The manufacturer initially stated that the material should be used within six months; this was later revised to one year. Since the calculation had to include the estimated amount of time between manufacture and arrival at the job site, the shelf life upon arrival was closer to eight months. During the course of the project it was found that product up to eighteen months old performed satisfactorily. The manufacturer has since revised their recommendation again, with a current stated shelf life (premixing) of fourteen months.

Despite its very high material cost, using Arte Mundit appears to be comparable to the estimated cost of other cleaning methods used on large scale architectural interiors, such as wet chemical cleaning and micro-abrasive methods. This is because labor costs for related activities, such as general worksite cleanup, containment of product during use, and waste product containment and disposal are much less for Arte Mundit than for the other systems.

7. Surface Preparation Considerations

Thorough vacuuming of surfaces to receive Arte Mundit proved to be essential to successful use of the product. There was a significant amount of loose particulate matter on the stone surfaces, which impeded contact of the latex with the substrate. Leaving the loose soil on the stone resulted in uneven cleaning results. A variety of vacuum nozzle attachments were used. Large nozzles with a soft brush permitted large flat surfaces to be vacuumed rapidly; small nozzles of different shapes gave access to molded stone and deep crevices in stone carvings.

Latex remnants can impair adhesion of new mortar, and latex remnants are particularly difficult to remove from the concealed faces of stone at joints between units. If repointing is a part of the scope of work, the order in which tasks are carried out must be carefully considered. Repointing may be performed first, to avoid the risk of residue affecting adhesion of mortar. However, there may be reasons to defer work with mortars until the stone is clean, including the desire to finalize the appearance of pointing and composite patches after the stone is cleaned. In these cases, insertion of a flexible, reversible material, such as a backer rod, can be used to protect the surfaces during Arte Mundit application.

The Cathedral's many stained glass windows had to be protected against the cleaning product. The risk of damaging glass as a result of the peeling of the dried latex was deemed to be unacceptable because of the strong adhesion of the latex to glass. Additionally, many pieces of the Cathedral's glass are painted and Arte Mundit has the potential to alter and/or remove paints. Also, the stable and uniform corrosion product on the lead came was affected by the product. Installation of protection was time-consuming because of the intricacy of the windows; the workers cut stiff plastic to fit the variety of shapes created by the window tracery.

8. Application Considerations

Arte Mundit can be applied by roller, brush, or spray. Workers have also been observed using trowels to apply the material. In addition to the mixing equipment needed to prepare the two components of Arte Mundit for any application method, the typical set up for a spray application will include a compressor, a container (hopper) to feed the wet material to a hose, a large diameter hose to carry the material to the point of application, and a spray nozzle. Although a diesel compressor can be used and may be advantageous for smaller jobs of shorter duration, at Saint John a large electric compressor was purchased so that it could be situated inside the building, avoiding the noise and odor issues associated with locating a diesel compressor in an urban neighborhood that includes a large hospital and many residential apartment buildings.

A spray application was found to be optimal at Saint John as well as at several subsequent projects (figure 2). Spraying facilitates the application of the product, particularly when the stone is deeply carved or has deep crevices, and has critical impact on cure time, the removal process, and the degree of cleaning largely because of the thickness and uniformity of application that can be achieved by spraying. Brush or roller application did not achieve comparable results at Saint John. Use of a roller resulted in too thin an application, especially on uneven and high relief substrates, because the stiffness of the roller did not allow the product to settle uniformly. Conversely, application of too thick a coating (more likely when using a trowel or brush) was found to be problematic because of its impact on cure.

Logistically, spray application presented several issues. The latex spray, although heavy, becomes air borne; residues from the spray application were observed at least 5 m from the work surface. However, containment proved to be a straightforward process because of the size of the particles; well-sealed sheets of polyethylene secured to the scaffold structure served to contain work areas. The latex overspray did coat the pipe frame scaffold pipe and wood planks, at times resulting in slippery surfaces. The latex-covered equipment initially caused complaints from the scaffold supplier when the rented scaffold was returned at the conclusion of the project, but after they found that the latex not only easily pulled off the frames and planks but that it removed soil from their equipment, complaints ceased. Worker and observer respiratory protection were controlled by the use of individual respirators. Given the high concentrations of latex in the air during spraying and the desire to reduce the risk of negative consequences or a breach in containment causing spread of latex to publically accessible areas and/or already cleaned surfaces, a negative pressure ventilation system was also installed. It consisted of large diameter hoses linked to fans equipped with filters. The biggest issue related to setting up and maintaining a negative pressure ventilation system turned out to be finding operable windows to vent the air in a Cathedral whose windows were nearly all comprised of fixed stained glass.

Latex allergies were a serious consideration. It was necessary to confirm that all personnel on the job site who would come in contact with the product did not have latex allergies.

A high degree of training and subsequently of on-going good concentration and sensitivity to the needs of the work effort on the part of the workers assigned to spraying was critical to successful application. The contractor arranged for a trainer from Belgium familiar with the system to do on-site training. Two workers were trained. It took approximately one month before they gained a sufficient level of expertise with the system to be able to produce consistently good results. Initially, it was thought that more workers would be trained but, given the amount of training and skill required, only the first two trained were assigned to this work for the course of the project. Impact of this limitation on schedule was considered, but because it takes far more time to remove the cured product than to apply it, the workers applying the product were able to stay ahead of the removal crews. Indeed, consideration of the speed of the spray application needs to be factored into the overall schedule. Thoughtful orchestration of tasks is needed since issues with removal can arise if the product remains on the surface too long prior to removal.

Individual worker strength is another important consideration because of the difficulties in maneuvering the heavy, cumbersome nozzle properly to achieve a smooth even application. The issue was compounded by the high percentage of high relief and carved elements at the Cathedral; a great deal of practice was required to master the correct duration and nozzle angle to achieve the right thickness on deeply carved surfaces.

9. Cure Considerations

Following spray application, the product is left to cure. The product must be fully cured prior to removal. Generally, cure is apparent because of the color change from a white opaque paste to a yellow, somewhat translucent film. In addition, following application to the substrate, the product has more 'give' when touched where it is still wet.

Cure time is dependent on air temperature and relative humidity as well as on surface temperature and substrate moisture content. FTB product literature states that they have tested their product and found cure to be acceptable under a variety of conditions, ranging from 5 degrees to 30 degrees Celsius and a relative humidity of 40 percent to 95 percent. Whether the product contains additives to increase the range of acceptable conditions is not known. In general, the warmer the temperature and the lower the relative humidity, the faster the latex will cure. A very high relative humidity may create moist conditions such that the latex will become brittle and therefore difficult to remove following cure. If latex freezes, it is unusable.

In practice, it was found that Arte Mundit does not cure adequately at a surface temperature below 10 degrees Celsius. Importantly, this means that issues with cure can arise when exterior temperatures are below 10 degrees Celsius and the work location is on the interior surface of exterior walls (thinner walls are more susceptible) or adjacent to windows. For example, stone tracery at stained glass windows has a tendency to maintain a surface temperature closer to the exterior environment.

Excessive cure times were associated with difficulty in removing the product and removing residual soil. Based on practical experience gained during the course of the project at Saint John, every effort was made to remove product after no more than a forty-eight hour dwell.

One of the most problematic cure-related issues is that latex becomes brittle in the presence of moisture. If the latex becomes wet prior to or during cure, the cured film cannot be removed in large sheets; when pulled, it breaks into very small (approximately 6mm square) pieces. At one wall in Saint John, where Arte Mundit was unknowingly applied over a damp substrate, workers spent several days rather than the normal few hours picking off small pieces of the latex. Re-application was then necessary when, after the wall had been scrubbed and left to dry, it was clear that the surface was not as clean as control samples. Therefore care must be taken to ensure the substrate is dry and relative humidity levels are within the recommended range. Inspections should be made following rain events to determine if water has infiltrated to surfaces prior to spraying. Since a surface may appear to be dry but still contain moisture, testing should be performed to confirm conditions where warranted. Comparative readings from a moisture meter may provide sufficient information; however, this method may necessitate creating holes in the stone surface to insert probes. ASTM International's standard D4263^{vii} provides a reliable non-destructive method. In brief, this method involves sealing a layer of transparent polyethylene sheeting on the substrate and noting whether water condenses on the inner surface of the sheeting after a proscribed period of time.

10. Removal Considerations

The cured latex is pulled off the surface in sheets (figure 3). The importance of applying a thick even film becomes apparent during removal as latex applied too thinly is more difficult to remove because it cannot be pulled in large sheets and tends to break off and stay in crevices where it is even harder to remove. This is particularly problematic on stone surfaces that exhibit honeycombing, such as unfilled travertine, because of the tendency for remnants to remain in deep crevices.

Over the course of the project, it was discovered that the way in which the film was removed affects performance. Pulling the cured film some distance from the still-adhered edge makes it more likely that the film will break in small sheets as applied force exceeds the material's tensile capacity. If the worker's hands are always close the adhered edge, sheets of greater size can be removed. Pulling the material farther from the substrate also appeared to have a relationship to the amount of residue left on the substrate.

Some soil is removed with the latex. At Saint John, soil also remained on the surface and required a combination of scrubbing and sponging with clean water for successful results. More scrubbing was required to remove soil when the latex was left on the stone for an overly long dwell time, and, following an overly long dwell it was more difficult and sometimes was not possible to achieve a uniformly clean surface without reapplication of the product. It was found that scrubbing needed to be done immediately following removal of the film to achieve the desired level of soil removal, so there was careful scheduling of how much film was removed at any one time.

Significantly less water is needed with Arte Mundit than for the typical rinsing required with wet chemical cleaning methods, so the system removes the need for control and containment of large quantities of waste water, which can be problematic and costly to set up and maintain. At Saint John, the contractor set up a pump at floor level to provide sufficient pressure to deliver water through a hose to the work area even at heights in excess of 30 m, as well as a

separate chute for disposing of waste water so that the workers did not have to leave the work area to obtain clean water. The workers were asked to always have two buckets of water: one in which to rinse a soiled sponge or scrub brush and one to obtain clean water prior to using the tool on the substrate. Regular changes of water were essential to avoid re-introducing soiled water into the stone, and the ease of access gave greater confidence that workers were exchanging dirty water for clean frequently enough.

At the start of the project, the workers began removal of the cured film at the top of the wall. The procedure was to expose only the amount of wall surface that could be scrubbed and rinsed during a typical work period of approximately four hours. The remaining adhered film below formed a lip that was initially considered helpful because it aided in control of waste water. However, because the rinse water carrying soil tended to settle and rest at this lip, it resoiled the stone. Simply scrubbing with water and a scrub brush did not remove this soil; another application of Arte Mundit was required at this line. Since the surfaces to either side of the line had already been cleaned, the product was applied by brush joint-to-joint on the effected courses of masonry.

