# Conserving Concrete Heritage

## An Annotated Bibliography

SECOND EDITION

**Bibliography**


Edited by
Ana Paula Arato Gonçalves
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Conserving Concrete Heritage: An Annotated Bibliography (Second Edition)
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The Getty Conservation Institute (GCI) works internationally to advance conservation practice in the visual arts—broadly interpreted to include objects, collections, architecture, and sites. The Institute serves the conservation community through scientific research, education and training, field projects, and the dissemination of information. In all its endeavors, the GCI creates and delivers knowledge that contributes to the conservation of the world's cultural heritage.

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Cover image: SESC Pompéia, São Paulo (1986), by Lina Bo Bardi.
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# CONTENTS

# INTRODUCTION

Anyone involved in the conservation of twentieth-century buildings and structures will inevitably come across concrete in some form or another. The development of concrete and the rapid industrialization of its production in the late nineteenth century made it ubiquitous in the built environment in most parts of the world, and advances in reinforced concrete in the twentieth century captured the imaginations of architects and engineers, resulting in some spectacular structures that are now being recognized for their cultural significance.

Many modern building materials pose specific conservation challenges, and concrete is no exception. There is a burgeoning level of knowledge about and experience with the conservation of concrete, but much work remains to be done to secure better conservation outcomes that are more compatible with current principles. Access to information about the material and its history, deterioration, evaluation techniques, and methods of repair will further this quest. Such information is a necessary part of the conservation practitioner's tool kit.

The primary purpose of this annotated bibliography is to assist practitioners involved in the conservation of concrete by identifying useful resources. Additionally, the bibliography is intended as an educational resource to professionals who are new to concrete conservation. To facilitate navigation of the listed references, a selected number of key resources are highlighted at the beginning of each chapter. Citations selected for annotation are mostly limited to English-language publications.

This annotated bibliography covers mass concrete, reinforced concrete, cast-in-place concrete, post-tensioned prestressed concrete, and precast concrete. It recognizes that the foundational knowledge in concrete conservation is shared with the much broader concrete repair field, with the key difference being the added requirement to identify and conserve cultural significance. Therefore, the annotated bibliography includes selected key resources on concrete and concrete repair as well as a comprehensive collection of conservation-specific references. Broader information on evaluation techniques, repair, and treatments not specifically created with conservation in mind is included with the understanding that it constitutes basic knowledge upon which the concrete conservation practitioner will need to add the appropriate conservation requirements. Given the focus on being a resource to practitioners, references that are not immediately applicable in the field, such as lab-based results of experimental treatments or methods, are not included.

This bibliography includes books, articles from professional publications, full-paper conference proceedings, PhD theses, bibliographies, glossaries, technical guidelines, and electronic and web-based references. It does not include primary sources (period references), as it would be difficult to draw boundaries to define a historic period, and also because primary sources are regionally specific. However, primary sources are clearly important resources in determining cultural significance of concrete and in understanding how it was built. Likewise, standards are not included, since their applicability will vary depending on the location of the practitioner. Standards are also periodically updated, and typically more difficult to access by those professionals who do not use them often. Practitioners should make sure to apply the most updated standards required in their region and by the type of work they are conducting, as they are applicable to all concrete regardless of cultural significance, and any necessary deviations to accommodate conservation requirements would have to be carefully considered and justified.

In the first edition of this bibliography, published in 2015, the references selected for inclusion were drawn largely from *Conserving Twentieth-Century Built Heritage: A Bibliography* (2nd ed., 2013) by Susan Macdonald and Gail Ostergren. This initial list was revised and augmented as additional publications were identified during the annotation process; others were removed as the information therein was determined to be out of date or considered of less-direct relevance to the subject. It was acknowledged that the list of references was not comprehensive, and that it would be useful to expand it in the future. This edition revises and significantly expands the first edition's reference list. Those references were re-analyzed for relevance, scope, and obsolescence, which resulted in a few being removed. In some cases, more recent publications by the same institution or research group covering similar subjects replaced references that had been included in the first edition. Some references were moved to a different chapter to better match the chapter theme. New additions resulted from comprehensive research in reference databases focused on filling any gaps in the 2015 bibliography, and in adding references published between 2015 and 2023.

After the identification of a preliminary list of new references, further culling was conducted by the annotation authors to confirm that references were within the scope of the bibliography, and that the content aligned with current conservation principles and knowledge. This selection process also aimed at balancing the various subject matters addressed by the references while offering a broad diversity of subjects. In addition, we tried as much as possible to make sure the references are accessible either online or through libraries, or available for purchase from publishers.

This bibliography is organized in five chapters, outlined below, which echo the usual steps in the conservation process and have been used in key books on concrete conservation. Publications that span more than one category are noted in all relevant chapters, with the full annotation appearing only in the chapter where it is most relevant.

## Chapter 1: History

These citations on the history and development of concrete include references on the development and use of constituent materials, construction techniques, proprietary systems, and structural typologies typical of concrete.

## Chapter 2: Characteristics, Deterioration, and Damage

These resources on the necessary background knowledge for understanding the behavior and deterioration of concrete cover terminology, structural and material characteristics, performance, and various types of deterioration, such as reinforcement corrosion and alkali-silica reaction.

## Chapter 3: Evaluation

References featured here cover methodologies and techniques for the evaluation of concrete. Also included are case studies that demonstrate how the evaluation phase is conducted so as to understand concrete's behavior and identify causes of deterioration. Also covered are in situ and laboratory testing, nondestructive techniques, and structural assessment.

## Chapter 4: Conservation Approach

These resources focus on conservation principles and their application in the repair and maintenance of culturally significant concrete. Included are case studies demonstrating how conservation principles guide the decision-making process.

## Chapter 5: Repair and Treatments

These citations focus on cleaning, patch repair, treatments, and other interventions typical of a conservation project. They include references concerning the materials and techniques used in various intervention methods, as well as case studies and research demonstrating their application and performance.

CHAPTER 1

# HISTORY

## Key References

Collins, Peter. 2004. *Concrete: The Vision of a New Architecture*. 2nd ed. Montreal: McGill-Queen's University Press.

A revision of a work first published in 1959, this second edition includes a new foreword by Kenneth Frampton and an introduction by Réjean Legault. The book traces the early relationship between reinforced concrete and emerging forms of modernism. Part 1 provides an authoritative background on the material and discusses its history, focusing primarily on France in chapter 1 and the United Kingdom in chapter 2. Chapter 3 discusses the development of reinforcement and reinforcing systems and patents in the United States, France, and the United Kingdom in the late nineteenth and early twentieth centuries. Part 2 covers the role of concrete in defining new architectural forms of expression in the nineteenth and early twentieth centuries. It explores the relationships between the innovative engineers and architects who began experimenting with the structural possibilities provided by this new material and those developing the material itself. Part 3 discusses the work of Auguste Perret, a pioneering figure in modern architecture, and his role in the development of the new structural approaches made possible by reinforced concrete. The revised edition closes with three previously unpublished essays, two of which are on Perret.

Forty, Adrian. 2012. *Concrete and Culture: A Material History*. London: Reaktion Books.

This book discusses various dichotomies in the perception and application of concrete, and concrete's many different associations, taking a global perspective. Each chapter explores a different dichotomy. For example, the first chapter discusses modern versus traditional aspects of concrete, its origins in scientific and industrial experimentation, and artisanal and crafts-based experiments in its application. Chapter 4 questions the idea that concrete is the same everywhere, even though it is perceived as a global medium and part of the idea of an "international style." The author presents national contributions to concrete development, and how concrete became part of national architectural identities, for instance in Brazil and Japan. Another interesting discussion concerns the myth that concrete construction requires no skill; on the contrary, the ability to match aesthetics dictated by designers, even when qualified as "rough," requires a high level of technical competency on the part of builders.

Jester, Thomas C. 2014. "Part II: Concrete." In *Twentieth-Century Building Materials: History and Conservation*, 45–86. Los Angeles: Getty Conservation Institute.

This book examines a wide range of materials found in twentieth-century buildings, and "Part II: Concrete" is a valuable introduction to the various cement-based materials and their conservation. First published in 1995 by McGraw Hill, *Twentieth-Century Building Materials* was among the early texts to highlight the complexities of modern building materials and systems. "Part II: Concrete" covers concrete block, cast stone, reinforced concrete, shotcrete, architectural precast concrete, and prestressed concrete. The history, origins, and development of the specific materials—for instance manufacturing, mix-design information, typical uses, and installation methods—are discussed. Each chapter, with the exception of the one on prestressed concrete, has a section on failures, condition assessments, and material-specific treatments. Discussions on conservation approaches and methodologies are brief, and assume best practices are being carried out. Knowledge of in situ diagnostics, forensics, and laboratory techniques is required and noted within the text. Typical methods of conservation and repairs are described, and replacement when necessary is discussed.

Meinheit, Donald F., and Anthony L. Felder. 2014. *Vintage Steel Reinforcement in Concrete Structures: A Comprehensive and Invaluable Treatise on All Forms of Steel Reinforcement Employed in the Design and Construction of Reinforced Concrete of Long Ago*. Schaumburg, IL: Concrete Reinforcing Steel Institute.

This book is a valuable resource for those investigating reinforcement systems in historic reinforced concrete structures. It is aimed predominantly at structural engineers, and the purpose is to assist the investigator in identifying the type of system used in a structure and provide resources for further investigation. The first five chapters—"Early Reinforced Concrete," "Early Steel Reinforcing Bars," "Early Welded Wire Fabric," "Early Systems of Reinforcement," and "Early Design of Reinforced Concrete"—provide a wealth of information on different types of reinforcements used in the past. The sixth chapter is a bibliography. The text is supplemented by a significant amount of technical data and numerous drawings and illustrations. The detailed appendices include "ASTM Specification A15-11," "Manufacturer's Standard Specifications 1914," "Simplified Practice Recommendations SPR 26-24," "Smithsonian Reinforcing Bar Exhibit," "Early Reinforcing Bar Patents," "Miscellaneous Advertisements," and "Descriptions of Foreign Reinforcing Bar Systems."

Odgers, David, ed. 2012. *Practical Building Conservation: Concrete*. Farnham, UK: English Heritage / Ashgate.

See annotation on p. 70.

Sutherland, James, Dawn Humm, and Mike Chrimes, eds. 2001. *Historic Concrete: Background to Appraisal*. London: Thomas Telford.

This book presents an expanded version of a set of papers on the history of reinforced and prestressed concrete first published in the *Journal of the Institution of Civil Engineers* in 1996. The content covers concrete development in Britain since the mid-nineteenth century, with a focus on practices that are today considered outdated. The book comprises an introduction (chapter 1), eighteen chapters, and four appendices. The chapters cover a comprehensive list of subjects: chapter 2 discusses innovative uses of concrete, with a view to the international context; chapter 3 covers the structural use of concrete and cement prior to 1890, when concrete was usually applied to specific elements like foundations and fireproof flooring; chapter 4 talks about the era of proprietary systems, from 1890 until World War I; chapter 5 offers a review of the development of design and practice based on concrete behavior and standards, starting in 1915 with the London County Council's Reinforced Concrete Regulations; chapter 6 describes the changes in properties, production, and performance of concrete due to factors such as new design standards, production methods, and changes in portland cement properties; chapter 7 focuses on the use of concrete in foundations over time; chapters 8 and 9 cover concrete shells; chapter 10 describes early uses of pre- and post-tensioning systems for prestressing concrete, including materials used; chapters 11 and 12 cover the history of concrete bridges since the nineteenth century; chapter 13 focuses on reinforced and prestressed concrete in maritime structures, such as quays, offshore structures, and lighthouses; chapter 14 tells the history of the Concrete Institute, which preceded the Institution of Structural Engineers; chapter 15 describes the use of concrete in tunnels and how it evolved with tunneling techniques; chapter 16 covers the use of concrete in water-retaining structures before 1920; chapter 17 talks about the history of concrete dams up to the development of thin concrete arch dams; chapter 18 describes the history of concrete roads; and chapter 19 covers concrete in military structures. The appendices contain further resources on historic concrete and detailed drawings of proprietary systems.

