CONSERVATION
of Historic Brick Structures

EDITED BY
N.S. BAER, S. FITZ AND R.A. LIVINGSTON
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Conservation of Historic Brick Structures

Case Studies and Reports of Research

Edited by

N.S. Baer, S. Fitz, and R.A. Livingston

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Preface

The present work finds its origins in a NATO-CCMS Pilot Study entitled, “The Conservation of Historic Brick Buildings and Monuments.”

In addition to its military component, NATO has several nonmilitary committees. The Science Committee, formed in 1959, operates an extensive program of international study institutes, research workshops and collaborative research in many areas. Because of its success in promoting cooperation among the NATO member countries, it was recommended that the concept be extended to other aspects of civilian life. The Committee on the Challenges of Modern Society (CCMS) was established in 1969 to study issues affecting the physical and social environment (Campbell 1979). The work of CCMS is decentralized with projects called Pilot Studies carried out by groups of NATO countries that provide their own resources. Pilot studies have been conducted on a wide range of topics ranging from air pollution modeling to emergency medical evacuation. In 1979, CCMS undertook its first Pilot Study in the cultural field on the conservation of stone monuments (NAS 1982). At the conclusion of that Pilot Study, several recommendations were made for further work, among them the conservation of historic brick structures (NATO 1985). In September, 1986, representatives of West Germany, The Netherlands, Norway, Portugal, Spain, and the United States met in Brussels to draft a broad outline for a future Pilot Study on the Conservation of Brick Buildings (NATO-CCMS 1986).

The suggestion of a Pilot Study on brick conservation was embraced by West Germany. A proposal was prepared and accepted by CCMS on May 11, 1987 (Appendix I). Five major topics were identified in the proposal:

1. Development of an Atlas of Damage to Historic Brick Structures,
2. Diagnosis of Damage,
3. Field and Accelerated Aging Tests,
4. Instrumental Methods Development and Standardization of Procedures with Emphasis on Non-Destructive Testing,
5. Treatment and Conservation Methods.

It was recognized that a brick building does not consist of bricks alone, but rather is a system composed of the bricks themselves, the mortar, and in many cases, a plaster rendering or stucco covering the surface of the brick.

West Germany assumed leadership of the Pilot Study, designating the Umweltbundesamt (Federal Environmental Agency) in Berlin as the coordinating agency. Participants came from Belgium, East Germany, The Netherlands, Norway, Italy, Turkey, Great Britain, and the United States.

One of the remarkable aspects of the Pilot Study was its witness to history as “the Wall” proved less durable than the Pilot Study. From the first Experts Meeting held in
1987 at the facilities of the Umweltbundesamt, in what was then West Berlin, to the 8th and final meeting in 1994 in Leuven, Belgium (see Appendix II for a complete listing of the dates and venues of the Experts Meetings), the political landscape of Europe was transformed.

The meeting in Leuven also marked a significant further development in the conservation of historic brick structures as it coincided with a major conference organized by DG-XII of the European Commission, marking an important source of support for research in this area.

It had been the custom of the Pilot Study Coordinator to prepare Postprints of the papers presented at the Experts Meetings. These postprint papers, revised and supplemented with new results, are the basis for the individual case studies and research reports that form the chapters of this book.

In 1997, Blaine Cliver, a participant at several of the Experts Meetings, observed that the papers in the postprints contained a wealth of useful information but were generally unavailable to an audience beyond the participants. He suggested that they be edited and consolidated in a single volume. This book is a direct consequence of his initiative.

--- Norbert S. Baer, Stephan Fitz, Richard A. Livingston, editors

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REFERENCES


Introduction

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Brick has been used as a building material since ancient times and is the construction material for many historic buildings in Europe and the United States. Among the causes of damage to brick are air pollution, acid rain, biodeterioration, salts, and freeze-thaw cycles. Although conservation of this form of the architectural heritage is a high priority, relatively little scientific research has been undertaken concerning the deterioration of this material, especially in comparison to the vast resources devoted to the study of stone deterioration.

As reviewed in the Preface, a NATO-CCMS Pilot Study, coordinated by the Umweltbundesamt (German Environmental Protection Agency), encouraged research efforts on the conservation of historic brick structures in five areas:

1. Development of an Atlas of Damage to historic brick structures,
2. Diagnosis of damage,
3. Field and accelerated aging tests,
4. Development of instrumental methods and standardization of procedures with emphasis on nondestructive testing,
5. Treatment and conservation methods.

The thirty-nine chapters that follow report on the results achieved by the participants in the Pilot Study. Although the Pilot Study has concluded, the programs begun under its aegis continue under other sponsorship, principally that of the European Community. While this volume represents a significant advance in our knowledge base for the conservation of historic brick structures, it also represents a research agenda as the individual research papers identify topics for future study. In the following discussion, organized by the five research areas listed above, a number of these research opportunities are described.
ATLAS OF BRICK DAMAGE

The Atlas, initially intended as a stand alone descriptive tool, has become an integral part of an expanded effort (Van Balen 1997) to develop a Masonry Damage Diagnostic System (MDDS). The Atlas provides descriptions and characterizations of the state of historic brick structures and of the materials themselves. It serves as the basis for:

- Identification of the causes of damage,
- Documentation of the extent of damage to a given building,
- Determination of appropriate treatment methods.

The development of the Atlas consisted of two steps. The first was the compilation of a standardized list of characteristic symptoms of brick and mortar deterioration, including photographs of each type of damage at various stages of the deterioration process, as well as verbal descriptions.

The second aspect involved the application of the Atlas to a survey of a number of historic brick buildings in Europe. Extensive documentation was made for each building. This included:

1. Characterization of the chemical composition and physical condition of the materials and structure, as well as any deterioration products, using an array of geological, physical, and chemical methods.
2. Characterization of the environmental influences on the building, such as air pollution, biodeterioration, microclimate, and soluble salts.
3. Description of the structural condition of the building, including design, foundations, settling, etc.
4. Historical documentation including former uses, major damages due to fire, flood, war, etc., and major repairs.
5. Mapping of the extent of damage.