Particularly when small pieces of latex remained on the surface and had to be individually picked off, pieces of latex tended to accumulate on the scaffold decking. Good housekeeping was important. Otherwise, the small pieces fell to lower levels where they adhered to walls, requiring careful inspection and additional removal later to ensure that no pieces remained on the building surfaces.

Testing confirmed that the waste product (removed latex film) could be disposed of as normal construction debris.

11. Inspection Considerations

As with any masonry cleaning project, evaluation of results included whether the desired degree of cleaning established at the start of the project surfaces had been achieved and whether the final effect was uniform. Use of stationary scaffolding can make it difficult to evaluate results because it is not always possible to stand far enough away from the cleaned surface to evaluate uniformity over large areas. Sometimes imperfections that appear problematic upclose are not deemed significant when viewed from a distance. In addition, the shadows created by the scaffold structure and work lighting can distort the appearance of the substrate. Where these issues are likely, consideration should be given to incorporation of specific requirements into the contract documents to avoid additional costs during the course of the project to create adequate viewing conditions. For example, the contractor may need to temporarily remove sections of protection and scaffold structure for acceptable viewing conditions, and/or provide a different light source.

As with any project involving the use of chemicals to clean masonry, evaluation also included whether any residues had been left in the stone or on its surface. In the case of Arte Mundit, evaluation was made both for physical remnants of the latex and for chemical components of the product.

Although the potential implications of latex remnants on the substrate itself are not fully known at this time, and further study is indicated, there are known issues. Since latex darkens over time and attracts soil, there is a risk of aesthetic implications. Additionally, latex remnants may affect the adhesion of subsequently applied coatings, patching materials, or mortars. At Saint John, the large amount of scrubbing that was needed to fully clean the stone surfaces following removal of the latex film helped to ensure removal of the latex. The final inspection included a careful review under excellent lighting conditions for visible remnants. But as Morasset confirmed in her thesis work^{viii}, latex residue may remain on the substrate's surface even if it is not visible to the naked eye. Morasset used ultraviolet light in laboratory tests to detect the presence of latex. Latex contains limoni; under ultra-violet light, cured latex fluoresces a characteristic yellow-green color. The success of this technique to detect the presence of latex is predicted on the substrate either not fluorescing or fluorescing a different color from the latex. Case-specific testing is probably the most reliable confirmation of whether the latex will be discernable under ultra-violet light, since impurities and small quantities of minerals can impact how a substrate fluoresces. Field testing thus far has been limited to the cleaning of brick work, where a significant difference in color of fluorescing components made the technique extremely useful in finding latex remnants. Where ambient light could not be dimmed sufficiently, the inspector wore a large dark cloth hood and performed the inspection using the darkness provided by it. Even when the ultra-violet light technique works well, however, to some degree latex remnants continue to be an issue with the Arte Mundit cleaning system because remnants can be trapped in deep crevices where the ultra-violet light cannot reach them.

The possible presence of EDTA residue was evaluated by periodically applying poultices to small areas of cleaned surfaces. Sterile cotton batting was submerged in distilled water and then placed firmly over a cleaned area

approximately 4" x 4" in size. The batting was covered with polyethylene sheeting, which was taped at the edges to retard evaporation. The batting was removed after 24 hours and brought to the laboratory where conductivity measurements using an Accumet 50 pH/conductivity meter were made to determine salt content.^{ix}

12. Conclusion

Because the Arte Mundit cleaning system was relatively new at the time of the project, the project team had little product-specific experience to draw upon. On-going evaluation of material and constructability issues during the creation of a large-scale mock-up and throughout the course of the work resulted in modifications that improved both efficiency and results. Ultimately, Arte Mundit was successfully used to clean the limestone and Akoustilith-clad interiors of Saint John the Divine (figure 4). The lessons learned can be utilized on future projects.

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Figure 1. View of scaffolding at nave. Center aisle is open, with plywood-roofed pedestrian walkway. Plywood secured to pipe frame, visible at center rear, provides separation between nave and crossing. Photograph by the author.



Figure 2. Spray application of Arte Mundit in progress. Photograph by the author.



Figure 3. Removal of cured Arte Mundit in progress. Photograph by the author.



Figure 4. Detail of limestone surface cleaned by Arte Mundit adjacent to uncleaned section of stone. Photograph by Andrew Wilson.

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^v Morasset, E. V. 2008. 'Cleaning historic building interiors: the question of residue using Arte Mundit® cleaning paste'. Master of Science thesis. Graduate School of Architecture, Planning, and Preservation, Columbia University.

^{vi} For a description of Akoustilith tile, see: Pounds, R. 1999. The unseen world of Guastavino acoustical tile construction: history, development, production'. *APT Bulletin*, **30**(4): 33-39.

^{vii} ASTM Standard D4263 – 83 (Reapproved 2012). 'Standard test method for indicating moisture in concrete by the plastic sheet method'. West Conshohocken, PA: ASTM International.

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CONDITION ASSESSMENT OF THE MARBLE FUNERARY MONUMENT TO ANTONIO CANOVA IN THE BASILICA DEI FRARI IN VENICE: A NEW MECHANISM FOR MARBLE DECAY

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Abstract

In recent decades, the funerary monument dedicated to Antonio Canova in the Basilica dei Frari has suffered serious decay phenomena. The sharp increase in deterioration processes observed in different areas has caused the loss of large areas of marble detail from the surface of the statues. As there is an urgent need to stop the increasing rate of marble decay the authorities responsible for protection of the cultural and monumental heritage decided to start a comprehensive survey to identify the causes of alteration. Macroscopic observation of the marble surface showed different forms of alteration as well as the massive presence of salt efflorescence. A number of different types of alteration were observed macroscopically and in order to assess the deterioration mechanisms samples were taken from the decayed areas. ESEM observations together with EDS analyses have enabled us to explain the stages, each corresponding to different features, through which exfoliation and lamination of surface scales is taking place.

A survey of the moisture content of the masonry structure under the steps of the monument has established that moisture from the ground is being transmitted by direct contact of the brick core with the marble. As a consequence capillary migration of water transports salt solution onto the marble surface, where it forms droplets.

In order to stop the rapidly increasing rate of decay, observed over the last ten years, there is an urgent need for action to prevent any further capillary rising damp by inserting a damp proof course and at the same time to detach the statues from the base in order to remove the salts embedded in the marble.

Keywords: monuments' condition, soluble salts, marble decay

1. Introduction

Given the unusual and serious problems of decay that have for some time affected the Cenotaph of Antonio Canova in the Basilica dei Frari in Venice, the Superintendency for the Architectural and Landscape Heritage of Venice decided to undertake a study of its state of conservation in an attempt to understand the nature of the problems and their possible underlying causes (Amoroso and Fassina, 1983). The investigations, carried out between 2009 and 2011, were designed to provide essential preliminary information prior to planning and initiating the necessary and urgent restoration work. This stage was financed by the English *Venice in Peril Fund* in the

framework of the UNESCO-Private Committees Programme for the Safeguarding of Venice. The monumental cenotaph of Antonio Canova was built in 1827 inside the Basilica dei Frari, against the wall of the south aisle, immediately after the first altar. On the death of Canova in 1822, his friend and biographer, Count Leopoldo Cicognara, then president of the Academy of Venice, organized a Europe-wide public subscription to collect funds for the erection of a funerary monument to celebrate the illustrious artist and to provide a final resting place for his heart. The execution of the work was assigned only to pupils of the Maestro and his assistants. They followed, almost without change, the project that Canova had designed for a monument to Titian; this was never executed but the design was later adapted for the tomb of Maria Cristina of Austria in the Augustinian Church in Vienna.

The overall plan of the Canova cenotaph is very similar to that of the Viennese version, though twice as big (Fig. 1). In execution and the choice of materials and subjects, however, the Venetian work makes clear reference to many other works by Canova, who represented the artistic culture of this period and provided a highly distinctive cultural model. So it is not only the use of the pyramid shape, sculpted by Vincenzo Fadiga, but also the theatrical arrangement of the melancholy figures in the sad procession that underline the very close relationship between this and Canova's other funerary monuments, which were so innovative and original compared with the tired culture of the period. On the right, two young women representing *Painting* and *Architecture*, sculpted by Luigi Zandomeneghi climb towards the central door, deliberately left half open to suggest the passage to the afterlife; together they bear a garland of flowers to offer to the deceased.



Fig. 1. The cenotaph to Antonio Canova

A young man with a torch stands between them and another young woman, veiled and moving slowly, her head bowed, holding the urn of ashes. This figure by Bartolomeo Ferrari represents *Sculpture*, Canova's favourite of all the arts and the one destined to hold his ashes. The group on the left is composed of two figures sleeping. Both are, in fact, images of the eternal sleep of death, which is celebrated in the

monument. One is a great *winged Lion*, the emblematic symbol of the *Strength* that must assist the deceased, but also of Venice, a city much loved by Canova; the lion is by Rinaldo Rinaldi, who also sculpted the naked boys in the procession on the right. A *Sleeping genius*, also naked and winged, a young man with extremely soft and sensual features, was the work of Giovanni Fabris. An effigy of Canova, by Luigi Bosa, is the subject of a large medallion supported by two female figures in flight, in the centre of the pyramid, above the door.

2. Decay forms

The main aim of this paper is to assess whether there is a relationship between the decay observed and the presence of salt efflorescences and secondarily to ascertain the source of the salts and consequently to propose a method of stopping any further cause of alteration.

In recent decades the funerary monument dedicated to Antonio Canova in the Basilica dei Frari has suffered serious decay phenomena. The sharp increase in deterioration processes observed in different areas has caused the loss of large areas of marble detail from the surface of the statues.



Fig. 2, 3. Details of exfoliation on the Sleeping Genius and on the womens' dresses.

Macroscopic observation of the frequent formation of droplets on some areas of the group of sculptures led the authorities responsible for their conservation to plan a survey to investigate the microclimatic conditions that could be responsible for the phenomena observed. Measurements of surface temperature on different areas of the statues' surfaces have revealed the slow change of surface temperature with respect to air temperature fluctuations (Camuffo et al. 1987, Camuffo, 1988). The thinner parts of statues such as arms, legs and hands show a faster change of surface temperature in relation to sudden air temperature fluctuations. The base of the pyramid, in contact with

the church floor, has a constant higher temperature due to heat transfer from the soil. It was surprising that the areas where droplets form are not very damaged whereas some other parts have suffered serious damage.

Many areas, like the chest of the Sleeping Genius or the robes of the women (Figs. 2, 3), show the presence of salt crystals associated with a marked exfoliation of thin marble layers, while droplets are present on the face of the Sleeping Genius, which is undamaged.



Fig. 4. Droplets visible on the marble surfaces

Previous microclimatic studies on the monuments' established that the formation of droplets due to condensation processes is not very frequent and the mechanism of marble deterioration is taking place inwards from the outside and the marble exfoliation is occurring with an increase in volume without any phase changes from calcite to calcite. According to these previous studies, biological colonization is responsible for the increase in volume which is detaching thin marble layers from the substratum.