## General References

Addis, Bill. 1997. "Concrete and Steel in Twentieth Century Construction: From Experimentation to Mainstream Usage." In *Structure and Style: Conserving Twentieth Century Buildings*, edited by Michael Stratton, 103–42. London: E & FN Spon.

This chapter discusses the historical development and technological advancements of both steel and concrete, with a focus on their evolution in Britain. The first half presents a chronological overview of concrete and steel from the 1900s to the 1990s, highlighting their parallel and interdependent material evolution. The author decided to present these two materials together due to their complementary roles in construction, such as the use of concrete to fireproof steel structures and the use of steel reinforcement in concrete.

Aprea, Salvatore. 2016. *German Concrete: The Science of Cement from Trass to Portland, 1819–1877*. Treatise on Concrete. Lausanne, Switzerland: EPFL Press.

This book is part of the series Treatise on Concrete, which focuses on historical uses of concrete and their associated construction techniques, materials, and architectural expression. The present volume offers a comprehensive history of binders and the use of concrete in construction in Germany at the end of the nineteenth century: it describes the evolution of knowledge, manufacture, and application of these binders in concrete, and techniques and uses for concrete in construction. The book starts with the use of lime and hydraulic mortars using trass in concrete applied in foundations and to fill in hollow masonry-faced walls, as well as the first attempts at making artificial stone. The book also describes the introduction of cement manufacturing. It presents the initial uses of portland cement in concrete foundations and in mortars for masonry, predating their application to structural elements in a more comprehensive way. High-resolution historic construction details are helpful in understanding how concrete was used and where practitioners can expect to find these early types of concrete when working on structures from this period.

Aument, Lori. 2003. "Construction History in Architectural Conservation: The Exposed Aggregate, Reinforced Concrete of Meridian Hill Park." *Journal of the American Institute for Conservation* 42 (1): 3–19. https://doi.org/10.1179/019713603806112840.

This article reports on the historical research conducted in preparation for conservation and repair work on Meridian Hill Park in Washington, DC (1915–36). It focuses in particular on John J. Earley's development of concrete technologies to achieve the desired finishes. The research looks in detail at preparation techniques, exposed aggregate finishes, and the use of reinforcement, and identifies the developments and advances in knowledge associated with each of the three phases of the project. From 1915 to 1916, when initial experimentation was undertaken, mock-ups were produced and construction started at the west wall. From 1917 to 1918, techniques were developed to improve color, texture, and form, and included important steps such as grading of aggregate and control of water. Between 1919 and 1936, the concrete work was completed, largely by other concrete contractors but following Earley's techniques. The dissemination of these techniques is identified as one of the major achievements of Meridian Hill Park. The article concludes with a brief discussion on future conservation and repair works at this site.

Basiricò, Tiziana. 2012. "The 'Mixed Structures' of the Sanatoriums Built in the 30s in Italy." In *Structural Analysis of Historical Constructions: Proceedings of the International Conference on Structural Analysis of Historical Constructions, SAHC 2012, 15–17 October 2012, Wrocław, Poland*, edited by Jerzy Jasieńko, 1021–28. Wrocław, Poland: Dolnośląskie Wydawnictwo Edukacyjne.

This paper describes the structure of a typical sanatorium built in the 1930s in Italy, where reinforced concrete was used in combination with traditional techniques. This "mixed structure" was common at this place and time, but the paper is also relevant to other parts of the world, as it was a widespread practice in the transitional period when reinforced concrete was still relatively expensive and less well known. In these structures, reinforced concrete was reserved for specific uses, such as floors, stairs, and overhangs. Load-bearing walls were typically constructed of traditional masonry, and roof structures were usually of wood. The investigation shows the application of nondestructive techniques, such as thermography, in the detection of reinforced concrete elements hidden in walls and behind decorative surfaces. This type of survey is especially useful when there is little known documentation on the structural design.

Bell, Joseph N. 1969. *From the Carriage Age . . . to the Space Age . . . The Birth and Growth of the Concrete Masonry Industry*. Arlington, VA: National Concrete Masonry Association.

This book documents the history of the National Concrete Masonry Association (NCMA) alongside the history and development of concrete block in the United States from the nineteenth century to 1969. The first half traces the chronological development of the concrete block industry from its beginnings in the early nineteenth century. It is divided into chapters covering eras of significant development for the industry, notable figures, and important milestones for the NCMA. The chapters in the second half address areas of particular importance and key developments for the concrete block industry: lightweight aggregates, low-pressure curing, autoclave curing, transportation and handling, concrete masonry machinery, and specifications. The text is detailed, with information on specific industry figures, manufacturers, and products, along with their relevant dates.

Berg, Samuel A. 2005. "History of Reinforced Concrete to 1950: The Development of the Composite in Properties, Computation Models and Safety." PhD diss., KTH Royal Institute of Technology.

This doctoral dissertation has three main aims: to fill a gap in contemporary technical literature on reinforced concrete, to document the historical importance of the construction revolution brought about by the creation of reinforced concrete, and to cover key contributions in the development of reinforced concrete. It addresses the trials and errors experienced during the development of reinforced concrete construction methods, identifying them as an important part of the process; it also discusses successes and progress made. The text is divided into seven chapters: "Variables in Stressed Materials," "Early Steps of Increasing Knowledge in Reinforced Concrete," "Theories of Reinforced Concrete," "Safety of Reinforced Structures," "Fresh and Hardened Concrete," "Qualification of Reinforcement," and "The Epoch of Construction Inventions and Patents." It examines the period from roughly 1850 to 1950, which encompasses the birth and development of the composite material known as reinforced concrete. It covers many technical aspects, identifies and discusses important aspects of its science and engineering, and includes calculations and technical drawings.

Berkowski, P., and M. Kosior-Kazberuk. 2016. "Historical and Structural Aspects of the Durability and Maintenance of a Reinforced Concrete Market Hall Building from the Early 20th Century." In *Concrete Solutions: Proceedings of Concrete Solutions, 6th International Conference on Concrete Repair, Thessaloniki, Greece, 20–23 June 2016*, edited by Michael G. Grantham, Ioanna Papayianni, and Kosmas Sideris, 335–43. Leiden, the Netherlands: CRC Press / Balkema.

This paper focuses on the construction history of an early twentieth-century concrete structure in Poland: Market Hall in Wrocław, designed by Richard Plüddemann and built between 1904 and 1908. The three-nave building measures thirty-nine by eighty-six meters in plan and twenty-one meters in height. Its main load-bearing structure is comprised of parabolic arches connected by transversal castellated beams. The authors stress the importance of developing an architectural and structural historical analysis to better inform conservation actions, but also to help build knowledge regarding these historic techniques. According to the authors, the historical analysis should focus on understanding design solutions, construction technology, properties of building materials, and calculation methods originally used for dimensioning structural elements. This approach is demonstrated in the research presented, which is based on a rich set of original drawings. Reference is made also to the ICOMOS charter Principles for the Analysis, Conservation and Structural Restoration of Architectural Heritage, which contains recommendations for diagnosis of and interventions in historic structures. The paper also mentions the need to develop a maintenance plan. A brief description of the current conditions of the Market Hall and some preliminary considerations for future maintenance are also provided.

Brueckner, Rene, and Paul Lambert. 2017. "Unexpected Effects of Historic Concrete Innovations." *International Journal of Heritage Architecture* 1 (4): 549–63. https://doi.org/10.2495/HA-V1-N4-549-563.

This article starts with the history of concrete and typically used binders, followed by sections on: portland cement, super-sulfated cement, high-alumina cement, asbestos cement, and calcium chloride admixture. For each, the authors explain basic composition, properties, compatibility issues, and any effect on the deterioration of concrete. The article indicates the periods when the materials were in use in the United Kingdom, which is useful to professionals investigating historic concrete. For example, super-sulfated cement, invented in 1908 and common after World War II, has high resistance to aggressive chemical conditions but is less protective against corrosion due to low alkalinity. The authors warn against using portland cement when repairing concrete made with it due to the high risk of gypsum and ettringite forming, leading to repair failure. The authors also cover high-alumina cement, popular in precast concrete in the 1960s and 1970s but banned in most of Europe in the 1970s, when it was found to make the concrete more porous and friable with time. For these structures, conservation could require strengthening or replacement. The article dedicates a large section to calcium chloride, an accelerating admixture first patented in 1885 and popular in cold-weather work and to speed up construction. It was banned in the United Kingdom in 1977, when it became evident that it was more damaging to reinforcement than initially thought. Electrochemical techniques such as cathodic protection and chloride extraction are presented as remediation options.

Burke, Amanda R. 2016. "Free Form Concrete: Establishing a Common Ground." In *Proceedings of the Mid-Century Modern Materials and Preservation Symposium: April 13–16, 2015, Saint Louis, Missouri*, edited by Kathryn Doyle, Andrew Ferrell, Frank E. Sanchis III, and Mary F. Striegel, 207–14. Natchitoches, LA: Friends of NCPTT.

This paper introduces the history of thin-shell concrete in the United States, briefly describes the most common construction techniques, such as shotcrete and Airform Monolithic Domes, then presents the appropriate nomenclature, derived from engineering and mathematics, to describe these free forms. According to the author, the three main types of forms used in thin-shell concrete structures are Gaussian, Analytical, and Experimental. Gaussian is the most common type and describes any shape formed by deforming portions of a flat plane, such as domes or hyperbolic paraboloids. Analytical forms were popular between the 1930s and 1960s and are formed by rotating a two-dimensional shape around an axis; examples include surfaces of revolution and ruled helicoids. Experimental forms were introduced by engineer Heinz Isler in 1959 and include organic shapes derived from experimentations with pneumatic, hanging, and flowing forms. The author provides examples of these forms in buildings, making it easy for the reader to understand the nomenclature.

Bussell, Michael N. 2007. "Conservation of Concrete and Reinforced Concrete." In *Structures and Construction in Historic Building Conservation*, edited by Michael Forsyth, 192–210. Historic Building Conservation. Oxford: Blackwell.

This book chapter on the conservation of concrete and reinforced concrete gives a general overview of historic uses and takes a brief look at issues of durability and conservation. The first part deals with the history and development of both unreinforced and reinforced concrete from the start of the nineteenth century, written from the perspective of developments in the United Kingdom. Chemical issues affecting the durability of historic concrete are introduced, and issues arising from construction are discussed. Specific examples illustrate various issues caused by historic changes in concrete, for example, developments in formwork or the use of high-alumina cement. Conservation is discussed briefly in terms of site investigation and assessment, and repair and remediation, followed by discussion on treating corrosion damage. Brief references are made to the treatment of other common damage typologies.

Bussell, Michael N. 2008. "Concrete and Reinforced Concrete." In *Materials and Skills for Historic Building Conservation*, edited by Michael Forsyth, 92–108. Oxford: Blackwell.

See annotation on p. 32.

Cassie, W. Fisher. 1955. "Early Reinforced Concrete in Newcastle upon Tyne." *Magazine of Concrete Research* 7 (19): 25–30. https://doi.org/10.1680/macr.1955.7.19.25.

This short article documents construction details of a house in Newcastle upon Tyne, England, built in 1865 entirely from reinforced concrete and demolished around 1955. The house was built using the Wilkinson patent, which dates from 1854 and utilizes flat bars and wire ropes as reinforcement. The author provides photographs taken during demolition and detailed drawings of the floor beams and slab, documenting the reinforcement system. The text also describes the results of an analysis of samples of the floor slab collected in two-inch-square cubes, such as compression strength, water absorption, and aggregate composition. The house is reported to have been in excellent condition at the time of demolition.