Van Balen (Chapter 12) provides an introduction to the Atlas and a completed questionnaire for a historic brick structure in Belgium. The MDDS and Atlas show considerable promise as possible teaching aids, e.g., the user may follow the logical sequence leading to a diagnosis for an example of damage to a monument illustrated in the Atlas.

A projected further application of the system incorporating proposed treatment strategies is in development.

DIAGNOSIS OF DAMAGE

This part of the Pilot Study concerned improvements in the ability to diagnose the causes of damage through a better knowledge of the damage processes themselves. These papers and the associated case studies include research on the mechanisms through which environmental agents produce damage. The influence of the composition of materials and workmanship on the damage process was also investigated. This
kind of research requires the use of a wide range of techniques beyond the resources of a single laboratory and so the work was shared internationally among a number of laboratories.

For mortars, the research was led by Middendorf and Knöfel of the University of Siegen, [West] Germany. This covered the chemical and mineralogical examination of samples of historic mortars for such factors as:

- Type of binder, e.g., gypsum, lime, Portland cement,
- Proportions of binders and aggregates,
- Nature of the aggregates,
- Admixtures including salts or organic compounds.

Physical properties of the mortar samples including:

- Elastic modulus,
- Swelling value,
- Strength of mortar,
- Porosity and water absorption.

Chapters 17 and 18 report on this work to characterize ancient lime and gypsum mortars from Germany and the Netherlands. In an appendix (17.1), the authors present in flow chart format a comprehensive approach to the chemical-mineralogical characterization of mortars. Further results on ancient mortar specimens from historic monuments in Turkey are reported by Gülçe (Chapter 19). Included are calcination analyses, porosimetric data, and photomicrographs documenting petrographic examination.

In an extensive series of studies on renderings, Hoffmann and Niesel describe their work on the effects of air pollutants (Chapter 22), the effects of orientation, and the development of specific reaction zones in the field (Chapter 23). In an introductory chapter (21), they detail their experimental protocols and the background to their study. To place the several studies of air pollution effects in context, Fitz (Chapter 20) reviews trends in air pollution in Germany. As has been observed in many of the developed nations, sulfur dioxide emissions are in substantial decline while oxides of nitrogen are increasing, complicating the analysis of retrospective damage studies. Arnold (Chapter 39) examines historic renderings on churches in Brandenburg. Interactions between the mortar and the brick were studied by Franke and Grabau (Chapter 15), Elsen (Chapter 16), and Hoffmann and Niesel (Chapter 31).

The study of the bricks themselves involved cooperation among the Technical University of Hamburg-Harburg, the Turkish National Museum, the Architectural Conservation Laboratory of Venice, the National Institute of Standards and Technology (U.S.), and the University of Maryland. Samples of bricks from a number of sites in Hamburg and in Lübeck were obtained and analyzed by a variety of chemical and mineralogical methods, including X-ray diffraction (XRD), X-ray fluorescence, optical microscopy, and SEM. Additional samples from Istanbul, Venice, Amsterdam,
Antwerp, and Copenhagen were collected. In the United States, samples were obtained from Colonial Williamsburg, Annapolis, and St. Mary’s City, Maryland.

Among the studies were the subsequent determinations of the firing temperature of brick (Franke and Schumann, Chapter 3). The authors also provided a brief history of brickmaking in northern Germany (Chapter 2). In a related study (Chapter 11), Livingston and co-workers attempted to develop a durability index based on the ratio of cristobalite/quartz XRD intensities. While in agreement with durability observations for bricks from Colonial Williamsburg, the technique proved inapplicable to historic German brick. The study suggested that there was a fundamental difference in the mineralogy of German brick when compared to that of this example of American brick.

As with the mortar analysis, the purpose of the Diagnosis of Damage part of the study was to characterize the brick damage as a function of materials properties including:

- Chemical composition of fluxes, e.g., K, Na, Ca,
- Nature and proportion of nonplastics, e.g., quartz grains,
- Presence of minerals formed during firing, e.g., plagioclase,
- Pore-size distribution.

Manufacturing practices, such as the addition of salt to the brick, were investigated for their influence on durability (Chapters 3 and 11). The presence of damaging salts, such as sulfates and nitrates from air pollutants, chlorides from deicing salts or sea water, and carbonates from grouting, was the subject of several studies (Chapters 6, 7, 15, and 24). Guillitte (Chapter 8) reviews the vegetation and bioreceptivity of brick structures, observing that moisture is the main factor in determining kinetics, biomass, and composition. Biodeterioration, including scaling, cracking of brick, peeling and crumbling of mortar, and disjointing, are ascribed to the main organisms which colonize brick structures.

FIELD AND ACCELERATED LABORATORY TESTS

Work to develop quantitative relations that describe the rate of damage as a function of time and the intensity of the agent of damage was done through a combination of exposures at field sites and accelerated aging tests in the laboratory (Chapters 4, 5, 6, 8, 13, 22, and 23). The laboratory tests provide a way to isolate the effect of one cause of damage, e.g., SO₂, while keeping all others constant. The field tests, on the other hand, provide confirmation of the damage functions in the real world (Livingston 1997). Of particular note is the attempt to achieve levels of environmental characterization comparable to those of the laboratory while retaining the benefits of field exposure by constructing full-scale models (Chapter 13). Binda and her group introduced moisture and salts under carefully controlled and monitored conditions. These data, combined with detailed monitoring of the decay process, produced significant results while developing important new test methods.
DEVELOPMENT OF INSTRUMENTAL METHODS 
AND STANDARDIZATION OF PROCEDURES

A major objective of the Pilot Study was the application of advanced methods of materials science to historic brick problems. The feasibility of each of the methods for the analysis of brick and mortar needed to be evaluated, requiring testing on specimens of known characteristics. Once feasibility was established, the procedures were to be standardized so the results from one laboratory would be comparable to those of another. Results are reported on a range of NDT methods including acoustic tomography (Chapter 10), XRD (Chapter 11), neutron scattering (Chapter 14), and physical methods (Chapters 9 and 13). Of particular interest is the use of acoustic tomography to follow the course of an injection grouting repair to a test pier (Chapter 10). Nappi and Côte (1997), in their parallel review of NDT methods applied to stone masonry, give similar examples of the use of ultrasonic tomography in evaluating the effectiveness of injection grouting in consolidating deteriorated stone in such monuments as a bell tower in Chioggia, Italy, and the Pont Neuf, Paris.