As this biological mechanism seemed not to be reliable the project directors asked for the reliability of this hypothesis to be verified. Our diagnostic plan was designed to identify the causes of alteration taking into account the construction techniques used. In fact many problems are probably related to the structure, which is taking all the weight of the marble blocks of the steps, the pyramid and the sculptures. As the structure is closely related to the moisture in the ground it was also decided to investigate the water content in order to evaluate if the capillary rise is influencing the presence of water droplets on the marble surface and if it is in some way related to the presence of efflorescences.

3. Sampling and analytical methods

As we were not convinced that the marked decay observed was ascribable to biological action further samples from decayed areas were taken following the CEN TC 346 European guidelines: these were micro-flake samples, representative of the different

forms of decay observed. Bulk samples for the measurement of moisture and salt content were also taken for investigations into the rising damp process.

An optical microscope (OM) and an environmental scanning electron microscope equipped with a dispersive energy micro-analyzer (ESEM-EDS) were used for thin and cross section observation. The characterization of bulk samples was performed by X-ray diffraction (XRD), while X-ray fluorescence (XRF) with WDS sequential spectrometry was used for the elemental composition analysis. Anion concentrations such as sulphates, nitrates, chlorides and oxalates were measured by ion chromatography (IC). The morphological characteristics of micro-flake samples were observed by examining 3D samples using secondary electrons of scanning electron microscopy (SEM). The presence of organic compounds was determined by infrared spectroscopy (FT-IR).

4. Results

4.1 Moisture content and constructional characteristics of the supporting structure

The supporting structure was investigated by the use of georadar and by drilling cores into the base to a depth of 2 metres. Georadar measurements established that the three steps are formed of marble blocks (35 cm thick) and the supporting structure consists of brick masonry. Georadar measurements also emphasized high water content in the supporting brick structure.

The moisture content profile from ground level up to the base of the pyramid was measured by drilling cores at different heights and depths. The water content is close to 25% up to a height of 80 cm and it slowly decreases to 18-20% up to 140 cm. At the base of the door (190 cm. from ground level), the water content decreases to 8.5% (Fig. 5). The data obtained indicated that the brick supporting structure is completely saturated with water and as there is no discontinuity between the brick structure and the marble blocks or statues the capillary rising damp phenomenon is causing the migration of salts from the brick structure towards the external surfaces of the marble blocks and statues.

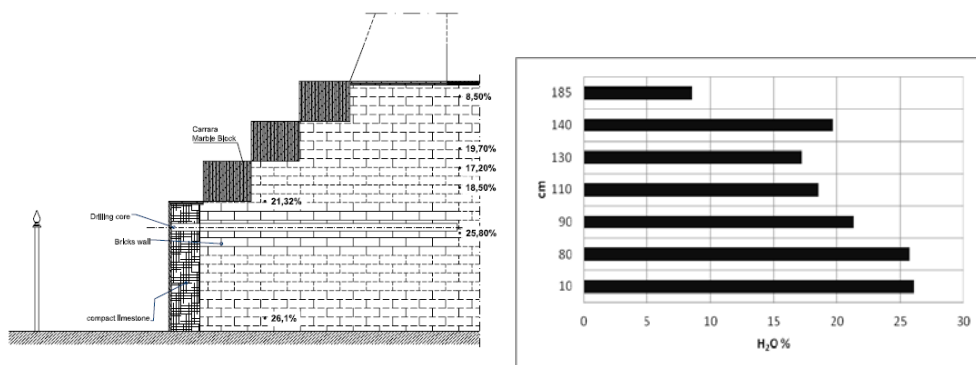


Fig. 5 a,b. Bricks supporting structure and moisture content at different heights.

4.2 Macroscopic features on the marble surfaces

Macroscopic observation of the marble surface showed different forms of alteration frequently associated with massive salt efflorescences. The following types of alteration have been observed:

- smooth dark grey areas in good condition (type a-fig 6),
- rough whitish grey areas showing a slight erosion without any crystal deposit (type b),
- areas with exfoliation or lamination of thin marble layers which are becoming detached from the substratum and with the formation of salt crystal powdering on the sound substratum (type c).
- red coloured round shaped areas.

4.2.1. Type **a**: smooth dark grey areas

In order to explain the different types of alteration observed, the crystal structure of a sample of sound material was analyzed by thin and cross section. Sound marble shows a compact structure and no inter-crystalline detachment. Also visible on the external surface is a wax deposit due to maintenance treatment (Fig. 6c)



Fig. 6. a) sample 9 from a sound area, b) cross-section at OM, c) cross section at ESEM. In cross section no micro-cracks are visible indicating that marble is in good condition, not weathered.

4.2.2 Type **b**: slightly eroded surface

Samples taken from slightly eroded areas generally show a colour change from grey to white due to the lower density of the outer marble surface layer (fig. 7). In cross section the presence of some inter-granular micro-cracks is ascribed to the crystallization of sodium chloride: this is the initial phase of decay in which crystals detach from each other and the structure becomes less compact and marble appears brighter (lower density).

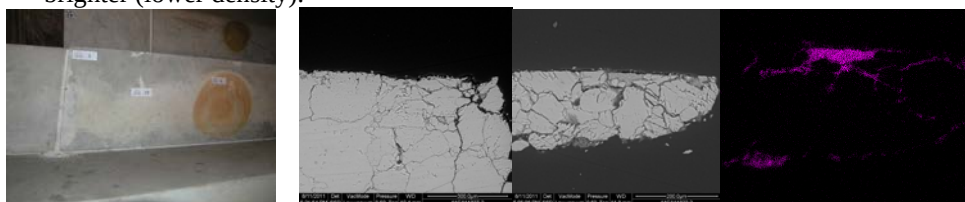


Fig. 7. a) whitish slightly eroded surface, b) cross section at ESEM showing micro-cracks at an initial stage, c) cross section at ESEM showing more numerous micro-cracks caused by sodium chloride crystallization, d) X ray map distribution of sulphur showing gypsum on the surface and its penetration inside micro-cracks.

The marble surface observed perpendicularly (fig. 8) shows a heterogeneous feature with dark areas (wax presence) alternating with white areas presenting some

micro-cracks. The same scale observed from the back which, before sampling, was in contact with the sound substratum, shows many micro-cracks associated with sodium chloride crystals.

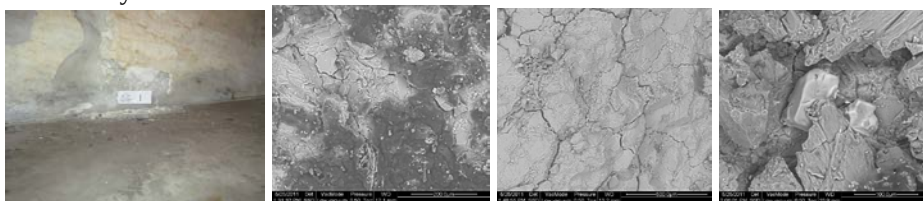


Fig. 8. a) sample location. b) external surface of the marble scale (wax is visible in the dark areas). c) back side of the marble scale shows a marked decohesion of grain crystals. d) sodium chloride crystal

4.2.3 Type c. areas with multilayer exfoliation of marble

In order to validate the biological colonization mechanism proposed by previous researchers a sample presenting the exfoliation phenomenon was taken from the same location. Visual macroscopic examination of the thin marble scale enabled six levels of progressive exfoliation to be identified (fig. 9). SEM observation shows the presence of sodium chloride crystals between different scales; these are responsible for the detachment. Microanalysis also emphasizes the presence of potassium chloride and gypsum.

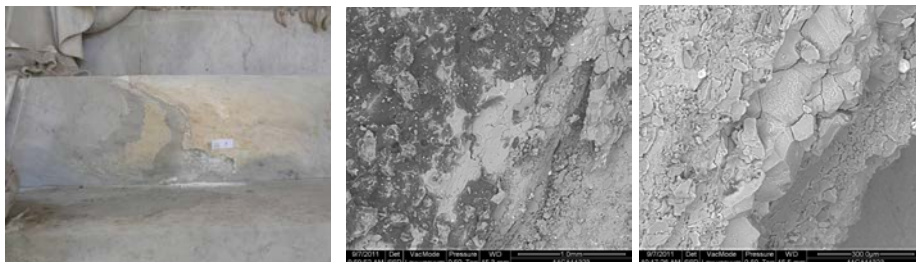


Fig. 9. a) sample location. b) three layers from outside. c) three more layers inwards

By analyzing the single layers we have observed that the different levels alternately feature calcite crystals with marked micro-fissures and small sulphur- and chloride-rich crystals without a regular shape, thus indicating a secondary gypsum formation (Fassina, 1978, 1994, 1995)) together with primary sodium chloride crystals.

5. Conclusions

The same sample was also observed in cross section (about 2 mm thick) and it is possible to distinguish up to eleven discontinuity levels instead of the six observed by the naked eye. This seems to suggest a completely different mechanism of marble decay from the one usually considered for outdoor monuments in the Venetian environment (Fassina, 1993a, 1993b, Sabbioni 1995)). In fact, up to now the generally accepted mechanism of marble decay is the following: severely damage is caused by the different texture of calcite grains which, after a certain time, allows water to penetrate into intergranular spaces, and favours the reaction of acid sulphur-bearing solutions which

form gypsum around the grains. This is the starting point from which a progressive attack of calcite marble takes place. Gypsum crystals found in the intergranular spaces can be ascribed to different mechanisms:

- i) primary formation due to the penetration of sulphuric acid solution coming from the atmosphere and the subsequent reaction with calcite crystals;
- ii) secondary formation due to the penetration of gypsum previously formed in the atmosphere;
- iii) gypsum, firstly formed on the surface, can penetrate inside the marble during the wetting phase;

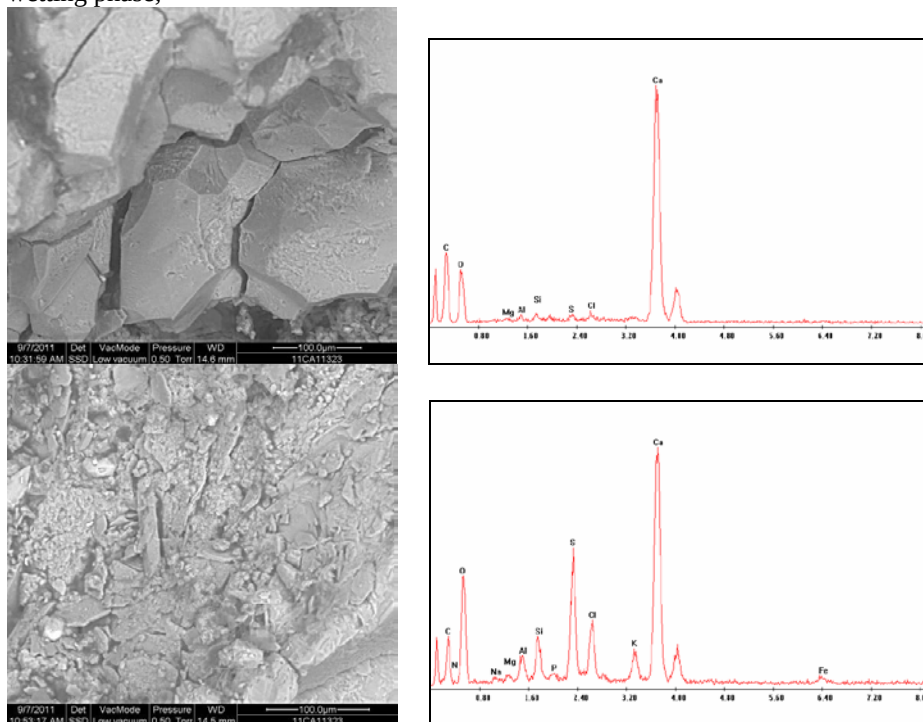


Fig. 10. a) level: marked micro-fissures in between calcite, b) EDS microanalysis enhancing mainly presence of calcium, c) small crystals of secondary gypsum formation, d) In addition to calcium, sulphur and chloride indicates the presence of gypsum and halite crystals coming respectively from atmospheric pollutants and rising damp of lagoon chloride-rich water.