Clarke, J. L. 2009. *Historical Approaches to the Design of Concrete Buildings and Structures*. Technical Report, no. 70. Camberley, UK: Concrete Society.

This publication provides useful information to engineers evaluating historic reinforced or prestressed concrete buildings, bridges, and other structures, including precast concrete systems. It draws from historic structural codes and standards in the United Kingdom to aid in understanding how structures were originally designed. The content is also useful in relating structural and material characteristics to specific construction periods based on contemporaneous codes and standards and what was available at the time of construction. The information is presented in a concise manner, but the document offers many useful references for further information. Chapter 2 gives a brief account of the development of concrete and concrete structures and refers largely to parts of *Historic Concrete: Background to Appraisal* (2001), edited by James Sutherland, Dawn Humm, and Mike Chrimes (see annotation on p. 10). Chapter 3 lists design codes from 1915 to 1987 and design standards from 1945 to 1990. Two chapters identify key changes in codes and standards: chapter 4 focuses on changes in materials, and chapter 5 focuses on changes in structural design. Chapter 6 covers historic guidance for specific concrete applications, such as precast systems, foundations, and water-retaining structures. The last chapter offers guidance regarding some types of concrete deterioration: alkali-silica reaction, sulfate attack, mundic (pyrite), and clinker concrete.

Cowden, Adrienne Beaudet. 1993. *Historic Concrete: An Annotated Bibliography*. NPS Reading List. Washington, DC: US Department of the Interior, National Park Service, Preservation Assistance Division. http://npshistory.com/publications/preservation/reading-list/hist-concrete.pdf.

This bibliography on historic concrete brings together key texts covering the period from 1900 to 1950, except for the first chapter, which includes texts written as early as 59 BCE. Its four chapters address the history and evolution of concrete as a building material; concrete manufacture and design; concrete failure, deterioration, and repair; and applications of concrete.

Croft, Catherine. 2004. "Introduction: The Challenge of Concrete." In *Concrete Architecture*, 10–23. London: Laurence King.

The introductory chapter in *Concrete Architecture* provides a detailed history of concrete from its beginnings. The author identifies the main phases of concrete development, key figures, and the development of cement technology. Also discussed are the generally negative public and professional perceptions of concrete and the resulting impact on its use and popularity. Even architects who were early users of exposed concrete—for instance Frank Lloyd Wright—are quoted as expressing negative views of the material. Its breakthrough after World War II, the author explains, was partly because it was readily available, but also out of an interest in modernization and a desire to break with the past.

de Jonge, Wessel, and Arjan Doolaar, eds. 1998. *The Fair Face of Concrete: Conservation and Repair of Exposed Concrete*. Preservation Technology Dossier 2. Eindhoven, the Netherlands: DOCOMOMO International / Eindhoven University of Technology.

These are the proceedings of "The Fair Face of Concrete," a 1997 DOCOMOMO International seminar. All nineteen papers are relevant to the conservation of historic concrete, and many provide insights into the early years of this practice. The publication is divided into three sections: "History and Development," "Diagnose and Remedy," and "Case Studies." The papers in "History and Development" introduce the subject, with discussions on the use of concrete and the philosophical issues posed by the deterioration of a reinforced concrete building. The four papers in "Diagnose and Remedy" focus on electrochemical techniques to treat historic concrete. The nine case studies present conservation works undertaken on exposed reinforced concrete structures dating from 1920 to 1968. Three case studies of particular note cover the Bahá'í House of Worship by Robert Armbruster, Saint Antonius Church and Goetheanum by Vojislav Ristic, and the Beethoven Hall of the Stuttgart Liederhalle by Rudolf Pörtner. The latter two papers are of particular interest because they offer very different options for treating deteriorating historic concrete: Ristic presents two case studies where the decision was made to remove the concrete cover from the whole facade and undertake a full replacement, while Pörtner advocates for minimal patch repairs.

del Cueto, Beatriz. 2016. "Hydraulic Mosaics and Concrete Blocks in the Spanish Caribbean." *APT Bulletin: Journal of Preservation Technology* 47 (4): 15–22.

Concrete block machines first arrived in Cuba in 1901 from the United States, and they were soon also in use in the Dominican Republic and Puerto Rico. Concrete blocks gained popularity as an economical, easy-to-produce, durable construction material and were applied in a variety of building types, from institutional to residential. This article discusses the use of concrete blocks—as well as hydraulic mosaic cement tiles, another popular prefabricated architectural element using Portland cement—in the Spanish Caribbean from the 1880s to the 1920s, and raises awareness of their historic and architectural significance there. It starts by explaining how portland cement products gained popularity after the Spanish-American War and with the establishment of the first local cement manufacturers. The second part discusses the manufacture and use of hydraulic mosaic cement tiles. The third part is dedicated to hollow concrete blocks used to imitate stone.

Draffin, Jasper O. 1943. "A Brief History of Lime, Cement, Concrete, and Reinforced Concrete." *Journal of the Western Society of Engineers* 48:14–47.

This article discusses the history and development of lime and cement binders and concrete up to 1943. The first section addresses the origins and development of the use of lime and cement binders, with subsections on early materials, hydraulic lime, natural cement, and portland cement, and further discussions of their physical properties. The second section focuses on concrete and its use and development. The initial discussion addresses the material itself: the choice of aggregate, mix proportions, water-to-cement ratio, and its placement. The subsequent discussion focuses on reinforced concrete, and introduces key figures involved in the development of different aspects of this composite material. Rather than following a straightforward chronology, various elements and types of reinforced concrete are introduced and discussed separately, including monolithic structures, mushroom slabs, reinforced concrete columns, and concrete bridges. This is followed by information on the types of testing conducted to better understand the systems and their physical properties and capabilities.

Du, Q., and B. Qiu. 2021. "A Study of the History of Concrete Technology Introduction in China." In *History of Construction Cultures: Proceedings of the 7th International Congress on Construction History (7ICCH 2021), July 12–16, 2021, Lisbon, Portugal*, edited by João Mascarenhas-Mateus and Ana Paula Pires, 688–94. Boca Raton, FL: CRC Press. https://doi.org/10.1201/9781003173434-202.

This paper investigates the introduction of concrete technology in China, with the aim to describe how this technology was integrated into the national engineering training and construction industry, how it gradually influenced construction in China, and how knowledge exchange between East and West unfolded. A crucial period of East-West exchange was from the late Qing dynasty to the early Republic of China (ca. 1840–1919), when young Chinese professionals were sent to Europe, the United States, and Japan to acquire new knowledge that could be disseminated in China. To understand how concrete technology was introduced and assimilated in the country, the paper reviews key Chinese technical publications from 1900 to 1949, including professional engineering publications, building codes and specifications, engineering practices, and higher and/or vocational education. Concrete technology had a strong impact in the Chinese construction sector in the twentieth century, and the authors argue that it would be hard to understand the modernization of Chinese architecture without awareness of the development of concrete technology there.

Friedman, Donald. 2010. "Reinforced-Concrete Buildings." In *Historical Building Construction: Design, Materials, and Technology*, 131–68. New York: W. W. Norton.

This book aims to help architects and engineers understand how historic structures were designed and built in the United States so as to minimize the impact of necessary adaptations to these structures, and chapter 8 is dedicated to reinforced concrete buildings. The author identifies three periods in the development of concrete construction in the United States: the earliest one, lasting until the 1900s, when concrete was used to imitate masonry, followed by a period when concrete imitated steel skeleton frames, and a final transition in the 1920s to structures making full use of concrete's unique characteristics. The author mentions common issues resulting from the experimental nature of early reinforced concrete structures, such as inadequate shear reinforcement in beams, and segregation of the concrete mix in structures built prior to the use of mechanical vibrators introduced after World War II. The chapter dedicates sections to the use of concrete blocks in masonry, Ernest L. Ransome's reinforced concrete systems, including his system for concrete curtain walls, the development of flat slab systems, the various patented reinforcing systems that coexisted before the first national standard was created in 1946, and precast concrete. The author presents the development of these different applications of reinforced concrete through descriptions of examples where they were applied and illustrations of key structural details. Another section describes the development of structural analysis for reinforced concrete, which trailed the development of structural design. The author also gives a brief account of the variability of materials used in reinforced concrete, for example the use of both natural cements and Portland cement starting in the 1870s; Portland cement was introduced in the US market around then, but would only become more common than natural cements after 1900.

Gaudette, Paul E., and Deborah Slaton. 2007. *Preservation of Historic Concrete*. Preservation Briefs 15. Washington, DC: National Park Service, Heritage Preservation Services. https://www.nps.gov/orgs/1739/upload/preservation-brief-15-concrete.pdf.

See annotation on p. 69.

Heinemann, Herdis A., and Timo G. Nijland. 2009. "Concrete in the Netherlands: Historic Use of Components and Conservation." In *Proceedings of the Third International Congress on Construction History: Brandenburg University of Technology Cottbus, Germany, 20th–24th May 2009*, edited by Karl-Eugen Kurrer, Werner Lorenz, and Volker Wetzk, 791–98. Cottbus, Germany: Brandenburg University of Technology.

This paper discusses the historic use of binders and aggregates in concrete in the Netherlands. The author argues that investigating the constituents of historic concrete is important for understanding material properties, and also for assessing historic significance of the materials, as they can be evidence of technological and social contexts and design intent. The paper starts with an overview of the earliest uses of concrete in the Netherlands, with reinforced concrete starting to be used in the 1880s. The next section describes different types of binders used through history, starting with pure Portland cement, then moving into binders that replaced part of the Portland cement clinker with different types of blast-furnace slag starting in the early twentieth century. According to the author, it was common to mix Portland cement with trass or lime in concrete, with trass being used into the 1970s. The article explains that the identification of binders in concrete is challenging, and that polarized fluorescent microscopy is needed. The following section is dedicated to aggregate types used throughout history—at first there was a preference for crushed stone, but gravel became predominant in the 1910s and 1920s. There were also many experiments with other materials, such as crushed brick, pumice, and slag. In certain cases, aggregates were specifically chosen for aesthetic reasons. Regarding reinforcement, the author mentions that smooth round reinforcement was most common in the Netherlands until after World War II.

Hellebois, Armande, and Bernard Espion. 2012. "Insight into Technological Aspects of the Evolution of the Hennebique Reinforced Concrete System." In *Structural Analysis of Historical Constructions: Proceedings of the International Conference on Structural Analysis of Historical Constructions, SAHC 2012, 15–17 October 2012, Wrocław, Poland*, edited by Jerzy Jasieńko, 1160–70. Wrocław, Poland: Dolnośląskie Wydawnictwo Edukacyjne.

This paper presents the results of an analysis of twenty projects built in Belgium by the Hennebique office between the 1900s and the 1930s. The research also covers an analysis of Hennebique Belgian patents and literature from this period. The authors focus on reinforcement, materials, construction technique, and calculation for the Hennebique system for beam-floor and column, with special interest in any changes adopted over time. The paper starts with a description of the reinforcement system, noting that it was simplified in the 1910s. The following section discusses what is known about concrete mixtures used by Hennebique and gives an account of how the concrete was mixed—first by hand, then mechanically starting in 1904—and poured. This part also describes results from tensile and metallographic analyses of seventeen samples of mild steel reinforcement from a site. The following section is dedicated to describing the Hennebique calculation method, which did not change in the period studied despite the adoption of new concrete calculation theories by national standards developed in the early decades of the twentieth century. The paper is a useful resource for engineers evaluating Hennebique structures, and for conservation practitioners seeking to ascertain the significance of a Hennebique structure based on how it relates to the evolution of that system.