A special need in this area is a standardized method for measuring brick durability. The reliability of tests involving sodium sulfate crystallization has been questioned. Cyclic freeze-thaw tests also have problems (Ritchie 1979). A most promising durability test method is the Clemens Hardness Tester used by the Royal Institute for Cultural Heritage in Brussels (De Witte et al. 1977). Another technique based on abrasion measurements was developed by the [West] German Federal Institute for Materials Research and Testing (UBA 1988).

In addition to measurement methods, other aspects also need to be standardized. These include procedures for taking samples, and for preparing them for testing in the field or in the laboratory. Standard protocols for measurement of environmental factors are also necessary.

Finally, of particular interest is the development of portable equipment that can be used in the field to make nondestructive tests. Among these are portable X-ray fluorescence, the neutron probe, infrared thermography, ground penetrating radar, and a number of sonic methods (Livingston and Frassetto 1987). Several of these methods were evaluated in the United States, using an historic brick building in Colonial Williamsburg (Chapter 37).

TREATMENT AND CONSERVATION METHODS

After the damage problem at a given building has been correctly diagnosed, decisions must be made about the best way to deal with it. Alternatives include application of treatments such as water repellents or consolidants. Other possible actions may include the installation of waterproof barriers to prevent rising groundwater in the walls. Methods of removing salt from contaminated brick walls are reviewed by Friese (Chapter 29) and a number of case studies deal with the effects of salts and approaches
to desalination (Chapters 32, 34, 37, 40). Most dramatic is the preservation challenge presented by the brick grinding house and other structures of a potash mine with huge salt depositions in the brick fabric (Chapter 40). Here the quantities of salt are thought to preclude desalination, leading to a decision to rely on internal climate control to arrest salt migration.

Specific conservation treatments are examined for adobe brick (Chapter 25), water-repellent treatment of an exposed brick facade (Chapter 26), the development of water-resistant mortars (Chapter 27), and injection grouting (Chapter 28).

It is often necessary in the conservation of an historic structure to replace missing brick or mortar. The analytical methods described above for diagnosis of damage can also be applied to determine the brick or mortar composition for replacement materials that is the most suitable match to the original material. Petrographic analysis and XRD are demonstrated to be of particular relevance in the characterization of historic mortars and plasters.

**SOME OBSERVATIONS**

**Case Studies**

As part of the Pilot Study, a number of case studies were conducted where individual monuments were examined in detail and in some cases treated. The extensive documentation and conservation program at St. Pancras Chambers is outlined by Davies (Chapter 33). The unusual case of a fire-damaged structure, Uppark (Chapter 38), the earthquake response of Hagia Sophia (Chapter 35), and the restoration of a significantly altered structure, The Octagon (Chapter 36), provide real world supplements to the laboratory studies. The important related material, terracotta, is the subject of an investigation and conservation treatment at Schwerin Castle (Chapter 30).

**Historical Correlations**

In the northern European countries participating, there seems to be general agreement that brickmaking technology was imported from Lombardy around A.D. 1100–1150. Subsequently, brick shape, appearance, and dimensions seem to have varied in ways that can be correlated with historical periods. Also there seem to be some correlations between the historical period and the durability of the brick. This tends to support the idea that significant changes in brick manufacturing over history (kiln design, fuel type, additives, etc.) have implications for durability. Similarly, the collaboration of conservators, scientists, and architectural historians (Chapter 39) has demonstrated that historic renderings and mortars are a fruitful subject for interdisciplinary study.
Salt Deterioration

One of the primary motivations for the Pilot Study was concern about the effects of air pollution and acid rain. It was initially thought that these agents of attack would be important for lime mortars, but not for the bricks themselves because of their silicate-based composition. Nevertheless, one discovery of this Pilot Study was that bricks are in fact sensitive to acidic deposition because of the migration of calcium-rich solution from the mortar into the brick’s pore space. This leads to the formation of calcium carbonate in the pores, which can then be attacked by SO$_2$ or acid rain.

On the other hand, these pollutants may be less significant in the future. The trends observed in Germany, demonstrating a substantial reduction in SO$_2$ emissions, find parallels throughout the major industrial nations (UN ECE 1998). However, attack by soluble salts, particularly sodium chloride and the less soluble gypsum, have been identified as a major problem in several countries, even where there are no local sources of natural salt. This suggests that salt may have been deliberately added in the process of brickmaking, in the mortar or in the plaster or whitewash. Research is needed on the phase relationships of these salts, particularly for the thermodynamics of complex mineral assemblages formed from solutions containing several cations (e.g., K, Ca, Na) and anions including Cl, SO$_4$, NO$_3$. The response of these mineral assemblages to changes in temperature or relative humidity needs to be characterized to understand the mechanisms of damage in porous materials. In recent times, salt damage has been aggravated by the introduction of heating systems into previously unheated structures. Microclimate studies are an area for further investigation.

Hand-molded vs. Machine-Made Brick

It is evident that one cannot make a simple classification of monuments on the basis of whether they were built with hand-molded or with machine-made brick. Due to extensive alterations or repairs, even medieval buildings contain a certain amount of nineteenth or twentieth century machine-made brick. Some of the most prominent brick deterioration observed in these buildings occurs in the machine-made bricks. It may be that some of these were made in the transition period around the turn of century, when the stiff-mud extrusion process and tunnel kiln firing was coming into use. Lack of experience with these techniques resulted in brick that has a definite laminated structure or a thin, hard outer skin. This shows up in characteristic patterns of deterioration that involve spalling or wrinkling of the surface. In conjunction with an experts meeting in Berlin, an Hoffmann kiln adapted to the production of hand-molded brick for the restoration of historic buildings in Brandenburg was visited. An historic preservation challenge is presented by the need to keep such historic technologies in production.
Protective Coatings

Another common theme is the intermittent use of coatings, either thin layers of whitewash or thick layers of stucco. During certain periods, these coatings were in fashion, but during others, bare brick was preferred. A builder planning to apply stucco or whitewash could use poorer quality brick. Conversely, if only inferior brick were being made, such coatings would have been unavoidable. The prevailing style in the use of coatings should be factored into the evaluation of the correlation between historical period of construction and durability. In terms of restoration, it is evident that the decision of whether or not to apply such a coating depends on the prevailing attitude at the time of construction rather than on modern taste.