The presence of gypsum crystals inside the marble can cause mechanical stresses inside the pores during the drying phase because crystallization causes expansion. To summarize, the mechanism of marble decay takes place in different steps (Fassina 2002):

- i) exposure to natural atmospheric thermal changes leading to a long-term effect of crystal de-cohesion (*physical alteration*);
- ii) penetration of sulphur-bearing solution into intergranular spaces (previously formed by thermal changes) and subsequent transformation of calcium carbonate into gypsum (*chemical alteration*);

iii) gypsum crystallization inside the pores due to the drying phase causes expansion and consequently mechanical stresses (*mechanical alteration*).

The first step is very slow and the time-scale for its occurrence is a hundred years. The second and third steps became important from the middle of the last century with an exponential relationship between time and damage effects. The time-scale for damage has been considerably reduced to a few decades.

The mechanism of marble deterioration that we are now proposing for marble artworks located in an indoor environment is more strongly influenced by capillary rising damp and the consequent salt migration of lagoon water than the outdoor influence of atmospheric sulphur-bearing solutions.

The ESEM observations and the microanalysis by EDS suggest that the mechanism of crystal decohesion and the consequent sugaring of calcite structure may have a different pathway which is manifesting as an exfoliation pattern that is generally common for sedimentary stone and follows the sedimentation layers, which are almost (more or less) parallel. Crystal decohesion, which was previously the first step in alteration, progresses forming a discontinuity line more or less parallel to the outside surface, a process that explains the layer exfoliation which is proceeding inwards from the outside layer of marble. We can define the process as multilayer exfoliation.

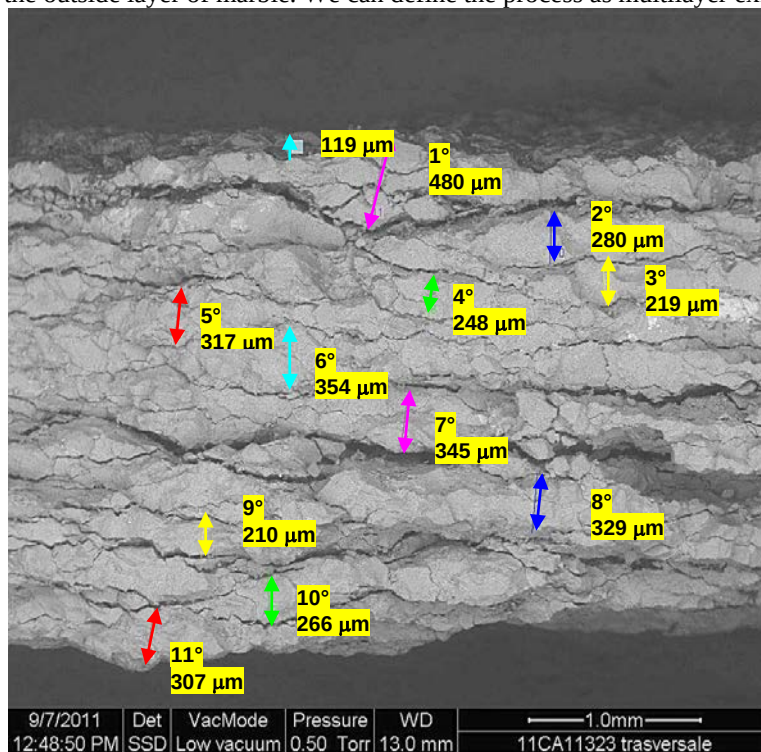


Fig. 11. The black layer (119 μm thick) on the outside surface is the wax treatment, the first layer is 480 μm thick and all the subsequent layers are about 300 μm. The total thickness is 3 mm.

To explain this unusual mechanism for marble decay it is important to take into account the intimate structure of marble and the process of its formation in geological times. Marble is a metamorphic rock with a granoblastic structure constituted mainly by different calcite grain size (60 a 800 μm), with an isotropic structure. Sometimes in unpure marble some veins, contaminated by silicatic or pyrite minerals, contained calcite crystals, with an isotropic structure, which are extended along a preferential orientation which was in turn generated by the metamorphic process.

These veins are responsible of preferential migration, both vertically and horizontally of lagoon water by capillarity. The source of salt solution is the brick supporting structure which is completely saturated with lagoon water. SEM observation showed a salt accumulation in these layers in a similar way of a sedimentary stone and the final result is an exfoliation process which is taking place at first on the external surface layer and successively is recessing in the internal layers as it clearly visible in fig. 11. The damage features actually observed showed an irregular front of the maximum height of the rising damp due to the orientation of these veins (horizontally or vertically oriented with respect to outside external surface) of the marble blocks of the step.

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DEVELOPING AN INTEGRATED DECISION MAKING SYSTEM FOR THE ASSESSMENT OF CLEANING INTERVENTIONS ON MARBLE ARCHITECTURAL SURFACES

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Abstract

In this work, the development of an integrated decision-making system for the assessment of cleaning interventions on marble architectural surfaces is presented. The suggested system resulted by the incorporation of a fuzzy logic model into GIS and its architecture includes: (a) a GIS based graphical user interface for features and attributes retrieval, management comparison, analysis and correlation; displaying the application site of the historic building under investigation, where decay diagnosis and pilot cleaning interventions took place; (b) a database, that contains all the required attribute data sets for the operation of the decision-making system, that is the recorded physical-chemical characteristics of marble surfaces, during different time periods (before and after cleaning); (c) a fuzzy logic model (Mamdani type) as solver, using for input variables cleaning assessment criteria, whereas output parameter is the cleaning performance index. This platform enables the constant response in relation to the cleaning performance under predefined assessment parameters and acceptance threshold levels in a pointed spatial entity and environmental conditions; developing an integrated decision-making system for the assessment of cleaning interventions. The suggested system is demonstrated in practice on marble surfaces of a historic building in Athens, Greece.

Keywords: cleaning, marble, modeling, decision making, fuzzy logic, gis, cultural heritage

1. Introduction

Cleaning is the par excellence non-reversible conservation intervention, and therefore the compatibility concept that should governs it, relies on the setting of a range of assessment criteria along with the determination of their acceptance threshold levels. In parallel, the decay that the applied cleaning interventions are appointed to remove, depends on the correlation of endogenous and exogenous parameters. Endogenous parameters focus on material physical-chemical characteristics, whereas exogenous parameters depend on surface location and orientation on building scale, protection

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degree from rain-wash and wind, as well as environmental conditions. Thus, the need for taking into consideration all the above-mentioned factors whenever cleaning interventions are to be assessed is high.

In the course of evolving a methodology for cleaning assessment on marble surfaces a fuzzy classification system was developed and successfully used (Delegou and Moropoulou 2008; Moropoulou *et al.* 2008). In this system, cleaning assessment criteria with corresponding parameters and their acceptance threshold levels were defined, based on the recording of the physical-chemical characteristics of the examined surfaces.

However, exogenous parameters were not included in the previous attempt, and therefore a tool to interrelate data between space (building, environment) and endogenous parameters (physical-chemical characteristics of the under investigation building material-surface), taking into account their variation over time, needs still to be addressed.

Within the framework of building pathology representation and building preservation, several scientific projects have investigated GIS potential (Salonia and Negri 2002; Inkpen *et al.* 2001; Moropoulou *et al.* 2005), due to its capabilities of recording, grouping, managing and analysing large volumes of spatially referenced data, as well as for the elaboration of data-bases and spatial data transformation and spatial analysis.

Therefore, the tool for correlating exogenous and endogenous parameters whenever cleaning interventions are to be assessed can be a GIS platform which can enable control and monitoring of the building surfaces under examination, through the processing of different background data like spatial and attribute data sets.

So, in this work an integrated decision-making system for the assessment of cleaning interventions on marble architectural surfaces is presented. The suggested system resulted by the incorporation of a fuzzy logic model into GIS thematic maps elaborated on focused working-scale, according to decay patterns and applied pilot cleaning interventions. The decision making system is demonstrated in practice on the scale of the representative investigation area of a capital of the National Archaeological Museum (NAM) historic building (Figure 1) in Athens, Greece, which presented the characteristic decay of black crust.

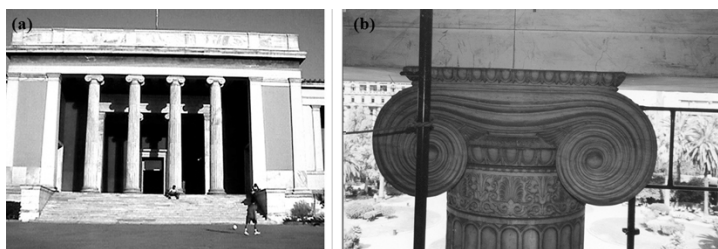


Figure 1. (a) The Historic building of National Archaeological Museum and (b) the representative investigation area of the capital

2. Methods

The following experimental techniques were used for decay diagnosis and the determination of the critical parameters of the cleaning assessment criteria:

Scanning Electron Microscopy with Energy Dispersion by X-ray Analysis (SEM-EDS) is applied on collected monument samples, before and after cleaning, using JEOL JSM-5600, OXFORD LINKTM ISISTM 300 with Energy Dispersive X-ray Microanalysis system, Accelerating Voltage 20 KV, Beam current: 0.5nA, Livetime: 50 sec, Beam diameter <2 μ m.

