Siegfried Siegesmund
Rolf Snethlage *Editors*

Stone in Architecture

Properties, Durability

5th Edition

Springer

Siegfried Siegesmund · Rolf Snethlage
Editors

Stone in Architecture

Properties, Durability

Fifth Edition

Springer

Editors
Siegfried Siegesmund
Geoscience Center
Universität Göttingen
Göttingen
Germany

Rolf Snethlage
Naturstein, Bauchemie und Bauphysik
in der Denkmalpflege
Bamberg
Germany

ISBN 978-3-642-45154-6 ISBN 978-3-642-45155-3 (eBook)
DOI 10.1007/978-3-642-45155-3
Springer Heidelberg New York Dordrecht London

Library of Congress Control Number: 2014930006

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Preface

Natural stone is a topic of interest to geologists and natural stone producers, as well as for architects, building specialists, conservators, monument curators, and of course, building owners. It is one of the oldest and more durable construction materials. However, its importance for the construction industry has changed over time and so has its perception by society. In the last three decades, a significantly increased demand has been noticed that can be attributed to its use as cladding material. Predictions suggest an even greater growth rate in the demand.

Natural stone is a construction material with a favorable ecological rating compared to manufactured materials such as Portland cement or bricks. In architecture, this material is particularly valued for its design possibilities, especially with regards to color, shape, and surface processing. This gives the building a unique value.

In past centuries, master builders and sculptors used locally available stones, since transport from distant sources was difficult and very expensive. Therefore, whole towns were built with a single type of stone. This resulted in the development of cultural landscapes that are characterized solely by the type of stone used. With globalization, this local type of landscape construction is being valued again, especially since natural stones are in essence a part of the landscape. They reflect tradition and identity and are fundamental to both the local community and tourism.

Although there may be a general belief that natural building stones are durable materials, all rocks undergo weathering and will literally turn to dust. The use of natural stone in buildings requires that the stone type have the required suitability for the intended purpose. Otherwise, their deterioration will occur even after short periods of time. The weathering and deterioration of historical buildings, as well as that of many monuments or sculptures using natural stones is a problem that has been known since antiquity. Although much of the observed world-wide destruction of these monuments can be ascribed to war and vandalism, many other factors contribute significantly to their deterioration, such as neglect and poor maintenance. There has been a significant increase in deteriorating structures during the past two centuries. This prompted Erhard M. Winkler in his book "Stone: Properties, Durability in Man's Environment" (1973. Springer Verlag) to make a pessimistic prediction, that at the end of the last millennium these structures would largely be destroyed because of predominantly anthropogenic environmental influences.

Erhard M. Winkler's book "Stone: Properties, Durability in Man's Environment" first published in 1973 marks a milestone in the series of publications on the conservation of our cultural heritage. In the year the book was published, science was not yet concerned with conservation and was still at the level of knowledge that had been accumulated by scientists at the turn of the nineteenth and twentieth century and the two decades between the two world wars. Conservation interventions were not widespread at that time and treatment with chemicals was barely in its infancy. Clever restorers used promising chemical products and applied them to stone conservation, but kept their formulas a trade secret.
Winkler was among the first who embraced the ideas of prewar scientists, such as Hirschwald, Schaffer, and Kieslinger. They advanced the idea that stone conservation should be placed into the context of understanding the processes of weathering and deriving remedies against deterioration. Therefore, he stressed the geologists' role in leading conservation interventions that start with the anamnesis of the building, followed by a correct diagnosis of the problem, and then the development of an appropriate therapy. Simultaneously, other relevant disciplines, such as chemistry, biology, and material science took interest in the conservation of architectural and archeological heritage sites. In 1972, the first international meeting on this topic was held in LaRochelle under the name of "International Symposium on the Deterioration and Conservation of Building Stone." Since then, ten more meetings were convened regularly, and the name simplified to Deterioration and Conservation of Stone. Other international conferences were also organized, such as the Conservation of Monuments in the Mediterranean Basin Meeting.