Hewlett, Peter C., and Martin Liska, eds. 2019. *Lea's Chemistry of Cement and Concrete*. 5th ed. Oxford: Butterworth-Heinemann.

See annotation on p. 28.

Holzer, Stefan M. 2016. "Canal Locks and Concrete, 1800–1860." *Construction History* 31 (2): 133–56.

This article describes how concrete began to be employed in hydraulic infrastructure in the nineteenth century. Unreinforced concrete was introduced in the 1820s and 1830s as a solution for waterproofing the bottoms of canals and locks, and as foundation for these structures, and evolved to structures fully built in concrete by 1854. The large-scale application of concrete in canal construction started in France, spreading rapidly to Germany and Prussia. In France, advances in production of hydraulic lime in the beginning of the nineteenth century allowed for its use in large-scale construction projects. In addition, engineers took advantage of concrete's known capacity to harden underwater to develop techniques for pouring canal lock slab underwater. These experiences aided the development of construction techniques and the advancement of knowledge around concrete behavior that would later inform its use in general construction practices.

Institution of Civil Engineers. 1996. "Historic Concrete: Special Issue." *Proceedings of the Institution of Civil Engineers. Structures and Buildings* 116 (3–4).

These fourteen papers on different aspects of the history and development of concrete are written by several different authors active in the field of concrete construction. Each focuses on a different period and/or key subject, with most featuring developments from the twentieth century. The issue was published as a historical guide for engineers. It identifies some of the key features of historic concrete structures, but also adds a cultural slant to this information. Topics include the use of concrete for foundations, maritime structures, and bridges; development and understanding of materials; and reinforced and prestressed concrete systems. The papers have a British focus, but often compare developments in other countries.

Isaacs, Nigel. 2015. "Hollow Concrete Blocks in New Zealand 1904–10." *Construction History* 30 (1): 93–108.

This article gives an account of the first concrete block production initiatives in New Zealand in the first decade of the twentieth century, and the origins of this technology in the United States. Most of the text is dedicated to the history of the first manufacture of concrete block in New Zealand at Wellington. Even though the company had little success, it helped introduce the new material to the country through advertisements in local newspapers. The blocks were produced using machinery and technology patented by the American Harmon S. Palmer between 1898 and 1901. The article presents a timeline of other concrete block manufacturing initiatives that soon popped up across the country, and identifies key differences between early concrete block construction in the United States versus New Zealand. In the latter, it remained in the realm of professional builders, while in the former it was also advertised to and used by amateurs. The other difference pertains to preference regarding concrete block surface patterns, with the US market demonstrating a stronger predilection for stonelike patterns.

Jones, Nick. 2017. *The World Recast: 70 Buildings from 70 Years of "Concrete Quarterly*." London: Artifice Books on Architecture / Concrete Centre.

This book presents a selection of works featured in the British magazine *Concrete Quarterly* between 1947 and 2017. The book is organized by decade, forming a timeline of how concrete has been used and perceived. Each chapter starts with a short introduction providing a context for the selected works, which represent notable concrete buildings from a diverse geographic spread. The buildings are presented through photographs and occasionally drawings with short texts highlighting the technical and aesthetic achievements that would have inspired *Concrete Quarterly*'s audience of engineers and architects. In some cases, the text also includes an update on the current state of the building, especially when there have been significant threats to its survival. The 1947–59 chapter shows concrete being used to overcome shortages in building materials for postwar reconstruction, employing techniques such as prestressed concrete and thin shells. The 1960s chapter describes that decade as the "heroic age of concrete architecture," with bold and sculptural buildings, followed by the 1970s chapter introducing a growing criticism of modernist ideas, but still including great architectural and engineering accomplishments in concrete. The 1980s and 1990s chapters are the shortest and represent the worsening perception concrete acquired due to its indiscriminate use in previous decades in poorly built mass housing. The last two chapters, covering the 2000s and 2010–17, show concrete's comeback with its application in iconic architecture, leveraging new knowledge to control color and texture, culminating with the popularization of older concrete buildings and efforts toward their reuse, such as Park Hill in Sheffield, England.

Kalisch, Manuel Arturo Román. 2017. "Construction Technology Development in Mérida, Yucatán, Mexico: From Reinforced Concrete Structures to Reinforced Concrete Shells (1903–64)." *Construction History* 32 (2): 109–30.

This article describes how reinforced concrete was used in Mérida, Mexico, in the first half of the twentieth century. It was first used under the Hennebique patented construction system, brought to Mexico in 1902 and applied in Mérida soon after, in 1903, in the construction of a three-story commercial building. The author argues that although there are other examples from these early days of buildings such as this one, constructed entirely of reinforced concrete, reinforced concrete was far more often used in combination with traditional building techniques until the mid-twentieth century. The author presents multiple examples of buildings where reinforced concrete was used in slabs, beams, and columns, combined with load-bearing masonry. Also included are examples illustrating how reinforced concrete construction technologies evolved locally in the late 1950s to allow for the use of folded reinforced concrete roofs and reinforced concrete shells.

Kemp, Emory Leland. 1982. *History of Concrete, 30 BC to 1926 AD: Annotated*. ACI Bibliography 14. Detroit: American Concrete Institute.

This annotated bibliography was produced by the American Concrete Institute as part of an effort to encourage interest in the history of concrete. The project was initiated in 1976, the year of the US bicentennial, and used the same age criteria as many bicentennial history projects, namely considering only references that were at least fifty years old in order to allow historical distance and greater objectivity in evaluating the sources. Thus, for primary sources, the ACI used a cutoff date of 1926, but later, secondary works on the history of concrete were included. Each reference includes a brief summary and identifies locations where the publication could be found.

Kurrer, Karl-Eugen. 2018. "Reinforced Concrete's Influence on Theory of Structures." In *The History of the Theory of Structures: Searching for Equilibrium*, 664–778. Berlin: Wiley, Ernst & Sohn.

This book chapter discusses how reinforced concrete structures were designed and calculated, and will be useful to engineers tasked with the structural assessment of a historic concrete structure. The publication focuses on Germany, but it should be useful to a broader audience, as a significant amount of knowledge on reinforced concrete structures came from that country in the early days of the technology. Chapter 10 presents a brief history of the adoption of the Monier system in Germany and the development of the first structural design method by Matthias Koenen, based on technical trials. The author introduces the design method of Paul Christophe, from Belgium, who developed a reinforced concrete theory in 1899 that would become internationally adopted, including as the basis for the German reinforced concrete standard. The author also highlights how developments in reinforced concrete structure pushed the evolution of structural theory, especially with the development of shell structures and prestressed concrete.

Landi, Stefania. 2021. *Grain Silos from the Thirties in Italy: Analysis, Conservation and Adaptive Reuse*. Architect(ure)s 4. Pisa, Italy: Pisa University Press.

This volume gathers the results of the first systematic study of the network of grain silos built in Italy during the 1930s, following the institution of the so-called *ammassi collettivi* (collective storage facilities) within the framework of the Fascist regime's agricultural policies. The national-scale inventory was carried out through an analysis of bibliographic and archival sources. This work evidences the adoption of a modern architectural language and the use of reinforced concrete as the main construction system, together with steel-and-glass glazing components, of the grain silo typology in Italy. Today largely unused, these industrial structures are threatened by demolition, alterations, and complete abandonment, which has caused significant deterioration. The assessment of their historical and architectural value, which is still not properly recognized, is, therefore, fundamental for their preservation. Based on such awareness, the research study includes an analysis of the formal, functional, and technological characteristics of this typology and tackles the complex challenges related to adaptive reuse and conservation.

Macdonald, Susan, ed. 2003. *Concrete: Building Pathology*. Oxford: Blackwell Science.

See annotation on p. 43.

Marcos, Ignacio, José-Tomás San-José, Leire Garmendia, Amaia Santamaría, and Juan Manuel Manso. 2016. "Central Lessons from the Historical Analysis of 24 Reinforced-Concrete Structures in Northern Spain." *Journal of Cultural Heritage* 20:649–59. https://doi.org/10.1016/j.culher.2016.03.003.

See annotation on p. 36.

Marcos, Ignacio, José-Tomás San-José, Amaia Santamaría, and Leire Garmendia. 2018. "Early Concrete Structures: Patented Systems and Construction Features." *International Journal of Architectural Heritage* 12 (3): 310–19. https://doi.org/10.1080/15583058.2017.1323241.

This article starts with a brief history of patented reinforced concrete systems and how they were adopted in Spain. In Spain, the main patented systems came from other European countries, but there were also national patents in use. Most of the article is dedicated to presenting case studies from the early twentieth century representing three different proprietary systems—Hennebique, Monier, and Blanc—including compressive strength results from cores and the main deterioration issues observed in each. The authors consider that even though the compressive strength values varied a lot in each structure, the mean values were high.

The authors also provide a description of the reinforcement systems as described in each patent and compare them to what was observed in each case study, noting instances of local adaptation, especially in the case of the Monier and Blanc case studies. Practitioners working on structures where these patented systems have been used will find this reference informative. It also demonstrates the need to combine historical research with investigation and testing to better understand the behavior of historic reinforced concrete.

Mascarenhas-Mateus, João, ed. 2023. *Changing Cultures: European Perspectives on the History of Portland Cement and Reinforced Concrete, 19th and 20th Centuries*. Leiden, the Netherlands: CRC Press / Balkema. https://doi.org/10.1201/9781003368656.

This two-part book provides a valuable overview of the origin and development of concrete technologies in Europe. The author describes how this fundamental chapter in the history of construction in the nineteenth and twentieth centuries was triggered by a conjunction of innovations in multiple fields: mathematics, chemistry, physics, materials production, and machinery. This period thus saw the parallel development of a multitude of new patents as well as new legislative frameworks. An intense knowledge transfer within a network of experts, manufacturers, and other key actors also contributed to the development of concrete technology. The volume explores these technological and business advances through case studies from the United Kingdom, Germany, Switzerland, France, Belgium, Portugal, Spain, and Italy. The author discusses the mutual influences resulting from the case studies' economic, social, political, cultural, and technological contexts, unveiling the histories of construction companies that realized both private works and major infrastructure.

Morris, Anthony Edwin James. 1978. *Precast Concrete in Architecture*. London: George Godwin.

This book provides guidance to those wishing to achieve high-quality design in precast concrete; it is not a technical guide. The author also brings attention to aspects of the field perceived as misinterpreted or overlooked. The first three sections document the history of the development of precast concrete through the 1970s. The final section, comprising the second half of the book, provides detailed case studies. Part 1, "Historical Origins," documents developments from the first half of the nineteenth century through 1950. The subject is dealt with chronologically, mainly focusing on specific figures and their contributions to the development of precast concrete. Also included are some nineteenth-century views on precast concrete systems as well as a section addressing the origins of and developments in precast concrete in the United States through 1950. Part 2, "The 1950s and '60s: An Era of Consolidation," focuses on the construction of London's Alton Estate West (Roehampton Lane Flats) (1953–58), which marks a time of change for the precast industry; precast concrete cladding and systems development are two key topics discussed. In the second part of this section, the author addresses developments in Britain and the United States in the 1960s and gives multiple examples of precast concrete architecture from this period. In part 3, "Technology of the 1970s," the author looks back on predictions he had made for the industry in 1966 and discusses different elements of the current technologies, systems, and processes, along with recent developments. The text is accompanied by technical details and drawings. Part 4 includes building case studies from Britain, the United States, and Europe, and takes a closer look at the histories and key projects of several architectural practices.

Nasser, George D., and Deborah J. LeBrun. 1981. *Reflections on the Beginnings of Prestressed Concrete in America*. Chicago: Prestressed Concrete Institute.