Digital Image Processing (DIP) of SEM images using the EDGE program which was developed by the US Geological Survey (Mosotti and Eldeeb 2000; Mosotti *et al.* 2002). EDGE program was developed for the analysis of back-scattered electron-micrograph images consisting of 512 rows with 512 pixels per row, where each pixel is encoded with 8 bits on a 256-shade gray-scale palette. The fractal dimension of the exposed surfaces of stone specimens cut in cross-section is measured, along with the near-surface fracture density (FD) of the stone which is a measure of the fraction of the stone volume filled by fractures, crevices, and pore space (Mosotti and Eldeeb 2000; Mosotti *et al.* 2002). The FD results are reported as the percentage of pixels identified as components of the fractures calculated until 100 μ m under the surface area.

Laser Profilometry (LP): 3-D micro-topography plots of the monument collected core samples were attained using the Proscan 2000 with a laser triangulation sensor of 1 μ m resolution. The roughness parameter Rq was estimated, according to BS EN ISO 4288:1988, whereas the ratio of actual to projected surface area was measured at each micro-topography.

Colorimetry: The Dr Lange color-pen LMG159/160 colorimeter, was applied in situ on the investigated marble surfaces, for measuring the L*, a*, b*, according to CIELab Uniform Color Space. Total color difference ΔE , was estimated according the ASTM D2244-93.

Moreover, the GIS thematic maps were elaborated in ArcMap/ArcInfo 9.2, using the CAD architectural drawings as the blueprint for the GIS base-map development.

Finally, a Mamdani type of fuzzy model (Mamdani 1974) was developed under Visual Studio using the C++ programming. Information flow through a fuzzy model requires that the input variables go through three major transformations before exiting the system as output information, which are known as fuzzification, fuzzy inference, and defuzzification (Vakalis *et al.* 2004; Moropoulou *et al.* 2008). The three steps are depicted in Figure 2, which shows the structure of a fuzzy logic model.

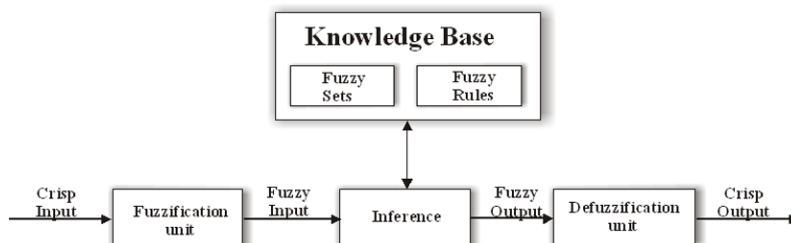


Figure 2. The structure of a typical fuzzy logic model

3. Results & Discussion

3.1 Architecture of the decision making system

The architecture of the suggested decision making system, as well as the information flow within the system are presented in the diagram of Figure 3.

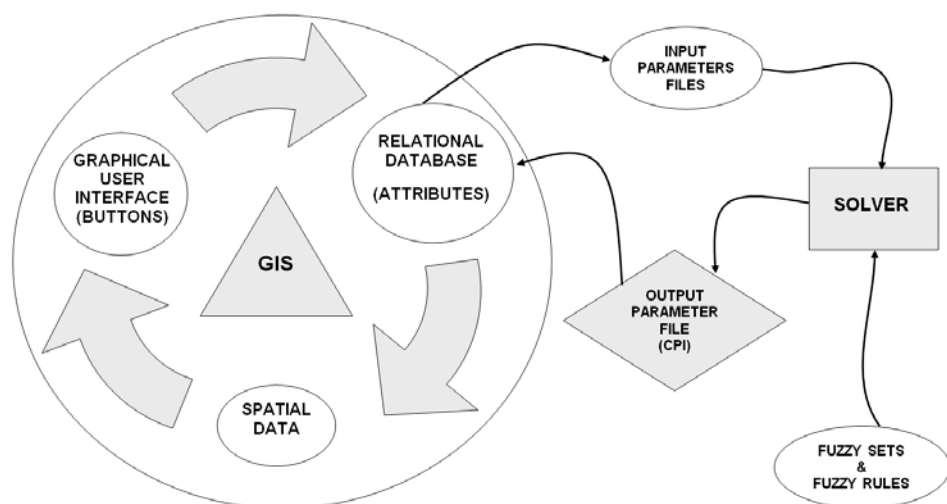


Figure 3. Architecture of the integrated decision making system for the assessment of cleaning performance

Two are the main parts of the suggested decision making system. The first one includes the GIS based graphical user interface for features and attributes retrieval, management, comparison, analysis and correlation. Spatial classification of decay and pilot cleaning interventions on the representative investigation areas, is taking place through the building of the thematic maps of decay and pilot cleaning interventions, respectively. Moreover, attribute databases consisting of physical-chemical characteristics' data are elaborated and linked to the attribute table of the corresponding GIS decay/pilot cleaning interventions' mapping project, thus resulting in relational databases (RDBs).

Finally, the thematic map of "conservation interventions' planning" is the resulting output theme of both decay and pilot cleaning interventions' thematic maps, after the application of the geo-processing analysis of the intersection operational tool. This new thematic map includes spatial information and attributes before and after cleaning; accomplishing comparison and analysis of the recorded to space physical-chemical characteristics of marble surfaces, during different time periods (Delegou *et al.* 2011).

The second main part of the suggested decision making system is the solver of the fuzzy logic model. The critical parameters of the cleaning assessment criteria are used as input parameters of the model, comprising in parallel data entries in the RDB of the thematic map of pilot cleaning interventions. As it is summarized in Figure 4, the input variables of the fuzzy model are (Moropoulou *et al.* 2008): (a) Patina preservation index-PPI (%), (SEM-EDS results); (b) Preservation index of gypsum layer-PIGy (%), (SEM-EDS results); (c) Fracture density, FD (%), (DIP of SEM images results); (d) Actual/Projected area ratio, r , (LP results); (e) Roughness (μm), (measured parameter: R_q ; LP results); (f) Total color difference, ΔE , (Colorimetry results). In both cases of the input parameters of "patina preservation index" and "preservation index of gypsum layer", input values are expressed in percentages, in order to have comparable input data for the fuzzy model from different surfaces of black crusts.

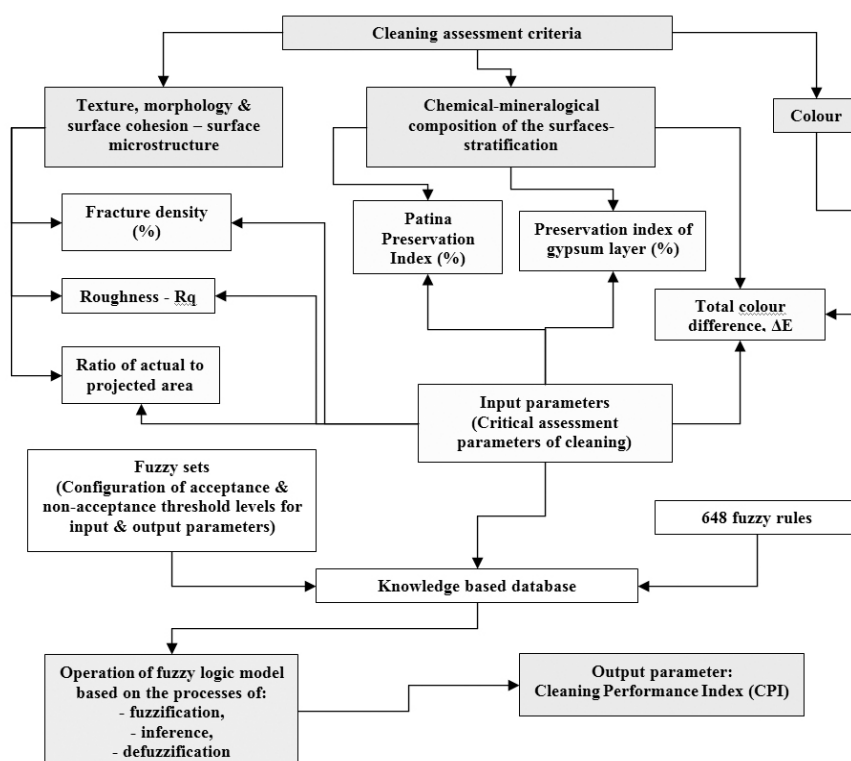


Figure 4. Flow chart presenting the development of the fuzzy logic model for the assessment of cleaning performance on black-grey crusts surfaces

Table 1. Definition of fuzzy sets for all input and output parameters of the fuzzy model

Input parameters– Output parameter	Definition of fuzzy sets			
	Low (0-70%), accepted		High (50-100%)	
Patina preservation index (%)	Low (0-40%)		High (50-100%), accepted	
Preservation index of gypsum layer (%) (PPI)	Low (0-40%)	Medium (30-70%)	High (50-100%), accepted	-
Fracture density (%) (FD)	Low (0-10%)	Medium (8-25%), accepted	High (18-35%)	Extra High (30-60%)
Ratio of actual to projected area (r)	Low (1-1.5)	Medium (1.25-3), accepted	High (2.5-4)	-
Roughness Rq (μm)	Low (0-10 μm)	Medium (5-20 μm), accepted	High (15-50 μm)	-
Total colour difference (ΔE)	Low (0-6)	Medium (5-15), accepted	High (13-40)	-
Output parameter: CPI	Non-accepted (0-4.5)	Medium (4-7.5)	Accepted (7-10)	Optimum-recommended (8-10)

In particular, quantitative and qualitative observations deriving from SEM-EDS regarding width, cohesion, continuity and homogeneity of patina/gypsum layer, are expressed in percentage in comparison to the corresponding data before cleaning applications. Therefore, variances of the examined layers in width and cohesion, from different areas or buildings can be classified in the designed fuzzy model.

During the development of the fuzzy sets the acceptance and non-acceptance threshold levels are configured for all input and output parameters, as shown in Table 1. Cleaning Performance Index (CPI) is defined as the output parameter, which classifies the cleaning interventions into non-accepted, medium, accepted and optimum-recommended ones.

Additionally, 648 “IF-THEN” fuzzy rules are developed using the logical operation “AND” (Moropoulou et al. 2008). Fuzzy rules development was based on the knowledge and experience that was acquired by the lab and in-field experimental results of 34 different and real scenarios of cleaned black crusted marble surfaces, taking under consideration the international bibliography of cleaning assessment thematic area, since an outcome should be given (output parameter–CPI) to each possible combination of each input parameter set. The operation of the fuzzy logic model was based on the processes of fuzzification, inference, and defuzzification.