In the 1980s, the forest decline resulting from increased pollution raised the awareness that "acid rain" could accelerate the deterioration of exterior works of art. This induced politicians—mainly in Europe and in North America—to support research into the effects of air pollution on materials. As a result, the volume of knowledge grew exponentially. In conjunction, the advances in instrumental analysis as well as in technology in general, allowed the development of various chemical compounds that could be adapted for the consolidation or the protection of stone. In the last issue of his book published in 1994, E. M. Winkler added a comprehensive chapter on conservation, a topic which had only been slightly touched upon in the previous editions.

The offer from Springer Publishing Company to prepare a new book to address more thoroughly all the acquired knowledge over the past 20 years will serve to follow the trail that Winkler blazed. The book will cover a wider spectrum with significantly more detail in all topics addressed. Therefore, an attempt was made to develop a natural stone nomenclature from a geoscientific point of view. The suitability of a given stone to the considered function it will have in a building or object is extremely important, therefore different structural engineering and relevant petrophysical and rock technical parameters were compiled for the different rock groups. Since negative material properties of a stone may become evident after a long or very long exposure, suitable testing methods are required for a meaningful stone evaluation. The resistance to weathering is extremely important because every stone at the outcrop or in a building is subjected to the destructive physical, chemical, and biological influences of weathering. Next to these geogenic factors, anthropogenic influences on the material properties and weathering processes are also decisive. These can be deduced from laboratory experiments and also from experience on historical buildings.

Rocks will react to changing environmental conditions; especially when high "multi-pollutant" situations dominate that are caused by various chemical pollutants, suspended particles, and dust. The pollution during the last two centuries has deteriorated many of our cultural assets that may be considered as "contaminated sites." Moreover, through climatic changes such as more precipitation, higher temperatures, freeze–thaw impacts, etc., the pollutants may react following different paths and new deterioration scenarios will develop.

Changes on the rock surface produced by weathering processes can be described with the aid of a specific terminology to avoid misunderstandings. To overcome this problem and to harmonize all the existing classification approaches, an updated version was produced by the ICOMOS-ISCS. These will help in the mapping of the various deterioration patterns and their intensity.

The objective of the new edition is to address practitioners like architects, civil engineers, stone producers, restorers, etc., as well as students who are interested in qualifying themselves for a career. All these professions require a basic understanding and experience in many disciplines such as geology, chemistry, material science, and biology. In the course of the past 20 years, knowledge has grown to such an extent that a single person can hardly acquire an overview of the field or even write a textbook on the subject. Therefore, the editors decided to elicit the aid of further specialists to create an up-to-date book containing the most recent progress in this field of science: A. Elena Charola for deterioration processes and salt decay, Michael Steiger for salt and weathering processes, Katja Sterflinger for biological deterioration and conservation issues. Peter Brimblecombe contributed to air pollution and climate change, Helmut Dürrast for the rock technical properties, Heiner Siedel for the characterization of stone deterioration on buildings, and Akos Török for the petrographical characterization of building stones. The editors are indebted to these colleagues for their essential and valuable help. Likewise, the editors want to express immense thanks to the following persons: J. Ruedrich, T. Weiss, W.-D. Grimm, B. Fitzner, K. Heinrichs, C. Schneider, G. Hundertmark, M. Reich, B. Siegesmund, M. Siegesmund, and A. Elena Charola and Christian J. Gross, who made great efforts in correcting the linguistic deficiencies of the German speaking authors.

January 2011

Siegfried Siegesmund
Rolf Snethlage

Acknowledgments

First of all, we would like to express our gratitude and acknowledge Springer Verlag, who considered and asked us to be authors for the 4th edition of this book, first published in 2011 as an up-to-date and completely rewritten and expanded continuation of the three earlier versions authored by Erhard Winkler. As a result of the sales success of the 4th edition, a revised version is being published including considerable improvements. We are very delighted to see that our book is being well received by technicians and professionals working in the field of monument conservation and preservation, and furthermore, is being used as a textbook in universities in many different countries. Reworking the chapters provided us with the opportunity to introduce more recent results, as well as eliminate some grammatical errors and polish the style of the text. In this context, we are especially grateful to our colleague Dr. George Wheeler from Columbia University in New York, who undertook the enormous task of checking the entire manuscript for scientific correctness and for spelling mistakes. Likewise, we would like to thank Elizabeth McTernan (Berlin) and Christian Gross (Hannover), who undertook the effort of improving the stylistic quality of the book by looking for and eliminating the German phrasing of the authors.