This book gathers a series of articles published in the *Prestressed Concrete Institute Journal* between 1978 and 1980 in celebration of the institute's twenty-fifth anniversary. All are focused on North America, with the majority specifically addressing certain states or regions, including Florida, Tennessee, Colorado, the western United States, and Canada. A few focus more specifically on people in the industry and their contributions to the development of prestressed concrete. The final three articles are a continuing series written to fill important gaps in the history of prestressed concrete that are not covered elsewhere in the volume. At the back of the publication is a chronological summary of milestone developments and events in the North American prestressed concrete industry between 1939 and 1958.

Newby, Frank, ed. 2001. *Early Reinforced Concrete*. Studies in the History of Civil Engineering 11. Aldershot, UK: Ashgate/Variorum.

The sixteen papers collected here were originally published in a range of journals and magazines across the twentieth century. The introduction provides a detailed summary of the history and development of binders, mortars, and concrete; a discussion of the structural design of reinforced concrete; and summaries of the development of reinforced concrete in Europe, the United States, Australia, and Britain. Some papers focus on the work of specific pioneers: Robert Smirke, William B. Wilkinson, François Hennebique, Louis Gustave Mouchel, and Paul Cottancin. Others trace the development and evolution of cement and concrete, reinforcements, and whole reinforced concrete systems through the early twentieth century. The final papers address specific case studies or case study areas: Ward House, Rye, New York (the first reinforced concrete structure in the United States); the Ingalls Building, Cincinnati (the first reinforced concrete skyscraper); early concrete bridges in California; and early reinforced concrete structures in New South Wales, Australia.

Palley, Reese. 2010. *Concrete: A Seven-Thousand-Year History*. New York: Quantuck Lane Press.

This book documents the history of concrete over the past seven thousand years. Broadly delivered in chronological order, each of the first seven chapters focuses on a particular period, and generally on one or more key figures. The second half of the book focuses on developments in the twentieth century and beyond, with the last six chapters addressing different contributors, such as Thomas Edison and Henry Flagler, as well as particular historical uses of concrete, for instance military or artistic. Much of the discussion on concrete in the twentieth century focuses on its military purposes, particularly in relation to World War II. The book is written in a narrative style, with some of the content reflecting the author's interests rather than a traditional set of key moments or figures. The author addresses some of the reasons why concrete usage has been sporadic rather than continuous, as well as many social factors that have influenced its place in history.

Peterson, James L. 1954. "History and Development of Precast Concrete in the United States." *Proceedings – American Concrete Institute* 50 (2): 477–96.

The author addresses the structural applications of precast concrete in the United States from the end of the nineteenth century to 1954. The article is divided into marine construction, bridges, buildings, concrete products, lift-slab construction, and prestressed precast concrete structures. Each topic is introduced and then followed by multiple examples of relevant structures, along with technical data on precast unit sizes and information on unit production and construction techniques employed. Many of the examples represent important developments in the technology and use of precast concrete.

Pfammatter, Ulrich. 2008. "How Concrete Became Lighter: 100 Years of Concrete Pioneers." In *Building the Future: Building Technology and Cultural History from the Industrial Revolution until Today*, 102–55. Munich: Prestel.

This chapter on the development of concrete technologies is from a book that addresses developments in construction materials, processes, and design since the Industrial Revolution. It begins with a history of the development of concrete technology, and each of the sections following addresses an aspect of this development and includes detailed case studies. The first section introduces the importance of concrete construction and design as a means for social change in the twentieth century. The three case studies in this section illustrate the development of concepts and design ideas. The next section looks at the Hennebique system and its importance in the evolution of the uses of reinforced concrete. The five supporting case studies are examples of European residential architecture and include key buildings of Dutch modernism. A section on the invention of the mushroom column explains how this technology enabled advances in design and use of interior space. Industrial and commercial case studies from Europe and the United States illustrate this technology. The final two sections address technological advances that have enabled new ways of utilizing space.

Prudon, Theodore H. M. 1981. "Confronting Concrete Realities." *Progressive Architecture* 62 (11): 131–37.

This article provides a comprehensive review of the history of concrete—its development, use, deterioration, investigation, and repair. It documents the development of early cements, cast stone, and concrete, plus the introduction and development of reinforced concrete, and notes the establishment of the American Concrete Institute (1905) and the Portland Cement Association (1916). The article covers the key problems that occur with historic concrete and gives brief explanations of the deterioration processes involved. Tools for the interpretation and assessment of deteriorating concrete are described. It concludes with an overview of several techniques available for the repair and conservation of historic concrete. Given the date of publication, more recent references should be consulted for up-to-date information on assessment and repair techniques.

Pyburn, Jack. 2018. "Schokbeton in the USA." In *Concrete and Modernism: Technology and Conservation*, edited by Theodore Prudon and Kyle Normandin, 16–23. Preservation Technology Dossier 14. New York: Docomomo US. https://docomomo-us.org/resource/files%2F2qn1vmmdpjmau9ral.pdf#page=16.

This article gives an account of the introduction in the United States of Schokbeton, a precast concrete technique developed in the Netherlands in the 1930s. This technique produced dense, high-quality, precast concrete by relying on a precise use of materials and production methods and an innovative method of compaction: subjecting the molds to intense shocks. The author situates the introduction of Schokbeton in the US context in the 1960s, where the Mo-Sai process developed by the Earley Studio was already well known. In fact, both precast techniques were being developed in parallel, but it was only after World War II and with the incentives of postwar reconstruction efforts that Schokbeton became known in the United States and was introduced in that market. Schokbeton became well accepted in the US thanks to the pre-existing experience of precasting companies and its creative adoption by modern architects such as Marcel Breuer, Durell Stone, Minoru Yamasaki, and Philip Johnson. These designers aesthetically explored the inherent characteristics of Schokbeton, namely the precise control of surface finish, the ability to develop bold sculptural forms, and the need to use the same form repetitively to create patterned elevations. See also, in the same publication, the article by Lucas van Zuijlen and Ronald Stenvert focusing on the development of Schokbeton in the Netherlands (see annotation on p. 26).

Quivik, Fredric L. 2013. "Cooling Mass Concrete: Owyhee, Hoover, and Building Large Dams." *Proceedings of the ICE – Engineering History and Heritage* 166 (4): 236–47. https://doi.org/10.1680/ehah.12.00015.

This article focuses on technological advancements brought about by the need for large constructions in mass concrete in the 1930s, specifically the technique for cooling concrete developed for the construction of the Hoover Dam. The author reveals how engineers from the US Bureau of Reclamation developed a technique to control volumetric changes in concrete during curing by cooling it via circulation of water through pipes within the concrete. This system was tested in the construction of the Owyhee Dam in eastern Oregon, and further developed based on monitoring of its performance. It was then applied in the Hoover Dam and other New Deal dams. The article illustrates the different types of value that concrete heritage can embody, such as scientific and historical value to the engineering field.

Raafat, Aly Ahmed. 1958. *Reinforced Concrete in Architecture*. New York: Reinhold.

This publication provides an analytical description of reinforced concrete's architectural potential and limitations, and is intended to fill a gap in the literature that the author dates to 1928. Though written primarily from a US perspective, it also discusses international developments in the use of reinforced concrete. The first half of the book, "Cycle of Growth," examines the background of reinforced concrete and addresses historical, technical, and regional developments. The author introduces key pioneers and early technical and architectural approaches to the use of the material. The second half of the book, "The Architecture It Creates," explores reinforced concrete's impact on architectural aesthetics, with a focus on developments and uses of architectural form and style, rather than on specific architects. The publication is well illustrated with case studies

and includes many photographs, illustrations, and technical drawings of different construction systems and buildings.

Ransome, Ernest L., and Alexis Saurbrey. 1912. *Reinforced Concrete Buildings; a Treatise on the History, Patents, Design and Erection of the Principal Parts Entering into a Modern Reinforced Concrete Building*. New York: McGraw-Hill.

This technical publication from 1912 provides an overview of then-contemporary theories and understandings of reinforced concrete in the United States. The first section addresses the history of the development of reinforced concrete, including a detailed look at existing patents, which the author highlights as a crucial source of information for engineers. The second part is a theoretical analysis of reinforced concrete, addressing factors such as adhesion, compression and expansion, bending, and stresses. The final part is on practical construction and looks at the materials, systems, and qualities of reinforced concrete systems. The text is illustrated with technical drawings and diagrams.

Reed, Peter, Kate Schoonees, and Jeremy Salmond. 2008. *Historic Concrete Structures in New Zealand: Overview, Maintenance and Management*. Wellington, NZ: Science & Technical Pub., Dept. of Conservation. https://www.doc.govt.nz/globalassets/documents/science-and-technical/sap248entire.pdf.

See annotation on p. 84.

Russell, Bruce W., and Shawn P. Gross, eds. 2005. *Ned H. Burns Symposium on Historic Innovations in Prestressed Concrete*. SP-231. Farmington Hills, MI: American Concrete Institute.

This collection of peer-reviewed papers was presented at a symposium held during the American Concrete Institute's fall 2005 convention. The papers cover a number of specialized topics on prestressed concrete, focusing on developments and uses over the previous fifty years. Topics include early uses of prestressed, pretensioned, and post-tensioned concrete in Europe and North America; the development of construction techniques, codes, and standards; and innovative modern materials and techniques. Some of the papers discuss processes and techniques that are no longer in use and are, therefore, of particular interest for the conservation and repair of historic structures. The first and last papers examine two important figures in the history of prestressed concrete: Gustave Magnel and Ned H. Burns.

Šćulac, Paulo, Davor Grandić, and Nana Palinić. 2021. "First Reinforced Concrete Building in Rijeka Port – Ferenc Pfaff's Warehouse No. 17." In *12th International Conference on Structural Analysis of Historical Constructions SAHC 2021*, edited by P. Roca, L. Pelà, and C. Molins, 245–56. Barcelona: International Centre for Numerical Methods in Engineering (CIMNE). http://congress.cimne.com/SAHC2020/frontal/doc/Ebook_SAHC2020.pdf#page=245.

This paper presents a detailed description of a reinforced concrete warehouse built between 1906 and 1909 in Croatia's Port of Rijeka. This case study has an exceptional level of detail in the description of the structural design and construction, which was possible thanks to the archival documentation still in existence, including structural calculations, detailed drawings of reinforcement, and the construction logbook. Such detail in describing the design of this structure can be useful in the understanding of how these proprietary systems have been applied in different parts of the world. The reinforcement system employed in this case was designed in accordance with the François Coignet and Napoléon de Tedesco systems.

Shand, P. Morton. 1932. "Steel and Concrete, a Historical Survey." *Architectural Review* 72:169–79.

This article looks separately at the history and development of iron, steel, and concrete, identifying the key players and technologies that led to development of these materials and associated construction techniques. It is written from a British perspective, but also discusses technologies developed in northern Europe and the United States. In the concrete section, the author identifies a significant rise in the strength of cement concrete from 1855 to 1930. This section looks at the development of Portland cement and reinforcement and has

subsections dedicated to mass concrete and reinforced concrete. The article concludes with a comparison of the advantages and disadvantages of steel and concrete construction.

Simpson, Pamela H. 1999. "Stone for the Masses: Concrete Block in the Early Twentieth Century." In *Cheap, Quick, and Easy: Imitative Architectural Materials, 1870–1930*, 9–29. Knoxville: University of Tennessee Press.