CONCLUSIONS

The CCMS Pilot Study approach has been applied to the study of the conservation of historic brick. It has been possible to coordinate the research of a number of institutions in several European countries and the United States. The ability to share resources and expertise made it possible to achieve far more than any one laboratory could have accomplished alone. The Pilot Study case studies and research reports make an important contribution to the scientific study of brick conservation.

The value of such a Pilot Study lies in the ability to identify promising new directions of research. However, given the organizational structure and the limited time frame of the Pilot Study, the results do not represent a comprehensive and complete research program. Consequently, other research programs should continue the work started here to apply the methods to a wider range of bricks and historic structures.

REFERENCES


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References

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2 A Brief History of Brickmaking in Northern Germany


3 Subsequent Determination of the Firing Temperature of Historic Bricks


4 Causes and Mechanisms of the Decay of Historic Brick Buildings in Northern Germany


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1(6):461--474. APPENDIX QUESTIONNAIRE Table of contents

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1.2.4 Damaged area _raJ wall CQuandation wall (add prospects appendix 1.2) nonbearing .... 1 colUaII exterior wall partitioli building frame stairs floor omanc:nTaI plliel Other part of the building: Bridge: sIluciuraI udt 0ther part of a coruIection 1.2.5 Use (previous and present) Barn until some years ago, no use for the moment 1.2.6 Historical data and accidental phenomena Notice about Sflismic (Occumce (dates, intensity, epicantre) Noti"" about accidental impact!, cxploaioIJJ, war fiahs in relation with the building: Natural disasfeI (81ofJI!Ih, fI00d. .. ) 1.2.7 General view of the building .. utt tower tower defensiw defensiw wall floor sIluciuraI sIluciuraI stairs

Address 1.2 1.2) Damage A tlas and Questionnaire/or Evaluation o/Deterioration 127 2 Visual Analysis of Damage DalAI: II -/10151-19141 Orientation ofthe analysed area: S,N,E Hcighthabovc ground level:S: 0.15m to 1.6m (Please UUI: one set of Cornu for each analysed area of the corumction) N: 0.0m to 1.7n 1.2.1 Characteristics of the original material 2.1.1 Masonry as whole: Bonding (add picture(5)"" appendix 2.1) Distribution or mapping of different kinds of textures (add map ifpossible appendix
Relative Humidity cycle Temperature eC/year) Relative humidity (% I year) Air Pollution (average value! in ppm): Period SO 2 Minimum NO. CO 2 Circumstances of the representative damages Frequency: each winter Location: low areas «2m high) each sununer sheltered areas other frequency: imed.under terraces/roofs Maximum L2L21 L1VI 03 exposed areas free edges Average Aerosols when heated other location A“id rain Iph Iph irregular near water transported clements uniform. OCuffTa1CC near protruding cJemcntJ mgular occurrence near chemical agressive produUl;ts Presence of: urine gu21I0 leaching agents Orientation of the affected area: East side sheltered/rom rain crusts fuine (N/SW/E): LSI facing the seaside Other: South Structural damage Backgroulld Information about . The material itself (if some information is already known) Brick Mortar Nature of the clay used Type of sand (calcaceous, siliceous") Percentage of sand content Type of binder Percentage of binder content Percentage of salts content W/Bratio The original manufacture Conditions offering: (if some information is known) Conditions of drying: Conditions of shaping: Environmental conditions during construction: Latter applied materials Type and date of surface treatment: hydrophobic agents painting coating Renewal of: bricks Consolidation: Reduction of moisture joints pointing backfill with inj.mortar Water proof membrane plaster rendering Other Other Rendering Masonry Other: painting of Joints cleaning IruuJation lruuJation lruuJation lruuJation cycle cycle cycle cycle cycle lruuJation lruuJation IruuJation 6.1

6.2

6.3

6.4

6.5

6.6 Non Destructive Tests in Situ Results of Analysis Pointing hardness tester (add plan with observed zonc=apx.6.1) Zone Period Pointing Hardness Conclusions: Conclusions: ... Sonic Survey (add schematic plan appendix 6.2) Type ofmQSW"e Direction Time,ls) Path Length(h(m) Velocity (mls) Variation coef Surfuce (h~1.22m) North 5500 -12150 0.39 (h~1.67 m) North 4138 0.39 Frequency I Equipment Conclusions: (average velocity, map ofvelocities, stillldard deviation ...) Results ".ith great variance. Great betroogeneity in the constitution of the wall Water absorption test. Tubes of Karsten technique
6.7 ND Tests Final Conclusions. Combined results Surface Depth 7.50"/ K. Van Ealen 7 Causes / Agents of Damage without laboratory analysis (Area ) 7.1 Damage(s) due to the material itselfandlor to fabrication process: ... 7.1.1 Wrong selection of building materials: nature of the clay used percent. of sand content percent of lime content percentage of salts Arguments" 7.1.2 Manufacture: I conditions conditions of drying conditions of moulding rugumcnts: Light red bricks more damaged than darker ones 7.2 Damage(s) due to the fabrication of masonry (composite): 7.2.1 Problems and defects of the originAllcchnology" conditions of construction wrong detailing bonding jointing and pointing isolation materials insufficient thickness of walls other: not enough 'bond Mtwftn pha.u., or conk! Arguments 7.3 Damage(s) due to the interaction with Environment 7. 3. 1 General dimmle and environmental conditions: Natural disasters: earthquake flood fire explosion hurricane Climate: rain hail frost snow wind rc10ltive humidity too high too low sun/radiation too much too Jess I Watu purdrilltilt. roofilt very bed conJJJion Itemporalurc "thermal charges Ngumcnt:!! 7.3.2 "onsfrClion of which m:ucrcia) or masonry room pout and use of environment: “ mechanical impact 'chemical aggressive products Arguments : 7 .3.3 Ground lntracction with the .soil (oundation: natural consolidation of Ole $Oil c:hangcs in the soil nature % and nature of salt content soil ruphlre resist3r1cc other: Arguments: used III! blllm “ ICr:llllit concentration of hone detritus 7.3.4 Water: Imotion of water 'containing ulu Arguments: Water from the KTound, swamp area 7.3.5 Air& Rain' !physical, chemical, biological emissions air content (SO2, CO2, NaCl, .. ) Arguments: .. 7.3.6 "ation: insects " bio corrosion biogenic miner:’.1.1 acids micro-organisms org.nic acids Arguments 7.4 Damage due to th"interaction ofmaterial(s)with other material(s)in contact with it 7A.1 Original or oriein11. liike m':".teri:’:! 1: brick and
monar brick and plaster metal and brick/plaster anchors
and masonry ste el "sandmaso limestone and brick
accumulation of ,db other: Arguments: 7.4.2 Latter
applied mains Is: exchanging of single bricks or puts of
masonry "thinje"e/mortar Wrong surface trutment: ~
outdoor waJ1-cov"r pain(ing cleaning hydrophobing
"onsolidation other Arguments Arguments reinforcement
reinforcement content Manufacture:

8 Sampling for laboratory Analysis (Area of construction )

8.1 Sampling by Name oflhe Jw.1ituation; KULeu’.. "n
Labol’Story Rcyntjcms

8.1.1 Type of sample: (add picture with masonry and sample
before and after SAMpling”apdx.7.1) Number Internally
Cored Full-size Powder Parts Masonry or cored on
surface bricks corw, samples as whole On damaged 1 3
b.icks Undamaged bricks

8.1.2 Sample Dimensions Weight Place of removal (m) Type
of precognized number (em) (g) Height above Depth in
laboratory analysis ground level the masonry (see
classification part I I ) 1 1.8 Physical tests 2 1.9
Chemical tests 3 2.0 Shrtnka’e test 4 2.0 Frost tcst 5
1.8 Chemical &I Physical tests

8.1.3 Description of sampling and conditions of removal:
Sample n. 1 Part of brick removed from south wall Sample
n. 2 Part of brick removed from south wall Sample n. 3 &
4 Full brick from south wall Sample n. 5 Mortar removed
from south wall 9 9.1 9.1.1 9.1.2 9.1.3 9.1.4 9.15
9.1.6 9.1.7 9.1.8 9.1.9 9.1.1 0 9. 1.11 9.2 9.2.1
9.2.2 9.2.3 K. Van Balen SAMPLEN.5 Laboratory Analysis
on sampli"Area af construction: Mortar. South Chemical
Analysis Insoluble residue 69,62 % Composition orBuilding
Material in % Zone Sample Si 0 2 A1,0J F”2’3 MgO Na2O
0,7 0,49 Zone Sample “o S03 co 2 CaO H 2 0 2,05 0,48
5,9 9,36 Soluble Ions (””‘1. • %) (water soluble contents)
Na+ K+ Ca+ 2 S03·2 Cl’ N03 Calculated salt contents:
Composition ofthe binder:. Composition of the aggregate"
Soluble S1O2 0,73% Binder-Aggregate ratio of the mortar ..
Calcium-carbonate content (wt-%) PFM microscopy
description Grey mortar with spots of lime and many quartz
crystals Difcolong test results: Diffaralometric analysis
of sampled salts (XRay Test): SM1pie Depth of sampling
(em) Salt name Salt Formula Efflorescence rate: no
effioresced ,lightly. moresced effloresced
Physico-mechanical tests Loss on ignition (105 0C) : 9,81 %
Gravimetric measurement: (gam meter, carbon carbide •... )
Sample Zone Dimensions Weight after Apparent Water cont.
Moisture Volume(cm) sampling (g) density(kglm3) on removal(g) cont.(v.1%) 1959.78 Porosity: Loss on ignition at 1050 °C: 11.67 % Porosity Hygroscopic behavior Sample Percentage Absol. density Coef.ofwater Capillary rise Initrate of ahsor in volume T1V (ml/g) (kglm3) saturation coef.(kglm2/l t) ption Kgml3/min 46.8 520/0 Granulometric analysis (add obtained curves).
Conclusions for: Orick Mortar Binder Plaster / rendering volume 10 10 .1 10.11 10.12 10.2 10.2.1 10.3 10.3.1 10.32

10.33

10.3.4

10.3.5

10.3.6

10A

10Al

10A.2 Causes! Agents of Damages. Final Conclusions confirmed by Labo. Analysis Damage(s) due to the material itself and/or to fabrication process: Wrong selection of building materials: nature of the cJay used percent . of sand content percent. of lime C"ent content percentage of salts Arguments: Manufacture: condiliollS offins conditions of drying condition. . ofmouJding Arguments: Litht uti bride .. mOrT dImllCtd than darker ones. Brito Woib high porosity Damage(s) due to the fabrication of masonry (composite) Problems and defects of the original technology: conditions of construction 'ATOns detail ing bonding jointing and pointing isolation materials insufficient thickness of walls other: not enough bond Ar...;&";..m_en_ts_: __ ftot eMiIch hond bt""n ditruc:n.t phue! or C'onstnction Damage(s) due to the interaction with Environment GeneraJ climate and environmentAl eondjtions: Natural disasters: earthquake flood explosion hurricane Climate: Rín hail frost wind relative humidity too high too low sun/radiation too much 100 less temperature. thcnnal chaJge:s Arguments: waler pen('rialion <rain, dampness) Use of the comJUC1ion of"ilich material or masonuy fOrT11$ pntt and usc of environment: "\'ibrntion.'i mechanical imp:\ct chtmical agresssiv products ArgumentsGround I Interaction with the soil foundation: natural consolidation of the soil changes in the soil nature % and nature of salt content soil
rupture resistance other: Arguments: probably high concentration of NOJ (used for honc.s) "ti" Water: motion of Miller containing salts other: Argument: Water: movement from the ground, high moisture increase on brick and mortar Air & Rain: physical, chemical, biological emissions air, "oot"" (S02, C02, Nael, ... ) Arguments: Deterioration: insects germ number hio "orrQsion biogenic mineral acids micro-organisms organic acids Arguments: roots of planu included on joinu Damage due to the interaction of material(s) with other material(s) in contact with it Original or original like material: brick and mortar anchors and masonry limestone and brick. Arguments: Latter applied materials: brick and plaster metal and brick/plaster reinforcement cement and masonry accumulation of salts other exchanging of single bricks or parts of m" bacldill with injection concretcmortar Wrong surface treatment pla.s\(f wall-co\)'"cr p ainin C hydrophohing consolidation repainting other Arguments: Manufacture: outdoor outdoor repainting This page intentionally left blank
13 Decay of Brickwork Surfaces:
Laboratory Tests and Studies on Outdoor Full-scale Models