Substantial additions and improvements have been made to most chapters. The quality of many figures and drawings has also been improved by providing better originals and by redrawing the old diagrams. Some chapters, like Chaps. 1 and 7, however, have been left unchanged in the new edition, since the limited amount of time between the 2011 publication and the latest edition was not sufficient for producing new scientific results.

The authors particularly want to thank Springer Verlag and especially Dr. Annett Büttner for offering us the opportunity to produce the 5th edition of the book. We hope that this edition will be as successful as the 2011 edition.

Göttingen, October 2013 — Siegfried Siegesmund
Bamberg — Rolf Snethlage

Contributors

Peter Brimblecombe School of Environmental Sciences, University of East Anglia, Norwich, UK; School of Energy and Environment, City University of Hong Kong, Kowloon, Hong Kong SAR, People's Republic of China, e-mail: pbrimble@cityu.edu.hk

A. Elena Charola Museum Conservation Institute, Smithsonian Institution, Washington, DC, USA, e-mail: charola_ae@yahoo.com

Helmut Dürrast Department of Physics, Prince of Songkla University, Kanjanavanich Road 15, HatYai, Thailand

Heiner Siedel Institut für Geotechnik, TU Dresden, George-Bähr-Str. 1, 01069 Dresden, Germany, e-mail: Heiner.Siedel@tu-dresden.de

Siegfried Siegesmund Geoscience Centre, University of Göttingen, Goldschmidtstrasse 3, 37077 Göttingen, Germany

Rolf Snethlage Natural Stone, Building Chemistry and Building Physics for the Conservation of Monuments, Wetzelstraße 24, 96047 Bamberg, Germany, e-mail: rolf@snethlage.net

Michael Steiger Department of Chemistry, Inorganic and Applied Chemistry, University of Hamburg, Martin-Luther-King-Platz 6, 20146 Hamburg, Germany, e-mail: michael.steiger@chemie.uni-hamburg.de

Katja Sterflinger Institut für Angewandte Mikrobiologie, Universität für Bodenkultur, Muthgasse 18, 1190 Wien, Austria

Ákos Török Geoscience Centre, University of Göttingen, Goldschmidtstrasse 3, 37077 Göttingen, Germany, e-mail: ssieges@gwdg.de

Contents

Chapter 1
Natural Stones in Architecture: Introduction

Rolf Snethlage

Abstract Since the prehistoric age, men have used stone for its unique durability to erect monuments of extraordinary, mostly religious importance. Due to lacking transportation facilities until the 19th century, stones from nearby sources had to be chosen to build churches, castles and towns. Only for exceptional cases were rare and decorative stones like marble transported over long distances when stone of the same color and beauty was not available in the near vicinity. The design of building structures and elements must be adapted to the mineralogical, physical and mechanical properties of stone. The high compressive strength and the low tensile strength of stone require special techniques to overarch gateways and to erect vaults. Mediaeval builders who succeeded in the erection of high and light structures like Gothic church choirs or spires could only stabilize the construction with the help of hidden steel anchors. Only with the emergence of steel and reinforced concrete, the limits that stone properties posed to building structures had been overcome, and a new era of architectural building design began.

1.1 Introduction

Wood, mud bricks and stone are the oldest building materials of men. While mud bricks and wood were mostly used for common buildings like residential houses or stables, stone was used to erect important and impressive buildings like temples, which were meant for extremely long service life and should endure for centuries or even thousands of years. Men regarded stone as ever lasting because the phenomenon of enhanced weathering due to environmental pollution did not exist in former times.

R. Snethlage (✉)
Natural Stone, Building Chemistry and Building Physics for the Conservation of Monuments, Wetzelstraße 24, 96047 Bamberg, Germany
e-mail: rolf@snethlage.net

S. Siegesmund and R. Snethlage (eds.), *Stone in Architecture*,
DOI: 10.1007/978-3-642-45155-3_1,

1.2 Stone Provenance and Provinces

Up to the beginning of 20th century, the availability of stone resources determined the appearance of whole cities. Transportation was difficult and slow because of the road conditions. Wherever possible, heavy stone blocks were transported by ships, preferably downstream. The Egyptians shipped obelisks quarried and manufactured in Aswan down the Nile to Luxor and even Memphis. In Roman times, valuable decorative marble and limestone from Greece and Turkey were transported into Italy to embellish Roman villas and temples. Likewise, the unique, red Porfido Rosso Antico (Imperial Red) from Mons Claudianus in Egypt was delivered to Italy for the exclusive use of the Roman emperor and for his imperial buildings.