It is worth-mentioning though that data movement within the system is accomplished by 2 intermediate files; the first extracts data from the RDB and the second loads and stores data into the RDB, after the code execution (Figure 3). In particular, the values of the critical cleaning assessment parameters (for every pilot cleaning intervention) are extracted from the corresponding fields of the RDB of the cleaning interventions’ thematic map to an intermediate file. This intermediate file feeds the solver (that is the fuzzy logic model) with the values of critical cleaning assessment parameters which are its input parameters. In succession, the executable code is retrieved, along with the fuzzy sets and the fuzzy rules whereas the results of the output variable (CPI) for every examined cleaning are stored into a new intermediate file. Data of this second intermediate file are retrieved by GIS and the CPI values are stored in the RDB of the thematic map of the conservation interventions’ planning. All the above mentioned operations are achieved by the user when the GIS graphical interface is employed along with the activation of two extra buttons specially created for the generation of the two intermediate files.

In addition, cartographic attribution of CPI sets into the spatial entities of the thematic map of conservation interventions’ planning can take place using the GIS capabilities. CPI is classified according to the threshold levels of the output parameter of the fuzzy logic model expressed though as crisp sets. Whenever CPI value changes set (because new data entries are imported into the RDB) the colour of the corresponding spatial entity (that is a cleaning intervention) automatically changes, indicating the new set under which the cleaning is classified.

3.2 Demonstration in practice: The case study of the historic building of National Archaeological Museum in Athens

Within the context of the above methodological approach, three representative marble surfaces of the NAM were selected to act as pilot projects for cleaning assessment, one of which is hereby presented. In neoclassical buildings like NAM,

marble is used as facings or load-bearing structures, presenting smooth or relief finishes. The representative marble surface of the capital was selected due to its high artistic value as a sculptured surface and the arising challenges on conservation issues for the preservation of relief surfaces. The capital under investigation is located on the first (from North) column of the propylon, has an eastern orientation, and is totally protected from rain-wash.

Decay and pilot cleaning data comprised the attribute data sets which describe the characteristics of the recorded spatial entities of the investigated surface. Therefore, ascribing the decay and cleaning results of the physical-chemical study to the features of the GIS base map, during building topology, led to the development of the thematic maps of decay and pilot cleaning interventions (Figure 5).

In decay thematic mapping each layer was classified and recorded according to its spatial properties and physical-chemical characteristics, before cleaning treatments. The sculptured surface of anthemion present front and side relief surfaces for which decay diagnosis results had indicated different physical-chemical characteristics like patina layer width and cohesion, gypsum layer width, roughness, surface area and fracture density. Therefore, two different layers were elaborated, one for each relief surface (front and side), which were displayed by light and dark grey respectively, along with 2 representative SEM images in Figure 5, left.

Furthermore, accordingly to the decay thematic map, two different layers were elaborated in the pilot cleaning interventions thematic map, one for each relief surface (front and side), whereas the areas of the pilot applications of the different cleaning methods were elaborated as features and displayed by different colours (Figure 5 right).

Moreover, attribute databases consisting of physical-chemical characteristics data were elaborated and linked to the attribute table of the corresponding GIS decay/pilot cleaning interventions' mapping project, resulting in relational databases (RDBs). In particular, the GIS attribute tables, which include topological characteristics like perimeter, area and adjacency info were linked with external databases, where data regarding petrography, chemical and mineralogical composition and stratification, total crust width, patina occurrence, macro-crystalline gypsum layer width, and micro-crystalline gypsum layer width (results of SEM-EDS); roughness R_q and Actual/Projected area ratio (LP results); fracture density (DIP of SEM images results); luminosity L , difference in red-green a^* , difference in blue-yellow b^* , and total colour difference ΔE (colorimetry results in CIELab colour space) were stored and classified. The databases were built using text and numerical elements as type of entries; whereas the data fragmentation permits the user to interrelate data regarding decay diagnosis and pilot cleaning interventions with the vector data, locating the info in a geometrically exact point or area, respecting the topological relationships among the various parts of the investigated surface. It is obvious that in the case of the RDB of the pilot cleaning thematic map the data of the critical cleaning assessment parameters are included as they comprise the input variables of the fuzzy model.

Using geoprocessing procedure and in particular the intersection operation tool for both decay and pilot cleaning interventions thematic maps, the resulting output theme is the conservation planning thematic map presented in Figure 6. This output theme contains combined spatial information and the aggregation of the attribute data of both decay and pilot cleaning intervention thematic maps.

Data movement across the integrated decision making system was accomplished by using the two extra buttons presented in Figure 7, specially created for the generation of 2 intermediate files. The activation of the first button extracts the values of the critical cleaning assessment parameters from the RDB of the pilot cleaning thematic map. The activation of the second button loads and stores the values of CPI into the RDB of the conservation planning thematic map, after the code execution. Some representative results from the test run of the fuzzy model are presented in Table 2.

CPI was classified according to the threshold levels of the output parameter of the fuzzy logic model expressed though as crisp sets, and displayed by different colours, as it is demonstrated in Table 3, and in Figure 8, left. When new data regarding the critical cleaning assessment parameters (which actually are the input parameters of the fuzzy logic model), give for the finally selected and applied cleaning intervention, values of $4.5 < \text{CPI} < 7$ (set of medium cleaning, mainly expressing the under-cleaning), then periodical conservation interventions on the marble surfaces of the investigated decay of black crust could be scheduled (Figure 8, right).

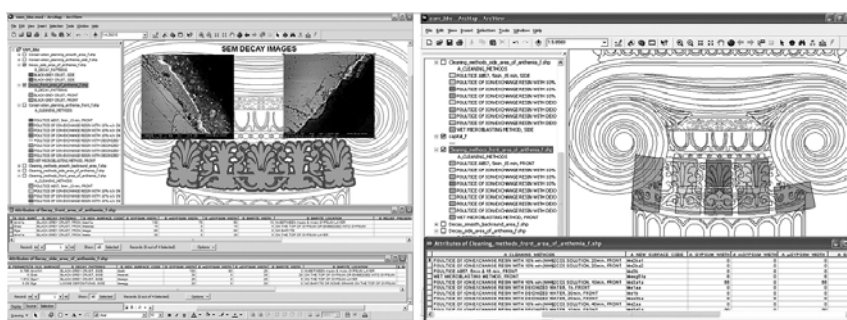


Figure 5. Thematic map of decay for the capital surface with corresponding RDBs and SEM decay images for both front and side anthemia surfaces (left). Thematic map of pilot cleaning interventions for the capital surface with the RDB of the front anthemia surface (right)

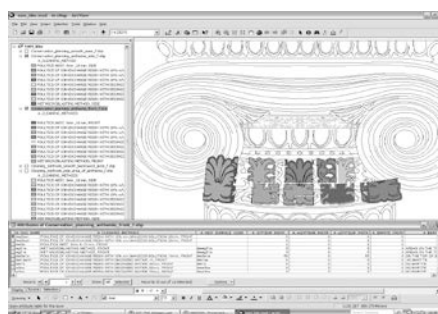


Figure 6. Thematic map of conservation interventions' planning for the capital surface with corresponding RDB



Figure 7. The two extra buttons specially created for the generation of the two intermediate files which permit data movement within the system

Table 2. Representative results of the fuzzy model. Values of crisp inputs (results of experimental techniques- critical assessment parameters of cleaning) – Values of output (CPI)

Pilot Cleaning Interventions	Values of Crisp Inputs-Results of experimental techniques						Output
	PPI (%)	PIGy (%)	FD (%)	r	Rq (μm)	ΔE	CPI
DS&NC ¹ (10min)	90	90	16.10	1.914	17	7.21	8.14
DS ² (10min)	25	80	23.10	1.542	11	9.56	6.62
AB57 ³ (5&15min)	1	1	11.20	1.740	10	15.30	3.36
Wet micro-blasting Method ⁴	65	70	36.60	2.593	30	6.48	6.65

¹: Poultice of ion-exchange resin with 10% w/v (NH₄)₂CO₃ solution; ²: Poultice of ion-exchange resin with deionized water; ³: Poultice AB57 (1lt deionized water, 30gr NH₄HCO₃, 50 gr NaHCO₃, 25 gr of bi-sodium EDTA, 10ml Desogen, 800gr sepiolite); ⁴: Wet micro-blasting method where spherical particles of calcium carbonate (diameter <80μm), were springing with a maximum function pressure of 0.5bar The proportion of water and spherical particles of calcium carbonate in the device's commixture barrel was 3:1.

Table 3. Classification of CPI

Colour	CPI Set	Description
Black	0<CPI<4.5	Non-accepted cleaning
Dark grey	4.5<CPI<7	Medium cleaning
Light grey	7<CPI<8	Accepted cleaning
Cross hatched	8<CPI<10	Optimum-recommended cleaning



Figure 8. Cartographic attribution of CPI sets into the spatial entities of the thematic map of conservation interventions' planning (left). Spatial entity of the cleaning intervention of ion exchange resin with (NH₄)₂CO₃ applied for 10 min, when CPI value changes from 8.14 (cross-hatched area in this Figure left) to 6.5 (dark grey area in this Figure right).

4. Conclusions

The development of an integrated decision making system for the assessment of cleaning interventions, with ultimate goal the scheduling of the periodical conservation

interventions, is presented. This system resulted by the incorporation of a fuzzy logic model into GIS, and it was successfully demonstrated in practice for the assessment of pilot cleaning interventions applied on black crusted marble surfaces. This platform enables the constant response in relation to the cleaning performance under predefined assessment parameters and acceptance threshold levels in a pointed spatial entity and environmental conditions.

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WINTER SHELTERS FOR MARBLE SCULPTURES OF THE SCHLOSSBRÜCKE BERLIN: CLIMATIC CONSTRAINTS

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Abstract

The long term exposure of marble objects leads to a successive deterioration of the rock fabric and may cause severe damage on cultural heritage objects. The magnitude of disintegration depends on the rock fabric as well as on the climatic conditions. Some types of marble show no considerable damage even if they have been exposed in northern Europe for several decades or centuries. Other types of marble are showing severe damage after a few years of weathering. The present study shows that marble decay, along with the initial thermal degradation, is mainly influenced by the hygric and thermo-hygric load, respectively. The influence of the rock fabric on the resistivity against weathering is also documented. The factors causing marble decay were compared to extensive climate data, which were collected during a scientific project that was started with the aim to develop a covering system for marble sculptures in Berlin. Based on the hygrothermal material properties of the marble and on the climatic conditions, the heat and moisture transport inside the material and hence the hygrothermal load changes were calculated with a high spatial resolution. The calculations showed that the temperature and moisture fluctuations inside the material are mainly controlled by the dimensions and orientation of the sculptural elements. The current state of preservation was investigated by two-dimensional ultrasonic tomography. The results show a good correlation to the calculated distribution of the hygrothermal load. Based on this finding, requirements on a protective winter shelter system for the sculptures were defined. The project results show that in addition to protective covers, regular inspection and maintenance combined with regular cleaning ensures an effective and sustainable protection of marble objects in northern Europe.