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pavimentazioni. Indagine eseguita con l 'uso di rugosimetro
14 Application of Neutron Scattering Techniques to the Investigation of Brick and Mortar


15 Transport of Salt Solutions in Brickwork


16 Influence of Brick Microstructure on the Characteristics of Cement Mortars


17 Characterization of Historic Mortars from Buildings in Germany and The Netherlands


APPENDIX 17.1: Method for the Chemical and Mineralogical Characterization of Mortars

General

The aim is to describe a simplified chemical and
mineralogical analysis of historic mortars, using flow charts. The term "historic mortars" refers to all mortars used before the fabrication of Portland cement. Several attempts have been made to overcome difficulties in finding suitable ways of analyzing historic mortars and of obtaining rele vant information from them (Dupas and Charola 1986; Jedrezejewska 1960; Wisser 1989).

Description of Method

The flow chart for the analytical method to characterize ancient mortars (Figure 1.0) begins with "sampling." It is very important for successful work that the sampling of the mortars is done very carefully and exactly. Therefore, the location of the object must be recorded and photographs have to be taken. A description of the method should explain how the mortar was sampled; for example, in the form of drilling cores or if a hammer and a chisel were used. Moreover, the state of the mortar (in a good or bad condition; what kind of damage) must be recorded. After sampling, the mortar must be stored in plastic bags, or something equivalent, to restore the moisture. The next steps take place in the laboratory, where the samples must be prepared for analysis. Normally, 150 g of mortar are used; however, if possible, one should try to work with more material, depending on the size of the aggregate. Preparation work is necessary, because any contamination by dirt or parts of
brick or natural stone will in validate the analysis. Usually a brush is used for the cleaning procedure of the mortar. Sampling location of the object documentation of the method storage of sampled mortar preparation of 150 g mortar crush 100 g thin-section for sample for SEM dry at T = 40°C mortar in coarse microscopic work with EDX-system crush in an agate grains or microprobe mortar until < 0.09 mm see Figure 1.1] see Figure 1.2

Figure 1.0 Flow chart of the analytical method to characterize historic mortars. Weigh the sample (first dry weight) dry at T = 40°C weigh the sample (second dry weight) dissolve the binder in HCl filter and wash the residue dilute to a definite volume determination of Ca I Mg I Fe I Al by using the AAS B. Middendorf and D. Knofel weigh the residue (third dry weight) boil with a saturated sodium carbonatesolution dry the residue weigh the residue (fourth dry weight)

Figure 1.1 Flow chart of the analytical method to characterize historic mortars.

From the 150 g of prepared mortar, ca. 100 g are crushed into coarse grains and the sample weighed (Figure 1.2). This weight reflects the weight of the laboratory stored mortar. After this, the mortar has to be dried at a temperature of 40°C to constant weight. It is very important, that the temperature is less than 40°C, because at higher temperature gypsum will dehydrate to CaSO4 . 12 H2O. When the mortar is dried it has to be weighed again and the difference between the first and second weight is the moisture content of the mortar. From the dried mortar, the binder has to be dissolved in HCl or other solvents, depending on the aggregate. The residue must be filtered and washed, and the filtrate must be diluted to a definite volume. This filtrate is used for determination of cations,
e.g., Ca$^{2+}$, Mg$^{2+}$, Fe$^{2+}$/Fe$^{3+}$, and or Al$^{3+}$, for which atomic adsorption spectroscopy (AAS) is used. The residue must be dried (third dry weight) and later boiled with a saturated, i.e., sodium carbonate solution. This procedure is used for the determination dissolve dissolve dissolve dissolve dissolve dissolve dissolve dissolve dissolve dissolve dissolve dissolve dissolve residue analytical analytical analytical analytical analytical analytical Mortars from Buildings in Germany and The Netherlands 191 (see Figure 1.0 ) analyzing X-ray determination determination determination the water determination determination determination determination determination determination determination determination determination determination determination determination determination determination determination carbonate patterns and components ≈ 0.04 mm) Figure 1.2 Flow chart of the analytical method to characterize historic mortars.

Figure 1.2 Flow chart of the analytical method to characterize historic mortars.

of the soluble SiO$_2$ content. After this step, the sample has to be dried again and must be weighed for the fourth time. The residue is used for the determination of the particle-size distribution. To calculate the binder/aggregate value (b/a) and the content of soluble SiO$_2$ (wt.%), the equations in Figure 1.1 have to be used. In Figure 1.0, three boxes have not yet been explained. For further determinations,

ca. 50 g mortar are necessary. One piece of mortar is used for SEM analyses, normally in combination with an EDX system. Another possibility to get information about the microstructure of the binder, or of the reaction products of binder and bricks or natural stone, is to use an electron microprobe. A very powerful method to determine the ori