Stone blocks were also used as ballast in sailing ships to give them the necessary weight for safe sailing on the sea. Plenty of Gotland sandstone from Sweden came this way into the towns along the Baltic Sea coast in Germany and further east where it was preferred for buildings, gateways and many tombstones. When sea or river transport was not possible, rare decorative stone blocks had to be pulled over long distances on ox or horse carts. This way, the Romans even brought Carrara marble over the Alps into their German provinces.

Transportation capabilities and capacities rapidly increased in the 19th century through the construction of canal and railroad networks. From then on, it became easy to transport huge stone blocks and even to send them into remote provincial towns. More and more imported stones from other countries entered formerly uniformly designed towns. In Germany, the impact of new stones in the 19th century is evident in nearly all towns.

For about 20 years, a new dimension of import stone has been observed all over Europe and the USA. Because of cheaper production, huge quantities of stones from China, India and Brazil have invaded Europe and America, thus forcing out the local stone industry. As an example, the floor of the new airport terminal in Munich is paved with Chinese granite because, in spite of the far distance, it is still much cheaper than the Bavarian Forest granite quarried just 100 km away.

The uniform appearance of historic town centers is an important part of our cultural heritage that should be preserved and not be altered by strange import stones. There are famous examples of historic town centers of extraordinary value, especially because their buildings consist of one stone type. A few are worth mentioning. Since Roman times, the buildings in the city of Bath, and of course its Roman bath as well, have been erected with a local Cretaceous limestone from the Great Oolite. Parts of Paris are situated over a system of underground cavities where the Tertiary limestone for the Parisian buildings has been quarried. Rome, on the other hand, is famous for the travertine. In Germany, the center of Dresden is an example of the use of two varieties of Elbsandstone, the Postaer and the Cottaer Elbsandstone (see Fig. 1.1), which come from quarries some kilometers up the Elbe river. The castle in Nuremberg sits on a sandstone rock to which the name "Burgsandstone" has consequently been attributed.

Fig. 1.1 Frauenkirche in Dresden, Germany. Postaer Elbsandstone

1.3 Natural Stone Structures

As already mentioned, the physical and mechanical properties of natural stone narrow its use as building material. Stone has high compressive, however, low tensile strength, which is about 10–30 times lower than compressive strength. Therefore stone should only be loaded with compressive forces because stones loaded with bending forces can easily crack and cause a failure of the whole construction. Already in prehistoric times, builders knew about these limitations.

Stonehenge is a good example to elucidate the expertise of Stone Age men. It has been found that the stone blocks come from a granite complex in Wales from where glaciers must have transported the blocks into the area of Stonehenge. Nevertheless, great efforts were necessary to manage the transport over the remaining miles to the building site, whereby the transportation method is now still under debate. In any case, the Stone Age builders must have known about the low bending strength of natural stone because the stone cross-beams bridging the gap between the vertical columns have sufficient thickness to exclude the risk of cracking (see Fig. 1.2).

Fig. 1.2 View of Stonehenge. Thick cross-beams were used to prevent crack formation

The reputedly biggest coherent stone block ever made by men is the beautiful marble relief on the north side of Baohedian in the Emperor's Palace in Beijing (Hall of Preservation of Harmony). The relief made from Fangshan marble has a length of 16.5 m, a width of 2 m and a thickness of 1.7 m. The Fangshan area is some 50 km away from Beijing. Chinese archives report that transport was done in winter time on an ice track onto which the stone block could be pulled with relatively little power because it was sliding on a film of thawed water between the stone and the ice track.

The Cheops Pyramid is the biggest accumulation of stone made by men. It consists of about 2,300,000 stone blocks, each of them weighing about 2.5 tons. The pyramid has a height of 146 m. Assuming an average rough density of the limestone as 2,500 kg/m^3, the compressive force onto the center of the ground plant results 3.65 MPa. This pressure is more than 10 times less than the compressive strength of the limestone. In spite of the enormous height of the Cheops Pyramid, there is no risk that the stone in the undermost layer could break (see Fig. 1.3).