This book chapter is an expanded version of a paper published ten years previously. The author dates the development and popularization of the manufacture and use of rock-faced concrete blocks to the early twentieth century, rather than the last third of the nineteenth century, as argued in other sources. Pre-1900, many patents were issued for the production of concrete block, but mass manufacture did not start until the United States issued a patent for Harmon S. Palmer's cast-iron concrete block manufacturing machine in 1900. Other factors contributing to the popularization of concrete blocks included the development and standardization of Portland cement, and intensive advertising of both concrete blocks and manufacturing machines. One of the great selling points for rock-faced concrete blocks was that they were inexpensive, and quick and easy to produce. Concrete blocks are noted as being particularly popular in areas without easy access to other construction materials such as timber, brick, and stone. In 1905, organizations such as the Concrete Block Machine Manufacturers' Association and the National Association of Cement Users were established. Despite the popularity of rock-faced concrete blocks among the masses, Simpson identifies several sources that indicate that the material was far less popular among architects and elites, who regarded it as a poor imitation of stone. A key problem identified with concrete blocks was weight, which seems to be the major factor that eventually led to its decline in popularity. In the late 1920s and 1930s, concrete blocks began to be widely replaced by the lighter cinder block.

Stanley, Christopher C. 1979. *Highlights in the History of Concrete*. Cement and Concrete Association Publication 97.408. Slough, UK: Cement and Concrete Association.

This well-illustrated brief overview of the history of concrete, produced by the British Cement Association, focuses on the United Kingdom. It is divided into chronological periods starting as early as 5600 BCE, although the majority of the publication focuses on the development of modern concrete from 1750 CE onward. The modern history is presented in sections titled "1750–1824: Experiments with New Cements," "1824–1848: The Invention of Portland Cement," "1848–1897: The Advent of Reinforced Concrete," "1897–1920: The Growth of Structural Concrete," "1920–1945: The Rise of Prestressed Concrete," and "1945–Present: Concrete in the Modern World." The text identifies many key players and provides illustrated case studies, including several firsts, such as the construction of the first all-concrete house in 1835.

Stierli, Martino. 2022. "The Politics of Concrete: Material Culture, Global Modernism, and the Project of Decolonization in India." In *Rethinking Global Modernism: Architectural Historiography and the Postcolonial*, edited by Vikramaditya Prakash, Maristella Casciato, and Daniel E. Coslett, 275–89. Abingdon, UK: Routledge. https://doi.org/10.4324/9781003120209-21.

This book chapter looks at the use of concrete construction in post-independence India, drawing parallels with what was happening in Brazilian architecture around the same time and looking critically at how the history of modern construction in the Global South has been portrayed in the conventional Eurocentric narrative. The author proposes that concrete adoption in India and Brazil did not represent a simple adaptation of European and Western ideals, but was the result of local labor and technological conditions and the creation of an architectural expression of progress and independence. The author illustrates this perspective with an account of how the technological innovations of New Delhi's Hall of Nations (1972), by architect Raj Rewal and structural engineer Mahendra Raj, came to be. This question of perspective is important in understanding the historical values embedded in significant concrete buildings of the Global South.

Talbi, Amira, and Soumia Bouzaher. 2022. "Towards Recognition of Industrial Heritage in Algeria: The Square Concrete Grain Silos of Setif." *Industrial Archaeology Review* 44 (2): 96–105. https://doi.org/10.1080/03090728.2022.2113204.

This article addresses industrial heritage in Algeria, with particular reference to the heritage of the French colonization period, starting from the recognition that its significance is still underappreciated, with the consequence that most of the structures have no legal protection. The concrete grain silos of Setif, built according to Hennebique patents, are taken as a representative case study. The authors first describe the historical context and the colonial agrarian strategy that led to the creation of the silos, and then analyze in detail the architectural and constructive features of this typology of storage building, with reference to its functioning and the grain-handling process. The ultimate aim of this research study is to unveil the historical, architectural, technological, and functional values of these buildings as a first step toward their preservation and management.

Tappin, Stuart. 2002. "The Early Use of Reinforced Concrete in India." *Construction History* 18:79–98.

This article covers the history of concrete in India up to 1947 (the end of British rule) and overviews the context that allowed for the creation and construction of modern architecture masterpieces in the second half of the twentieth century. At the start of the twentieth century, British engineers at the Public Works Department in India began to experiment with reinforced concrete in small structures, and by the mid-1930s, reinforced concrete was being widely used for structural frames in large housing blocks and for most large-scale public buildings. In smaller-scale buildings, it became common to use reinforced concrete elements, such as flat roofs and stairs, combined with traditional load-bearing masonry construction. The increased application of reinforced concrete in India in the 1920s and 1930s was connected to rapid urban growth and the development of a national production of cement and steel reinforcement. These conditions enabled architects, engineers, and contractors to adopt concrete into their practices in various regions. Another important factor that made reinforced concrete well suited for the Indian context was the low cost of labor. During this early period, British standards and patented systems were used, and in 1929 the Concrete Association of India was established and began publishing information on various applications of reinforced concrete, further contributing to its adoption.

Urquhart, Dennis. 2013. *Historic Concrete in Scotland*, part 1, *History and Development*. Short Guide 5. Edinburgh: Historic Scotland. https://www.historicenvironment.scot/archives-and-research/publications/publication/?publicationId=c2a38944-eb81-44e8-bd5e-a59100fb611a.

This is the first of a three-part Short Guide produced by Historic Scotland. It introduces the history and background of concrete as a construction material, then examines its use in Scotland, from mass concrete in the first half of the nineteenth century to no-fines concrete, precast concrete, and reinforced concrete. It describes a natural progression from the traditional rammed-earth construction used in many parts of Scotland to mass concrete. This guide focuses on pre-1945 concrete, but there is also a note on post-1945 concrete, identifying some of the constraints and developments of that period. Codes of practice are discussed throughout; section 3.5 includes a table detailing the key codes for structural concrete in the United Kingdom from 1907 to 2000. The final two sections give brief overviews of the characteristics of early concrete and principles for the repair of historic concrete. These two topics are discussed in greater detail in parts 2 and 3 of this Short Guide (see annotations on pp. 67 and 109). A detailed appendix provides a list of pre-1945 concrete buildings in Scotland, noting each structure's type, date, and location, plus additional comments.

Van de Voorde, Stephanie, Inge Bertels, and Ine Wouters. 2015. *Post-War Building Materials in Housing in Brussels 1945–1975*. Brussels: Vrije Universiteit Brussel. https://cris.vub.be/ws/portalfiles/portal/18209694/post_war_building_materials_VUB_Boek_web.pdf.

This book resulted from a research project aimed at filling knowledge gaps to support the retrofitting of existing postwar housing while maintaining its cultural significance. Each chapter covers the development and application of a building material or technique typical of postwar housing in Brussels. For the purposes of this bibliography, the most relevant chapters cover the following topics: lightweight concrete; prefabricated floor systems; precast concrete facade panels; and load-bearing prefabricated systems. Each chapter provides a timeline of the development of each material or system in Belgium, how it was typically used in construction, and a clear description of materials and method of fabrication. The chapters are illustrated with images from period product catalogs and architectural periodicals. Despite its regional focus, much of the content will be useful in other contexts that utilized similar materials. This book is written in English, Dutch, and French.

van Zuijlen, Lucas, and Ronald Stenvert. 2018. "Schokbeton: Zwijndrecht/The Netherlands/International." In *Concrete and Modernism: Technology and Conservation*, edited by Theodore Prudon and Kyle Normandin, 9–13. Preservation Technology Dossier 14. New York: Docomomo US. https://docomomo-us.org/resource/files%2F2qn1vmmdpjmau9ral.pdf#page=9.

This article describes the development of Schokbeton in the Netherlands. It begins with a brief account of the history of concrete in that country and how the predominance of masonry prevented more widespread adoption prior to World War II. Despite this, there were still significant architectural masterpieces and technical experimentation in concrete before the war. The development of Schokbeton is described as an accident, in which G. Lieve, a concrete worker in Zwijndrecht, noticed that it was possible to obtain stronger concrete by shocking the material rather than shaking it. The technique he developed with M. E. Leeuwrik in 1932 involved compacting the concrete during pouring by dropping the mold multiple times from a height of eight to twenty-five millimeters. This resulted in higher strength without adding more cement—an expensive material, especially given the era's economic crisis. The need for rapid and economical construction in the postwar period accelerated the adoption of concrete techniques, such as Schokbeton. This was also when Schokbeton experienced its international expansion. See also in the same publication the article by Jack Pyburn focusing on the adoption of Schokbeton in the United States (see annotation on p. 22).

Wouters, Ine, Stephanie Voorde, Inge Bertels, Bernard Espion, Krista Jonge, and Denis Zastavni, eds. 2018. *Building Knowledge, Constructing Histories: Proceedings of the Sixth International Congress on Construction History (6ICCH 2018), Brussels, Belgium, 9–13 July 2018*. 2 vols. Leiden, the Netherlands: CRC Press.

These conference proceedings on construction history contain two thematic sessions dedicated to concrete and various other papers on concrete presented at open sessions. In the session dedicated to precast concrete, six papers were presented covering the following subjects: the use of precast concrete blocks in breakwaters and jetties in the nineteenth century; World War I submarine shelters in precast; precast concrete as artificial stone and how the aesthetic of stone masonry was transferred to precast concrete; the use of the NEMAVO Airey system in Dutch housing after World War II; large-panel systems, prefabrication, and typification in Poland; and handcrafted aspects of Italian precast concrete between 1950 and 1980. The session on early thin shells contains nine papers, seven of which are on concrete shells. These cover the concrete dome of a nineteenth-century church in Germany; concrete hangars in the early twentieth century; the work of Eugène Freyssinet; the Zeiss-Dywidag system in Italy; and the cupola of the Novosibirsk Theater in Siberia. Other papers discuss prestressed concrete innovations adopted in Denmark; the history of the concrete construction industry in Italy; the history of concrete in Portugal; the emergence of scientific knowledge in reinforced concrete construction; early concrete work by François Coignet; precast concrete in Thailand; a history of flat slabs and mushroom columns; the use of reinforced concrete to replace wood in roof trusses postwar; and the application of the Hennebique system in Belgium.

CHAPTER 2

# CHARACTERISTICS, DETERIORATION, AND DAMAGE

## Key References

Bertolini, Luca, Bernhard Elsener, Pietro Pedeferri, Elena Redaelli, and Rob B. Polder. 2013. *Corrosion of Steel in Concrete: Prevention, Diagnosis, Repair*. 2nd ed. Weinheim, Germany: Wiley.

This book describes in detail the process of chloride- and carbonation-induced corrosion of steel reinforcements in concrete elements, describing transport mechanisms and electrochemical concepts. It also includes references to other types of corrosion and degradation of concrete. The authors discuss the relationship between design, execution, and durability, describing new methods for condition assessment and new repair techniques for reinforced concrete elements. The book is structured in five parts. Part 1 covers properties of cements and cement paste, with a chapter dedicated to transport properties and another on concrete degradation, which are all influencing factors in reinforcement corrosion. Part 2 is a detailed, comprehensive description of corrosion mechanisms of steel reinforcement, including both carbonation and chloride induced, among others. Part 3 focuses on preventive treatments, including corrosion inhibitors and surface treatments. Part 4 is dedicated to diagnosis techniques for condition assessments and monitoring. And part 5 describes repairs, including conventional repair and electrochemical techniques (in other references, electrochemical techniques are classified as treatments or protective systems, not repairs). The volume represents a significant reference for all experts and professionals involved in corrosion protection and/or the rehabilitation and maintenance of reinforced concrete structures.

Broomfield, John P. 2007. *Corrosion of Steel in Concrete: Understanding, Investigation and Repair*. 2nd ed. London: Taylor and Francis.