gin of binder and aggregate is the use of a petrographic microscope. For the prepara
tion of thin-sections, a mortar piece of 109 is needed. In Appendix II, examples are shown. For the determination of \( \text{CO}_2 \), proteins, etc., ca. 30 g of mortar have to be dried at 40°C and then crushed in an agate mortar until the grain size is smaller than 0.09 mm. This powder is used for the determination of proteins (Figure I.2), sulfate, carbonate and the water soluble components, e.g., efflorescence. For X-ray diffraction patterns the powder has to be crushed into an agate mortar again, until the grain size is smaller than 0.04 mm. If there is not much material available, only a small amount of sample can be measured on a Si sample holder and X-rayed afterwards. X-ray diffraction patterns in combination with the information obtained from a petrographic microscope are very powerful for the identification of binder and/or aggregate. If the historic mortar was made of hydrated lime or dolomite, the analysis can be stopped here. For the determination of gypsum and/or anhydrite mortar, further investigations have to be made (Figure 1.3). Exactly 3 g of dried mortar will be burnt at a temperature of 350°C to constant weight. The burnt sample has to be weighed and the weight difference can be calculated as the water of crystallization for gypsum. The first branching of Figure 1.3 shows that 5 g mortar must be dissolved in 80 ml of HCl and afterwards must be boiled for nearly two minutes. To this volume, 200 ml hot distilled
Figure 1.3 Flow chart of the analytical method to characterize historic mortars.

boiled afterwards for two minutes again. The hot solution has to cool down and must be filtered. It is possible to calculate the b/a value for a second time. The filtrate has to be diluted to a volume of 500 ml. For this filtrate, which contains the binder, the cations will be measured by using the AAS. EDTA is used to determine the sulfate content.

This procedure is described in Figure 1.4. From the diluted volume, 5 ml have to be taken to dilute them with distilled water.

The pH value has to be adjusted with KOH solution to 12. A small amount of indicator (1 g Calceine and 99 g KN03) must be put in and, by using an UV lamp, it should be titrated with EDTA until the color changes from green to orange. To precipitate the sulfate as BaS04, the pH value has to change to 1 or 2. Add a measured volume of a known BaCl2 solution to the sample and warm it up. The sulfate anions react with the barium cations to barium sulfate which has to be filtered. For further investigations, the filtrate is used. First the pH value has to be changed from acid to 12 by using a concentrated KOH solution. Now the content of barium can be measured in the filtrate. If the barium content is known, the sulfate value can be calculated.

dissolve 5 g mortar in 80 ml 3 HCI (boil 2 min.) add 200 ml boiled distilled water and boil for 2 min. cool down, filter and clean the residue dilution to 500 ml measuring of sulfate with EDTA see Figure 1.4 measuring
of Ca, Mg, Fe, and Al with the MS dry 3 g of the mortar at 350°C until constant weight. Weigh the sample weight difference is water of crystallization for gypsum. Weigh the residue; see Figure 1.0. Calculate the b/a value.

Historic Mortars from Buildings in Germany and The Netherlands. 193. Dilute 5 ml with distilled water (e.g., 100 ml). Adjust the pH value: 7.12 with KOH solution. Put in the indicator and titrate until the color changes from green to orange (use an UV lamp). Change the pH value with HCl to acid. Add a definite volume of BaCl₂ solution to the sample and warm it up. Filter the precipitate (barium sulfate) and adjust the pH value: 7.12 with KOH solution. Titrate until the color changes from green to orange. Account for the sulfate value.

Figure 1.4. Flow chart of the analytical method to characterize historic mortars. If all determinations have been carried out as described in the flow charts, the mortar has been very well characterized. Generally, it can be said that this method works quite well if the aggregate is not soluble in the solvent used, but if the binder and aggregate are of the same material, e.g., lime mortar with carbonate stones as aggregate, an other way to determine the b/a value has to be found.


APPENDIX 17.11: Examples of Photomicrographs of Thin-Sections of Mortars

General
By using the petrographic microscope, mortars and aggregates can be characterized quite well. Some examples are given in the following microphotographs.

Part I: Historic Mortars

Figure 11.1 Different kinds of aggregates in Figure 11.2 Residue of a dry-slaked lime in a lime mortar. In the middle of the photo is a lime mortar. Sample: WSG VII.

small piece of a shell. Sample: WSG Ia.

Figure 11.3 Healed crack through crystallization of calcium carbonate in a gypsum/anhydrite mortar. Sample: Ba III. Figure 11.4 General view of mortar sample with fine-grained aggregate. Sample: ST5, Historic Mortars/rom Buildings in Germany and The Netherlands 195

Part II: Different Aggregates Used in Historic Mortars

Figure II.5 Limestone from Oland with fossils, Figure 11.6 Limestone from Estland with fossils, fossils,

Figure II.7 Charcoal pieces used to darken the mortar. matrix,

Figure 11.8 Piece of anhydrite in a gypsum mortar, with a reaction border.

Part III: Laboratory-made Mortars

Figure 11.10 Hydrated white lime with small cracks in the same binder (arrows). marked with arrow).

Figure 11.12 Mixture of hydrated white lime
and gypsum. Figure 11.13 Mixture of hydrated white lime and Portland cement with the typical interference color of calcite and residues of cement clinker (arrow).
18 Gypsum and Lime Mortars of Historic German Brick Buildings: Analytical Results and Restoration Material Requirements


19 Characterization of Mortars and Plasters from Historic Monuments in Turkey


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23 Effects of Air Pollutants on Renderings: Reaction Zones on Buildings vs. Orientation


24 Salt-induced Gypsum Formation on Renderings


25 Adobe Brick of an Ancient City Wall in Reggio Calabria


26 Water-repellent Treatment on the Brick Wall of the External Facade of the Scrovegni Chapel in Padua


NORMAL 11/85. Assorbimento d'acqua per capillaritit


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310 V Fassina et al.

27 Water-resistant Gypsum-Lime Mortars for the Restoration of Historic Brick Buildings


APPENDIX: Assessment of Mortars Intended for the Repair of Masonry

General

For repair work using mortars, it is often of interest to know other quality characteristics in addition to those stipulated by standards. Therefore a working group including research workers and practical professionals undertook the task of describing other important qualities and corresponding test procedures for mortars, especially for the
repair of masonry, going beyond those stipulated by the standards. These additional qualities concern, in particular, the durability of masonry, especially fair-faced masonry. Questions concerning structural stability were not considered in this connection. These statements do not in any way affect the applicability of standards DIN 1053, part I, DIN 1855 and DIN 18557.