A look at the forest of columns in the Karnak Temple in Luxor in Egypt demonstrates that the builders had a precise knowledge about the limitations the natural stone properties posed to the construction of the temple hall. As shown in Fig. 1.4, the columns stand extremely close to each other because of the low bending strength of the sandstone beams connecting the capitals of the columns. As a general rule, the thickness of a freely hanging stone block resting on both ends should be one third of its length. In the Karnak Temple, the distance of the columns amounts to around 4–5 m so that the thickness of the cross-beams should be around 1.30–1.50 m, which corresponds quite well to the real situation (see Fig. 1.4).

Bending strength of a stone beam also depends on its moisture content. Because moisture strongly reduces bending strength, it has to be made sure that the beams are not wetted by rain or snow. The technical bending strength measured in a laboratory under standardized testing conditions is higher than the value of

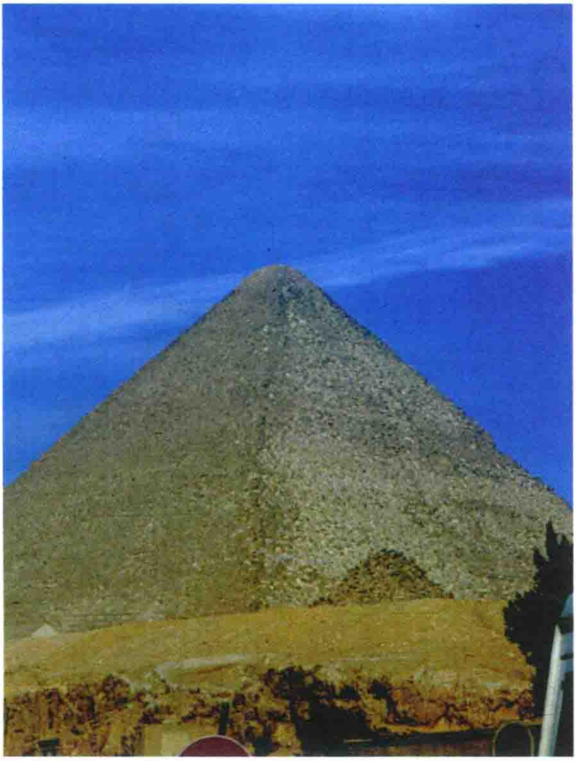

Fig. 1.3 View of the Cheops Pyramid. In spite of the height of 146 m, the pressure at the base is much less than the compressive strength of the limestone

bending strength in practice. In a building, a stone element is exposed to permanent stress, causing cracks to grow under much less force than measured in a laboratory. Moreover, the thickness of stone beds in the quarry limits the height of available stone beams and, thus, may indirectly determine the distance of columns in a building.

It should also be taken into account that Egypt had a lack of appropriate wood for construction purposes. Consequently, there was a need to take recourse to stone as the main building material because the mechanical properties of palm wood, the only tree available in great quantities, were insufficient for construction. This situation is completely different from classical Greece. The architraves resting above the columns of Greek temples normally have a thickness of around 1 m. Their thickness varies with the distance of the columns; however, the rule that the thickness should be around one third of the length is always obeyed. The cella of the temple, however, is too wide to be covered with stone beams. Instead, it was roofed with a wooden construction able to span over the whole distance between the cella walls. This roof construction was only made possible because, in contrast to stone, wood can bear high tensile forces and, of course, due to the availability of high quality wood.