Keywords: Schlossbrücke, marble decay, weathering processes, ultrasound wave velocities, climate impact, numerical simulation, maintenance

Introduction

The “Schlossbrücke” over the Spree Canal is situated in the centre of Berlin on the edge of the Museum Island, a UNESCO world cultural heritage site. It provides a traffic link between Unter den Linden, the Lustgarten (Pleasure Garden) and the former Berlin Palace. Eight monumental sculptural groups made of Carrara marble border the bridge on high pedestals. The central concern is the in situ preservation of these historical and valuable sculptures. Due to their long exposure to the elements the sculptures now show signs of considerable damage. Empirical findings show that even a traditional wooden

cover reduces the damage to the sculptures. No scientific study has been done on the weather-dependent moisture penetration and the climatic conditions in such protective enclosures or on the damages to marbles related to the effect of weathering processes. An inter-disciplinary model project – supported by the Deutsche Bundesstiftung Umwelt (DBU) - was planned with the aim of developing an innovative winter covering system for these marble statues (Rieffel et al. 2010). It included a detailed evaluation of the restoration history, the current condition of the sculptures as well as a distinct climate monitoring and a numerical modelling of the effect of different winter shelter systems on the microclimate inside.

1. History of the sculptures

In the beginning of the 20th century Berlin was one of the capitals that displayed the most public monuments in Europe. The “Schlossbrücke” with the sculpture ensemble was constructed between 1822 and 1824 in the classical style according to a design by Karl Friedrich Schinkel. The theme of the eight sculptures is to create larger than life representations of ancient goddesses with young warriors. The Schlossbrücke ensemble of sculptures made from Carrara marble evokes the feeling of the Ponte Sant’Angelo Bridge in Rome. It can be considered an excellent example of the 19th century Berlin School of Sculpture, which attained a European wide reputation. When compared internationally, these figures belong to one of the most elaborate sculptural assemblies created from this period.

The sculptures were constructed during the period from 1842-1857 using the “best second grade Carrara marble (Ravacione)” by sculptors from the Schadow and Rauch School. In the period between 1855 and 1916 a regular maintenance and cleaning of the sculptures is documented. They were treated with a coating of soluble glass, with an emulsion wash and they were cleaned regularly with Venetian soap (saponified olive oil). Up to 1943 no further work on the figures is documented, and a comparison of historical photographs shows that regular cleaning and care of the statues was no longer carried out. The condition of the figures deteriorated progressively, and in places they were distinctly blackened. In 1943, the sculptures were stored at various locations in the western part of the city to protect them from war damage. The transport and the poor storage conditions led to significant damage of the sculptures. At the end of the 1960s, the sculptures were reassembled again, stored under a shelter and missing parts were replaced. From 1978, they were stored in a “lapidarium” to protect them from weathering. After the sculptures were returned from West Berlin to the GDR in 1981, they were cleaned, reinforced with silicone resin and treated hydrophobically. In 1983/84 they had been erected at the original location. During a restoration work in 1992/93, the silicone resin coating was removed abrasively by microblasting. In 2007, a careful restoration program began. It was based on a minimal intervention concept.



Figure 1: Centre:
Historical photo of
the “Schlossbrücke”
before 1857. One
sculpture (to the left)
has not yet been
assembled in this
view.
Small pictures:
Current state of the
sculptures. The
photos are arranged
in the same order as
the sculptures in the
historical photo.

2. Marble weathering

The degradation process of the marble started about 150 years before when the sculptures were assembled on the Schlossbrücke. The initial degradation is caused by thermal dilatation processes. Calcite shows a pronounced anisotropy of the thermal expansion coefficient in different crystallographic directions (Kleber 1959). This leads to stresses inside the material during temperature changes. When these stresses exceed the threshold of cohesion, a non-reversible deterioration is observed which is not limited to the surface. Depending on the rock fabric the formation of microcracks results in non-reversible changes in length (Kessler 1919). Even small temperature changes of 20–50°C may result in damage (Battaglia et al. 1993), but this process stops after a few heating cycles if moisture is absent (e.g. Sage 1988; Koch and Siegesmund 2004). In the presence of water, a progressive residual strain, indicating an increasing deterioration, is observed on thermally treated marbles (Siegesmund et al. 2007, 2008). Within the project, a Carrara marble was treated thermally at four cycles (20°C – 60°C – 20°C)

under dry conditions, followed by five heating cycles at 60 % relative humidity and 90% relative humidity for the next eight cycles. The measured residual strain (Fig. 3) indicates that a progressive deterioration also occurs at high air humidity without the presence of liquid water.

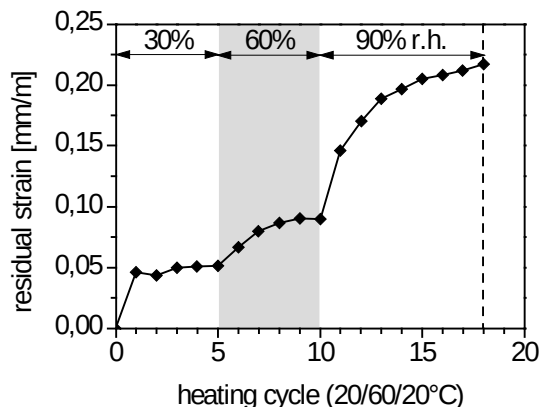


Figure 2: Residual strain of a marble comparable to the marble of the sculptures during thermal treatment under different moisture conditions.

The hygro-thermal deterioration is limited to a zone near the surface where the influence of the environmental conditions on the amplitude of material moisture changes is significant.

For a fresh Carrara marble freeze-thaw action plays a secondary part and chemical solution processes just roughen the surface if the matrix is dense. These processes accelerate the subsurface deterioration process, but not until the cracks are open to a certain extent and the capillary water uptake increases (Ondrasina et al. 2002; Ruedrich 2003).

3. Present condition of the sculptures

The macroscopic fabrics of the marbles show a bright white color and irregular dark grey veins which are typical for Carrara material. The veins have no preferred orientation and they range in width from 0.3 to 1.0 cm. Two samples were drilled out from the plinths of two sculptures on the south side of the bridge in order to estimate the microfabric and the petrophysical characteristics. The grain fabric of these samples is nearly equigranular polygonal with a grain size between 20 and 600 μm , but frequently the grain size is around 180 μm . Compared to Carrara marbles, which usually have an effective porosity of around 0.2 Vol.-% (e.g. Weiss et al. 2000), a porosity of 0.5 Vol.-% in both samples is significantly greater.

As a result of their eventful history and their long exposition time the sculptures show considerable signs of damage. Significant mechanical damage was caused by the incorrect transport and storage during World War II. These damages have been repaired and missing parts have been replaced. In general, the back-weathering of the original material is moderate. The surface locally shows a pronounced roughness and in some areas a sugar-like crumbling. In these parts, the marble fabric is strongly deteriorated. Even if the sculptures were carefully cleaned in 2009, the surfaces have shown a pronounced biological colonization. In areas of increased roughness the biofilm penetrates deep into the microcracks and accelerates the deterioration.

The structural integration of the sculptures was assessed by measurements of the ultrasonic velocities. Figure 3 shows the results for the sculpture on the south-west side. According to a damage classification for Carrara marble presented by (Köhler 1991, Siegesmund & Snethlage, 2011), the condition of the sculptures can be described in the following way: massive parts with diameters above 15 cm show ultrasonic velocities between 3 and 4 km/s. The condition of these parts can be classified as „increasingly porous“. The ultrasonic velocities of more filigree elements with a thickness below 15 cm such as the wings of Nike or the arms and legs typically range between 2 and 3 km/s. After the classification by Köhler these parts can be designated as “sugar-like disintegrated”. Therefore, the sculpture can be classified as distinctly deteriorated, but the stability is not in acute danger. The distribution of the ultrasonic velocities in general points to the conclusion that the deterioration is more distinctive near the surface (Fig. 3). The results are representative for all sculptures of the Schlossbrücke, except one sculpture, which is in a critical condition.

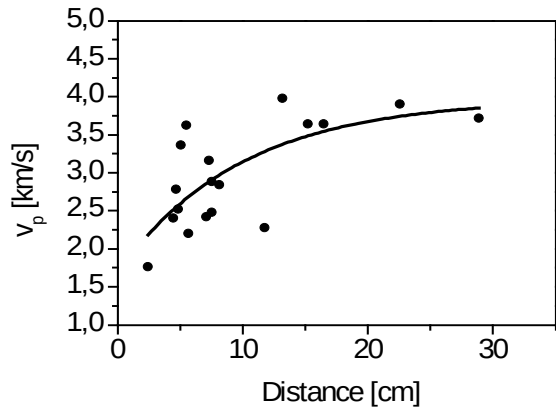
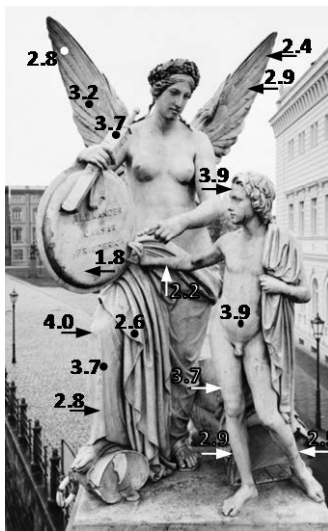


Figure 3: Results of the ultrasonic measurements on the sculpture on the south-west side of the bridge. The ultrasonic velocities are given in km/s. The comparison of the velocities and measurement distances clearly show that the deterioration is more pronounced on filigree parts.

A drilling core was taken from a vertically oriented surface of the sculpture on the south-east side of the bridge. The x-ray computed tomography (Fig. 4) clearly shows a distinct damage profile. Near the surface strong microcrack deterioration parallel to the surface can be observed.

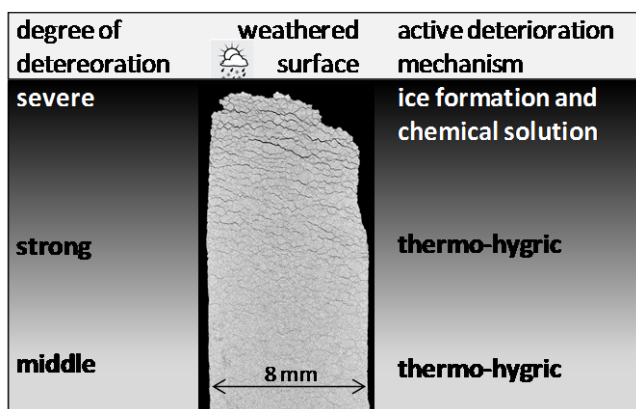


Figure 4: The x-ray ct-image of a drilling core shows a pronounced damage profile with a distinct cracking near the surface. The condition of the material is related to the depth and to the assumed deterioration mechanism.