This book lays a foundation for understanding corrosion science, corrosion-related deterioration, and corrosion engineering for steel-reinforced concrete structures. It is directed at industry professionals, students, concrete stewards, and owners. Chapter 2 discusses the corrosion process, types of corrosion, and the basics of electrochemical cells. Chapter 3 focuses on causes of corrosion, primarily carbonation and chloride attack, and the subsequent damage to reinforced concrete. Chapter 4 outlines condition evaluation processes for corrosion, including methods for surveying, nondestructive testing procedures, and electrochemical and chemical test methods. For each test method, instrumentation, methodology, results, and data interpretations are provided, and the limitations of the methods and factors that can influence results are identified. This chapter alone provides significant resources for the reader. Chapter 5 discusses traditional and surface-applied chemical repair options, including patch repairs, sealers, coatings, and corrosion inhibitors. Chapter 6 provides an understanding of electrochemical treatment techniques for corrosion mitigation. This includes cathodic protection systems—both sacrificial systems, based on the galvanic series of metals, and impressed current systems, which utilize permanently embedded anodes and an external power source. System design, criteria, and installation challenges and requirements are also presented. Chloride extraction and electrochemical chloride removal are provided as examples of other electrochemical techniques. The chapter ends with a comparison of techniques. Chapter 7 provides a step-by-step guide through repair methodologies, outlining why an owner or consultant would choose a specific treatment, technical differences in repairs and treatments, and side effects and limitations. To further support chapter 4, chapter 8 provides deterioration and durability calculations, and assesses risks of activity based on data collected from the corrosion evaluation. The foundations of service life modeling are included, which the investigator can apply to historic concrete buildings to be predictive in the evaluation process. Finally, the book concludes with a chapter addressing building for durability in new construction, and methods and preventive treatments that are available today.

Dyer, Thomas D. 2014. *Concrete Durability*. Boca Raton, FL: CRC Press.

This book introduces the multiple factors that contribute to concrete durability: deterioration mechanisms; materials and methods used in construction; and maintenance and repair. Chapter 1 serves as the introduction and explains how the book is organized. Chapter 2 focuses on physical deterioration mechanisms, such as shrinkage, thermal cracking, freeze-thaw, and abrasion. Chapter 3 deals with chemical deterioration mechanisms such as sulfate attack, alkali-aggregate reaction, and acid attack. Chapter 4 is dedicated to corrosion of steel reinforcement. For each deterioration mechanism presented, the author explains the deterioration process and the various factors contributing to it, as well as how to avoid damage. Chapters 5 and 6 discuss design and construction requirements that make a durable concrete; though not directly applicable in concrete conservation, these chapters can be a useful comparison between what is currently considered best practice in the concrete construction industry and what was known and applied in the past. Chapter 7 is dedicated to identification and management of durability issues in concrete. This last chapter gives an overview of the condition assessment process, including in situ and laboratory testing that can be useful, and briefly introduces different types of remediation methods.

Hewlett, Peter C., and Martin Liska, eds. 2019. *Lea's Chemistry of Cement and Concrete*. 5th ed. Oxford: Butterworth-Heinemann.

This is a comprehensive reference book on the chemistry, physics, and material science of cement and concrete. Chapter 1 offers a history of calcareous cements (defined as cements where lime is one of the main constituents, as in Portland cement) from prehistory to the contemporary era. Chapter 2 covers the manufacture of Portland cement. Chapters 3 and 4 discuss constituents of Portland cement. Chapter 5 covers the hydration, setting, and hardening of Portland cement. Chapter 6 is dedicated to the durability of concrete, how it is affected by the environment, and available durability tests. The chapter starts by explaining that concrete's permeability is the most important factor in determining its durability, and the rest of the chapter is organized in sections addressing different deterioration mechanisms categorized as: physical attack, chemical attack, and corrosion of metals. For each mechanism, the author describes the process and discusses influencing factors and resistance assessment. The mechanisms described are the following: freeze-thaw; fire; salt crystallization; surface wear; cracking; efflorescence and leaching; sulfate attack; effect of sea water; acid attack; effect of chloride on metal corrosion; corrosion of other metals; alkali-aggregate reaction; electrolysis of concrete; and action of gases. Chapter 7 focuses on physicochemical and mechanical properties of Portland cement. Chapters 8 to 13 are dedicated to different types of cement, such as pozzolanas (chapter 9) and blast furnace slag cement (chapter 10). Chapter 14 covers admixtures, and chapter 15 is dedicated to aggregates. Chapter 16 discusses geopolymers and other alkali-activated materials. And chapter 17 discusses the influence of water-to-cement ratio on the sustainability of concrete. This book was first published in 1935 by Sir Frederick M. Lea and Cecil H. Desch, with substantial changes between editions, including authorship. Each different edition serves as a snapshot of the state of knowledge on concrete technology at the time of its publication.

Macdonald, Susan, ed. 2003. *Concrete: Building Pathology*. Oxford: Blackwell Science.

See annotation on p. 43.

Mehta, P. Kumar, and Paulo J. M. Monteiro. 2014. *Concrete: Microstructure, Properties, and Materials*. 4th ed. New York: McGraw-Hill Education.

This comprehensive textbook covers fundamental knowledge on concrete. The parts likely to be the most useful in concrete conservation are highlighted as follows. Part I focuses on the microstructure and properties of hardened concrete. Chapter 1 introduces the general topic of concrete. Chapter 2 describes in detail the microstructure of concrete, the aggregate phase, the hydrated cement paste, and the interfacial transition zone.

Chapter 3 discusses strength, factors that affect it, and behavior of concrete under various stresses. Chapter 4 covers elastic behavior, drying shrinkage, creep, and thermal shrinkage. Chapter 5 is dedicated to durability. It starts by introducing the concept and its significance, then discusses water as an agent of deterioration, followed by contributing factors to permeability. The next sections in this chapter are dedicated to different deterioration mechanisms: surface wear; crystallization of salts in pores; frost action; effect of fire; deterioration by chemical reactions; and reactions involving the formation of expansive products, such as sulfate attack, alkali-aggregate reaction, and corrosion of embedded steel. The last sections are dedicated to the development of a holistic model of concrete deterioration and concrete in the marine environment. Part II dedicates a chapter to each of the constituent materials of concrete (hydraulic cements, aggregates, and admixtures), mix proportioning, early-age properties (such as workability and plastic shrinkage), and nondestructive evaluation methods. Chapter 11 covers nondestructive evaluation methods such as surface hardness, absorption and permeability tests, ultrasonic pulse velocity, acoustic emission, resistivity, corrosion potential, polarization resistance, cover meters, ground-penetrating radar, and infrared thermography. Part III presents special types of concrete, such as lightweight concrete, high-strength concrete, shotcrete, and mass concrete. This part also covers concrete mechanics and sustainability.

## General References

American Concrete Institute. 2008. *Guide for Conducting a Visual Inspection of Concrete in Service: Reported by ACI Committee 201*. ACI 201.1R-08. Farmington Hills, MI: American Concrete Institute.

This illustrated guide presents terms and definitions for physical manifestations of deterioration mechanisms observable on a concrete surface during inspection. The description of distresses (or conditions) is divided into: cracking, with various cracking patterns described; distress, which includes different types of conditions, such as dusting, efflorescence, and scaling; and textural features and phenomena, such as bug holes, honeycombing, and staining. For some types of distress, such as spalling, the guide also helps in classifying the scale of the distress by providing dimensions of what can be considered a small versus large spall. This document also includes general guidance on how to conduct a visual inspection and what should be included in a visual inspection report. The adoption of this terminology is recommended for all professionals working in the United States and other English-speaking countries, and it can be used as guidance for professionals working in other languages to search for the appropriate translation. Also included in Mark E. Hughes and Carl R. Bischof, eds., *Concrete Repair Manual* (2013, see annotation on p. 100).

American Concrete Institute. 2021. *ACI Concrete Terminology*. ACI CT-21. Farmington Hills, MI: American Concrete Institute.

This comprehensive glossary of terms used in the concrete field contains definitions for terms used to describe structures, types of deterioration, construction techniques, repairs, treatments, materials, and equipment used to build and repair. This document has a broader scope than the International Concrete Repair Institute's *Concrete Repair Terminology* (2022, see annotation on p. 101) and includes some of the same terms. It is a useful document, as it provides a common language that can be shared across the different types of professionals working in concrete conservation. The adoption of this terminology is recommended to all professionals working in the United States and other English-speaking countries, and it can be used to guide professionals working in other languages in searching for appropriate translations. A Spanish version is available for the 2016 edition.

Australian Concrete Repair Association (ACRA), Commonwealth Scientific and Industrial Research Organisation (CSIRO), and Standards Australia. 2006. *Guide to Concrete Repair and Protection*. 2nd ed. SAA HB 84-2006. Sydney: ACRA / CSIRO / Standards Australia.

See annotation on p. 89.

Bartholdy, Julie, Poul Klenz Larsen, and Jørn Bredal-Jørgensen. 2020. "The Damaging Effect of 'Eco-Friendly' Deicing Salts on Building Materials." In *Monument Future: Decay and Conservation of Stone: Proceedings of the 14th International Congress on the Deterioration and Conservation of Stone*, edited by Siegfried Siegesmund and Bernhard Middendorf, 413–18. Halle, Germany: Mitteldeutscher Verlag.

Based on an awareness of the damaging effects of sodium chloride used as a deicing agent on building materials, and recognizing that the effects of the most recent "eco-friendly" deicing salts are still largely unknown, the research study presented in this paper investigates the effects of different deicing products (sodium, magnesium and calcium chloride, sodium and potassium formate, calcium magnesium acetate, and urea) on six different types of building materials (concrete, limestone, sandstone, granite, and red and yellow clay brick). Four different test procedures were used to compare the effects of the selected products: cycles of wetting and drying, cycles of freezing and thawing, varying relative humidity, and wick test. For each test procedure, details are provided on sample type, testing methodology, and quantification of deterioration. The tested concrete samples that revealed visible decay were: those treated with calcium chloride, which under the wick test fractured or disintegrated; those treated with sodium formate, which under the freezing and thawing test showed superficial degradation; and those treated with calcium magnesium acetate, which under the wick test showed superficial degradation.

Boccacci, Giulia, Francesca Frasca, Beatrice Bartolucci, Lisa Vergelli, Chiara Bertolin, and Anna Maria Siani. 2023. "Climate-Induced Conservation Risks of Historic Reinforced Concrete Buildings: Preliminary Results from Literature Review." *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XLVIII-M-2-2023:227–34. https://doi.org/10.5194/isprs-archives-XLVIII-M-2-2023-227-2023.

This paper gathers preliminary results from a literature review about the impacts of environmental conditions on the deterioration of historic reinforced concrete structures, focusing on climate-induced risks and paying particular attention to mechanical, chemical, and biological deterioration. To develop this literature review, the authors used a three-step process defined by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow chart, which led to the inclusion of forty-five documents identified via Scopus and Web of Science search engines. The results point to the most investigated types of deterioration being chemical and mechanical ones, mainly triggered by salt weathering and freeze-thaw cycles. The authors also provide some useful considerations to evaluate specific research gaps and needs in the field of climate-induced risks affecting reinforced concrete structures. Undoubtedly, this paper provides a valuable basis to those investigating climate change impacts on concrete cultural heritage, both in science and in professional practice.

Boothby, Thomas E., M. Kevin Parfitt, and Charlene K. Roise. 2005. "Case Studies in Diagnosis and Repair of Historic Thin-Shell Concrete Structures." *APT Bulletin: Journal of Preservation Technology* 36 (2–3): 3–11. https://www.jstor.org/stable/40004699.

See annotation on p. 72.