A list of relevant qualities has been drawn up. The appropriate test methods are contained in Knöfel and Schubert (1990). For the assessment of the test results, characteristics and/or requirements have been set up which will be weighted individually in accordance with their significance.

Qualities and Requirements

To begin, mortars intended for the repair of masonry are subject to wet and hardened mortar tests and properties that go beyond what is stipulated by the applicable standards. The purpose of these tests is to achieve a more complete knowledge of the qualities of the mortar (see Table A1). The tests are divided into two groups, of which the first includes the "necessary" and the second the "desirable" tests. For the assessment of the mortar, recourse should be had at least to Group A ("necessary"). This group includes, in addition to wet mortar tests, hardened mortar tests both of the actual mortar and of the stone-mortar masonry structure.
For the production of the stone-mortar masonry structure to be tested, the same type of masonry stone or stones having the same properties should be used. If necessary, evidence of the same properties can be obtained by corresponding tests or expert opinion. The extent of the tests should be related to the significance of the building measure. It goes without saying that the tests should cover only mortars which are known (or proved by tests) to be permanently, chemically compatible with the other building materials contained in the masonry.

Guiding values or requirements for assessing the test results are given in Table A.2. These guiding values are, in part, absolute data (e.g., shrinkage, adhesive strength). This is appropriate where assessments of the mortar (e.g., shrinkage) or minimum values of the stone-mortar masonry structure are made irrespective of the stone qualities. Other guiding values are the quality relationships between the mortar and the stone material. This is appropriate where for increased durability the qualities of the mortar are to be adjusted to those of the stone material (e.g., E-modulus). Other guiding values or requirements contain only indications such as "similar to stone" or "as low as possible" as characteristics. Such general statements are sufficient for many qualities (e.g., tendency to segregate). Some qualities are not subject to any require
ments at all (e.g., volume weight) because they are irrelevant for the durability of the masonry despite their importance for characterizing mortars.

Assessment

Since the qualities mentioned are of varying significance for the durability of masonry, their weighting must vary accordingly. A weighting of the quality characteristics is contained in Table A.3 for the tests of group "necessary."

Table A.I Mortar tests.

GROUP A (Test is necessary):


Hardened mortar:


GROUP B (Test is desirable)


Hardened mortar:


The extension of the mortar characteristics beyond those stipulated by the applicable standards, which is provided for by this test schedule
in connection with the mentioned guiding values and requirements, with due consideration being given to the weighting of the test results, is meant to enable the expert to assess the suitability of a mortar for a given masonry with greater certainty. Any quantitative assessment of the suitability of a mortar for a given masonry structure that would go even further by using "value ratings" from quality tests which could be assessed and weighted may easily give a false impression of accuracy.
Group Mortar Quality Test Base Value I Requirement Method (J) Mortar Mortar Stone (2) wet mortar consistency slump: (17 ± 0.5) cm unless otherwise required workability to meet A2; ::: I water retention A3 greater with highly absorbing stones, small with little absorbing stones hardened dynamic modulus A4 1...1.0, as little as possible mortar not coefficient of thermal expansion AS 0.5...1.5, as close to 0.5 as bond with stones swelling, shrinkage A6 2mm1mn necessary freeze thaw cycle resistance A7 minor spalling, no major or continuous as close set to 0 as possible cracks water absorption coefficient A8 hardened adhesive tensile strength A9; ::: 0.1 N/mm² adhesive tensile strength mortar adhesive shearing strength A10; ::: 0.1 N/mm² adhesive shearing strength bonded compressive strength A11; ::: 2N/mm² as a rule (3) preferably with stones reaction to atmospheric influences A12 out cracking, spalling wet mortar art tendency to as low as possible volume weight B1 as low as possible evolvement B2 no requirement air content B3 no requirement B hardened permeability to steam B4 roughly the same as for stone desirable mortar not absorbing moisture B5 roughly the same as for stone bonded efflorescence B6 as little as possible with stones total porosity B7 as low as possible compressive and bending tension B8 no requirement strength B9 no requirement (I) (3) See Knobel and Schubert (1990). (2) Relationship of qualities of mortar and stone, e.g., "ST
m o r t a r I ~ S T s t o n e ' G r e a t e r i f n e c e s s a r y, d e p e n d i n g o n s t a t i c r e q u i r e m e n t s . ~ ~ B. Middendorf and D. Knöfel

Table A.3 Weighting of mortar qualities for the Group A, necessary tests.

GROUP A Necessary Tests: Weight Factor

Wet mortar: Weighting is omitted for the time being

Hardened mortar:

a: not bonded with stone
1. Dynamic E-modulus
2. Coefficient of thermal expansion
3. Swelling and shrinkage
4. Resistance to freeze-thaw cycle
5. Water absorption coefficient

b: bonded with stone
1. Adhesive tensile strength
2. Adhesive shearing strength
3. Compressive strength of the joint
4. Reaction to atmospheric influences

x: For the time being, these criteria are not considered because there is insufficient experience

with the proposed testing method.

Such accuracy is unrealistic for several reasons, e.g., some test methods lead to widely scattered results, certain criteria may have to be defined more precisely in the future and even the weighting of the qualities could be altered in some details.

Nevertheless, the working group is convinced that this paper will be able to help the expert in assessing with greater precision a mortar that is to be used for the repair of masonry. More experience will have to be gained.


Investigations of Some Historic Mortars. In:


28 Injection Grouting for the Repair of Brick Masonry

American Petroleum Institute. Recommended Practice 13(b), Standard Procedure for Field Testing of Drilling Fluids.


L'Association Francaise de Normalisation (AFNOR), NF P 18-091. Special materials for hydraulic concrete structures, materials for grouting concrete structures, sand column grouting test in wet and dry media.


29 Desalination of Brickwork and Other Porous Media


Figure 29.8 (continued) (c) Change of salt contamination after one week.


(c)

Salt content [weight %] 8 654 1 0N03S04-Na+ K+ Total amount of salts 3 6 em 03 em Layer 3 6 em 0-3em
After desalination Before desalination 8 8 8 This page intentionally left blank
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