4. Climatic conditions

The current state of preservation of the marble sculptures is a result of their long term exposure to the climate. Figure 4 illustrates the weathering history of the Schlossbrücke. The present data originates from a meteorological station in Potsdam, located about 30 km south-west of the Schlossbrücke. They are available freely from the German Meteorological Service (DWD 2012). Since 1893, air temperatures range from -25°C in the winter up to 40°C in the summer. This represents a temperature span of about 65°C. During their exposure on the bridge, the sculptures may experience about 140 air temperature fluctuations ranging from -15°C to 30°C. Even under dry conditions these temperature fluctuations led to a deterioration that also affects voluminous parts of the sculptures. Besides these long term fluctuations, the daily temperature changes also play an important role. Since 1893, on more than 4500 days the difference between the temperature maximum and minimum is greater than 15 K, and on more than 20,000 days it exceeds 10 K. In combination with the air humidity, that typically ranges from 50 % to 95% in summer and 75% and 95% in winter, these high number of temperature fluctuations is responsible for the high degree of deterioration in the near surface zone. Due to the partially increased porosity, the surface is locally sensitive to freeze-thaw action. The climate data from Potsdam show that during the last 120 years on more than 700 days the temperature decreased from +1°C to -5°C and on about 1600 days the maximum temperature was below -3°C. Therefore, the impact of freeze-thaw action is not negligible.

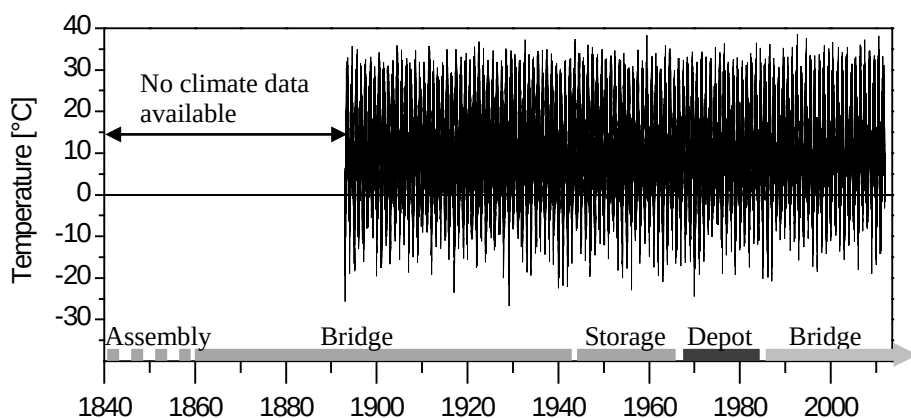


Figure 5: Daily maximum and minimum air temperature in Potsdam (data based on (DWD 2012)) compared to the exposition history of the sculptures at the Schlossbrücke in Berlin.

In order to acquire more detailed information for the project, an extensive climate monitoring was operated for three years. Generally, local climate data such as air temperature, relative humidity, wind speed and global radiation as well as surface temperatures and surface humidity were measured at three sculptures. The comparison to the climate data from Potsdam in the same period shows a good correlation.

The data show that the surface temperature of the sculptures is determined by the temperature of the surrounding air and by the global radiation. But the influence of the solar radiation is lower than expected. In winter the difference between the surface temperature on the north and south side did not exceed 4 K, and also in the summer the maximum surface temperature difference was below 10 K. However, it also has to be considered that the surface during the measurements was clean and white. In historical periods when the surface was blackened by air pollution, the impact of the solar radiation may be higher.

The combination of thermal and hygric fluctuations is the most important driving force for marble deterioration. The measured climate data shows that during the spring and summer, when the daily temperature rise is the highest, the surface temperature of the sculptures almost every morning falls below the dew point.

Figure 6 illustrates an additional phenomenon that accelerates marble degradation. On the 3rd of July 2009, the air temperature on this sunny day increased from about 20°C in the morning to about 30°C in the afternoon. At the same time, the surface temperature on the west side increased from 20 to 35°C. In the afternoon, the temperature on the west side suddenly decreased to 27°C within 1 h. The reason is a sudden rain shower. After the rain, the temperature again reached up to 30°C and the surfaces dried. Events like this may be relatively rare but they are significant for marble deterioration. On the afternoon of the 4th of July 2009 it started raining again, but due to the temporarily overcast condition, the temperature drop was less abrupt.

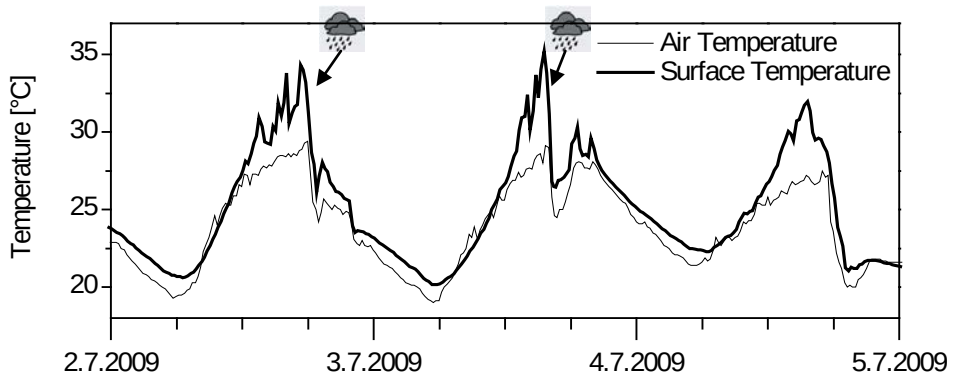


Figure 6: Air and surface temperature measured on the sculpture at the south-west side of the bridge at the beginning of July 2009. Sudden temperature drops are due to driving rain.

5. Numerical simulation of heat and moisture transport

The basis for the simulation of environmentally dependent heat and moisture transport inside the sculptures are the hygrothermal material properties of the marble. Since a complete determination of the material functions requires numerous samples, the valuable original Carrara marble of the sculptures cannot be sampled in the required amount. Therefore, a comparable Carrara marble has been selected for the measurements, representing the inner parts of the sculptures. Due to the increased deterioration and to historical conservation treatment, the marble surface shows different properties. Two small samples of the original marble were used for the estimation of the surface properties.

The complex geometry of the sculptures does not allow the simulation of all the details. Thus, in the numerical model the sculpture is represented by elements like arms and a head with a smaller diameter and a massive torso and strong legs.

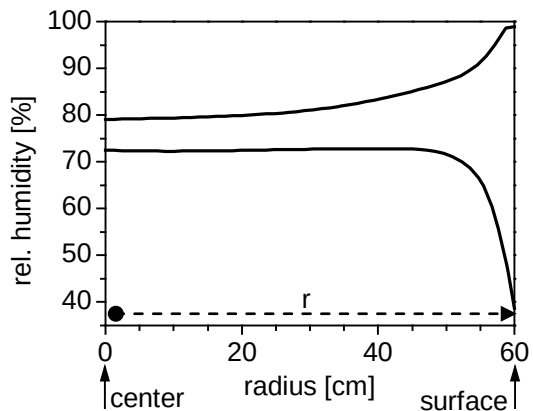
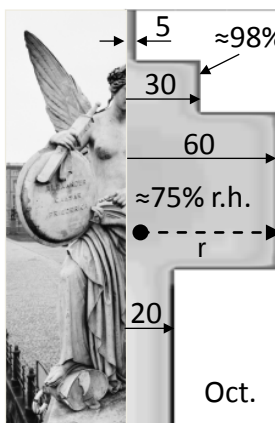


Figure 7: Calculated moisture distribution for October in a numerical model of a sculpture (left) and moisture fluctuation (minimum and maximum) from October to April along the cross section (r) of the torso.

In the first step, the temperature and moisture distribution within a freely exposed sculpture were calculated (Fig. 7) based on the climate data from Potsdam. The results of the simulation clearly show that the moisture fluctuation inside massive sculptural parts are relatively low, whereas the moisture within around 5 cm below the surface ranges between 40 and nearly 100 % relative humidity. In regards to the deterioration mechanism mentioned above, this is in a good agreement with the present condition of the sculptures.

In the second step, the microclimate inside of different types of winter shelter systems and their effect on the sculptures were calculated. Different influence factors such as the air ventilation rate inside the shelter, the diffusion coefficient and reflectivity of the walls were varied. The output functions of these models are very complex and they show that the different studied design concepts have individual advantages and disadvantages. In order to find the optimal design for winter shelters for the sculptures on the Schlossbrücke, a system of five performance indicators have been developed. These indicators, describing the thermal and hygric treatment of the marble, should be minimized by the design concept of the shelter. Regarding the technical limitations, the evaluation of numerous simulation results implies that a shelter with an airtight and opaque membrane skin provides the best protection against weathering.

6. Care and Maintenance

Today public monuments are not maintained on a regular basis. Instead, the already damaged or endangered sculptures and statues are restored at great cost, only to be abandoned after these restoration measures have been completed. In the long term, however, continuous maintenance proves more economical - and more appropriate to the value of the objects - as monuments and as art - than extensive, costly restoration measures, which always go along with a loss of authenticity and originality.

In addition to protective covers, only regular inspection and maintenance ensures an effective and sustainable protection of marble objects in northern Europe. Such a maintenance program is the precondition for preserving the sculptures on the Schlossbrücke as a historical ensemble. Therefore, the Berlin State Office for the Preservation of Historical Monuments decided to initiate long-term maintenance work at regular intervals on the public statues in the centre of the city as a pilot project because of their outstanding artistic, historical and urban value. The maintenance concept developed by the public restoration office comprises a multi-phase, systematic time schedule and was introduced in 2009.

For this purpose, a specific plan was developed for 30 statues. In general, it comprises the documentation of the condition (mapping, photos), a regular inspection once a year (check-list), maintenance according to requirements of the fabric including regular cleaning, anti-graffiti coating, and - last but not least - preventive measures to protect the objects by a fence and winter covers. As a result of the inspection, the necessary measures required can be carried out depending upon what is demanded in the short, medium or long-term situation.

7. Summary

The Schlossbrücke is one element of the historical sculptural ensemble in the centre of Berlin. The central concern for conservators is the in situ preservation of the culturally and historically significant sculptures of the bridge. The goal of the project

presented in this paper was to develop a winter sheltering system, with regards to the complex interaction between the marble, the deterioration mechanisms and the climate.

The study involved a detailed documentation of the conservation history, the ascertainment of historical and current local climate conditions, the assessment of the current condition of the sculptures and investigations on marble deterioration from a geoscientific point of view. Along with these findings, many numerical simulations of the effect of different shelter systems on the microclimate around the sculptures were done. The requirements for an effective shelter system are formulated on the basis of these results. The project shows that winter shelters are a reasonable measure for protecting marble sculptures, but the results also point out that the local climatic loads during spring, summer and autumn are significant for marble disintegration.

Since it is not possible or desirable to cover the sculptures all year around, a regular inspection and maintenance program is essential.

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