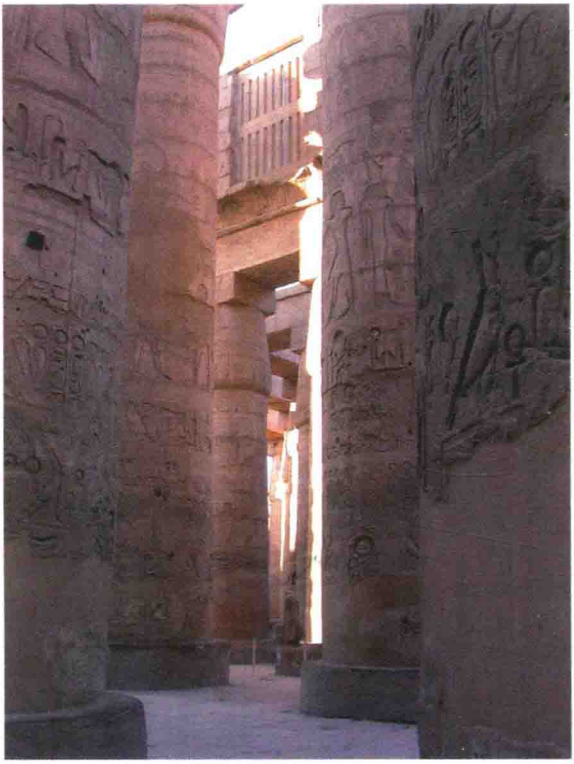

Fig. 1.4 Columns in the Karnak Temple in Luxor, Egypt. The thickness of the cross-beams on top of the columns takes into account the low bending strength of the sandstone

The first solution builders found to overarch bigger rooms is the so-called "false vault". In contrast to a real vault, in this case, stone blocks were put upon each other, the upper one always protruding a little over the lower one. In order to avoid the toppling of the layers, heavy stone blocks or earth filling had to be put on the opposite side as counter weight. Examples of false vault constructions are the trulli in Apulia in Italy or the Tomb of Atreus in Mykene in Greece (see Fig. 1.5).

In addition to the counter weight, the construction is stabilized by the fact that the stones of each layer form a closed ring so that they cannot fall out. Thus, within the ring, the stones are loaded only by compressive forces so that the whole construction is very stable.

A progression in architectural design is the capability to build real arches and vaults allowing lighter and material-saving constructions. In the case of a real arch, the stones support each other and rest on strong corner points. Figure 1.6 shows a limestone arch over the tunnel between the sacred area and the stadium in Olympia, Greece. Different from constructing a false vault, scaffolding is needed for erecting a real vault or an arch. The stones of the arch are laid out upon the scaffolding, and only when the arch is closed can the scaffolding be demounted. In this construction, the stones are mainly loaded with compressive forces. The

Fig. 1.5 View of the false vault in the Tomb of Atreus in Mykene, Greece

Romans were perfectly capable of building arches, as, for example, long aqueducts like Pont du Gard and bridges in all of Europe demonstrate.

Romanesque architecture resumes the building principles of the Romans. Romanesque churches are characterized by thick walls and narrow window openings. Portals and window frames are terminated with round arches. Romanesque architecture takes into account the mechanical properties of natural stone. The stone is not loaded up to its strength limits. Romanesque buildings make an impression of solidity and compactness (Fig. 1.7).

The Gothic style marks a complete change in architectural design. The formerly solid walls become light and open. Through wide windows decorated with delicate traceries, light floods into the interior of the building. Slim spires reach enormous heights. Quatrefoils between their ribs let wind and rain pass through. Flying buttresses span from the walls of the main nave to the supporting pillars. The elongated structures of Gothic cathedrals go to the limits of the mechanical properties of stone. Therefore, the safety of choirs and spires had to be secured by iron ring anchors invisibly imbedded in the stone in order to hold the structural elements together. Without anchors, the whole structure would be endangered by

Fig. 1.6 View of a Roman arch in the district of Olympia, Greece

Fig. 1.7 View of Romanesque stonework of Worms Cathedral, Germany

collapse. In some cases, serious damage has been caused because iron bars running through the window openings had not been seen as parts of ring anchors but have been cut to enable easy demounting of the stained glass windows. The choir of St. Lorenz church in Nuremberg demonstrates the light and rising construction principles of Gothic architecture (Fig 1.8).

With Gothic architecture, the final point of building with natural stone is reached, which cannot be surpassed. The low bending strength of stone does not allow more extreme building constructions. Only in the 19th century did new materials and production techniques open the way to new design concepts. With the emergence of steel and concrete, a new era began. What are the reasons for this change? The Industrial Revolution in the 19th century brought forth new methods of generating energy and production techniques. Modern blast furnaces and converters produced steel of until then unknown high and standardized quality. Subsequently, technically innovative steel constructions could be erected, like the