Brencich, A., and M. Nebiacolombo. 2021. "Anchorage of Reinforcement Bars in Hennebique R.C. Structures." In *12th International Conference on Structural Analysis of Historical Constructions SAHC 2021*, edited by P. Roca, L. Pelà, and C. Molins, 59–70. Barcelona: International Centre for Numerical Methods in Engineering (CIMNE). http://congress.cimne.com/SAHC2020/frontal/doc/Ebook_SAHC2020.pdf#page=59.

This paper discusses the performance of anchorage for reinforcing bars used in the Hennebique system based on results obtained in laboratory testing. The authors tested fish-tail bars and plate stirrups made to emulate the ones found in Hennebique structures. Each type of anchorage was cast into cubes of concrete using five different mixes representing concrete found in historic structures. These specimens were subjected to loading up to collapse to measure anchorage strength and ascertain the collapse mechanism of the anchorage. Results revealed that for fish-tail ends, anchorage strength depends on the strength of the concrete as it resists crushing when load is applied to the bar. In the case of plate stirrups, collapse happens due to the rectification of the bent ends as the stirrups slide through the concrete mass.

Broomfield, John P., and Chris Atkins. 2007. “Repair Guidance Note 1: Corrosion of Steel in Concrete.” *Concrete* 41 (4): 13–15.

This is the first in a series of Repair Guidance Notes that supplement BS EN 1504 Products and Systems for the Protection and Repair of Concrete Structures. Definitions, Requirements, Quality Control and Evaluation of Conformity. It summarizes the major causes of corrosion-related deterioration in reinforced concrete structures. Carbonation and chloride attack are identified as the two main mechanisms that can induce corrosion of reinforcements. The processes associated with each of these two mechanisms are described, and the relevant reference within the standard is identified. The corrosion process is explained, including the required conditions for it to occur.

Broomfield, John P., and Chris Atkins. 2007. “Repair Guidance Note 2: Degradation of Concrete.” *Concrete* 41 (5): 16–17.

This is part 2 in a series of Repair Guidance Notes that supplement BS EN 1504 Products and Systems for the Protection and Repair of Concrete Structures. Definitions, Requirements, Quality Control and Evaluation of Conformity. This note summarizes the major causes of deterioration in concrete, divided into three groups: design and construction defects, environmental influences, and structural damage. The design and construction defects include poor cover of reinforcement, poor protection from moisture ingress, poor compaction of the mortar, high water-to-cement ratio, addition of chlorides to the mix, alkali-aggregate reaction, sulfate attack, and the use of high-alumina cement concrete. Deteriorations with environmental causes include staining, erosion, efflorescence, freeze-thaw damage, and chemical attack. Each of the above is briefly described and the corresponding part of the standard identified. A few factors that can cause structural damage are identified, but no details are given.

Building Research Establishment. 1995. *Carbonation of Concrete and Its Effects on Durability*. BRE Digest 405. Watford, UK: Building Research Establishment.

This BRE Digest discusses the carbonation of normal dense-aggregate concrete that results from the reaction of atmospheric carbon dioxide gas with hydrated cement compounds. It is related particularly to the assessment of risk of steel reinforcement corrosion. The digest describes the carbonation process and how the depth of carbonation can be measured. It outlines various factors influencing the depth and rate of carbonation, and indicates the possible effects produced in hardened concrete. Maintenance of concrete structures is briefly discussed. Laboratory and field tests are described, and European Standards are noted. This is an older text, but it provides a solid description of reactions occurring in concrete. Also included in Mark E. Hughes and Carl R. Bischof, eds., *Concrete Repair Manual* (2013, see annotation on p. 100).

Building Research Establishment. 2000. *Corrosion of Steel in Concrete: Durability of Reinforced Concrete Structures*. BRE Digest 444, part 1. Garston, UK: BRE.

This is the first in a three-part series on corrosion of steel reinforcement in concrete. It focuses on describing the deterioration mechanism of corrosion in reinforced concrete and the factors that contribute to it. The document offers a detailed description of how concrete prevents the occurrence of corrosion on the reinforcement by providing a highly alkaline environment, and how this protection can be lost due to carbonation or contamination with chlorides. The description covers the influence of concrete cracks on reinforcement corrosion and of the aggressiveness of the environment where the structure is situated. The following section concerns the design of new structures. Even though it is not directly applicable to concrete conservation, it provides a good list of factors that should be assessed when evaluating the risk of corrosion for a reinforced concrete structure. Note that the section on codes and standards is outdated. Part 2 (see annotation on p. 48) describes assessment techniques and diagnosis of reinforcement corrosion, and part 3 (see annotation on p. 91) covers repair and preventive treatment options for this type of deterioration. Also included in Mark E. Hughes and Carl R. Bischof, eds., *Concrete Repair Manual* (2013, see annotation on p. 100).

Building Research Establishment. 2004. *Alkali-Silica Reaction in Concrete: Background to the Guidance Notes*. BRE Digest 330, part 1. Watford, UK: BRE.

This document provides basic information on alkali-silica reaction in concrete. It was written as background information to the guidance notes on minimizing risk of alkali-silica reaction in new construction presented in parts 2 through 4 of BRE Digest 330. This document contains a description of the alkali-silica reaction mechanism; information on how to identify alkali-silica reaction, including representative photographs; analysis of structural effects; monitoring of the development of damage; repair methods; and, finally, information on minimizing risk in new construction. The last part includes a more in-depth discussion of aggregates and test methods.

Bussell, Michael N. 2007. "Conservation of Concrete and Reinforced Concrete." In *Structures and Construction in Historic Building Conservation*, edited by Michael Forsyth, 192–210. Historic Building Conservation. Oxford: Blackwell.

See annotation on p. 13.

Bussell, Michael N. 2008. "Concrete and Reinforced Concrete." In *Materials and Skills for Historic Building Conservation*, edited by Michael Forsyth, 92–108. Oxford: Blackwell.

This chapter is part of a book dedicated to properties of historic building materials, which is part of the series Historic Building Conservation. The chapter overviews concrete properties, the development of Portland cement and reinforced concrete, and construction techniques. It starts with a brief description of concrete properties, then overviews the historical development of concrete from the Roman period to the advent of Portland cement and reinforced concrete in the nineteenth century. Next, the author discusses the role of concrete cover in the durability of reinforced concrete. The following sections describe constituent materials, including aggregates, cements, and reinforcements, and how they influence concrete properties. The last sections present formwork, placing, curing, and finishing techniques. Precast concrete and concrete blocks are briefly mentioned.

Chun, Qing, Koenraad Van Balen, and Jianwu Pan. 2016. "Experimental Research on Physical and Mechanical Performance of Steel Rebars in Chinese Modern Reinforced Concrete Buildings Built During the Republic of China Era from 1912 to 1949." *Materials and Structures* 49 (9): 3679–92. https://doi.org/10.1617/s11527-015-0748-6.

This article describes the results of laboratory analysis of reinforcing steel samples from concrete buildings built between 1912 and 1949 in China. The goal of this research was to determine the physical and mechanical properties of historic reinforcing steel, and to inform the assessment and repair of concrete structures from this period, considered the earliest reinforced concrete buildings in China. The analyzed samples included reinforcing bars with rectangular and round sections of various diameters. The analysis compared results between the historic samples and current standards, and included surface geometry characteristics, tensile test results, chemical composition, metallographic structures, and microstructure through scanning electron microscopy. Results revealed that physical and mechanical properties of the analyzed samples were very different from contemporary reinforcements. They also revealed that the historic reinforcements were all made of hot-rolled low-carbon steel bars.

Clayton, N. 1999. *Structural Implications of Alkali-Silica Reaction: Effect of Natural Exposure and Freeze-Thaw*. Watford, UK: CRC.

This report presents results from research conducted at BRE concerning the structural performance of concrete suffering from alkali-silica reaction. The first part describes tests on concrete specimens and prestressed beams undergoing alkali-silica reaction while on the exposure site. The main conclusion is that structural concrete and elements in which alkali-silica reaction has occurred under natural conditions undergo similar expansion, strength loss, and change of structural performance as found in accelerated laboratory tests. This finding is crucial, because it means that all the research studies using accelerated conditioning can be reliably assumed to be directly applicable to real structures. The second part describes freeze-thaw tests on additional concrete specimens with alkali-silica reaction from the exposure site at BRE. The conclusion is that concrete with alkali-silica reaction is more susceptible to the onset of freeze-thaw attack than similar unaffected concrete, which would lead to more expansion and damage than that produced by alkali-silica reaction alone.

The Concrete Society. 2000. *Diagnosis of Deterioration in Concrete Structures: Identification of Defects, Evaluation and Development of Remedial Action*. Technical Report 54. Crowthorne, UK: Concrete Society.

This technical report offers a broad introduction to concrete deterioration and defects, outlining the major causes and mechanisms and covering investigation of current condition, diagnosis, and selection of appropriate solutions. The contents include the following: "Preliminary Investigation," with in-depth descriptions of planning and preparations for preliminary inspections, how to undertake preliminary inspections, and preliminary diagnosis; "Recognizing Defects and Probable Causes," with in-depth description of types of cracking and other defects related to construction, load-induced cracking and structural design inadequacies, environmental effects, deterioration related to aggregate properties, chemical attack, and reinforcement corrosion; "Testing," with in-depth descriptions of selection of sampling and test locations, access, sampling, in situ testing, and laboratory testing; "Evaluation," with in-depth description of main objectives, assessment of structural integrity, interpretation of nondestructive test results, use of results, and predicting the behavior of a structure; "Development of Appropriate Solutions," with reference to the process of selecting appropriate options, assessing the extent of repair, and evaluating repair and protection techniques; and "Case Histories," with a selection of building types, including office building, car park, marine jetty, sea wall, and a case of a beam damaged by alkali-silica reaction. The publication also includes numerous references and appendices on test methods and interpretation of test results. Also included in Mark E. Hughes and Carl R. Bischof, eds., *Concrete Repair Manual* (2013, see annotation on p. 100).

The Concrete Society. 2010. *Non-Structural Cracks in Concrete: A Concrete Society Report*. 4th ed. Technical Report 22. London: Concrete Society.

This report explains the principles governing the formation of cracks in concrete and defines various types of nonstructural cracks. The factors influencing crack formation are described to inform diagnosis and selection of procedures for control. Plastic, early thermal, and long-term drying shrinkage cracks are dealt with in detail; cracks due to crazing, corrosion of reinforcement, and alkali-silica reaction are also described. The significance of cracks is discussed, and the common practice of judging cracks by their surface width is generally deprecated. It is concluded that while intrinsic cracks are sometimes unpredictable, they can often be minimized and controlled by careful attention to design details and construction techniques. Finally, the report describes some of the materials and methods that may be used for remedial work. This publication incorporates updates to reflect Eurocode 2. Also included in Mark E. Hughes and Carl R. Bischof, eds., *Concrete Repair Manual* (2013, see annotation on p. 100).

The Concrete Society. 2013. *Visual Concrete: Weathering, Stains and Efflorescence*. Camberley, UK: Concrete Society.

This publication addresses the effects of weathering on concrete surfaces, referring primarily to natural forces such as rain, wind, and sunlight, which might act in conjunction with human-generated forces such as pollution. The volume is articulated in six different chapters, covering weathering of concrete, including an introduction to the topic, with reference also to ancient buildings; the weathering system, focusing on the properties of concrete surfaces and the visible effects of rain and dirt; control of weathering, distinguishing between prediction and control measures and providing thirty-two case studies addressing different topics; removal of stains and growths from concrete, including a description of different treatments and guidelines on some cleaning techniques; efflorescence on concrete, with different types described; and prevention and removal of efflorescence, with a focus on specific treatments. Finally, a brief list of references is provided.

The Concrete Society. 2015. *Relevance of Cracking in Concrete to Reinforcement Corrosion*. 2nd ed. Technical Report 44. Camberley, UK: Concrete Society.

This report examines in detail the relevance of concrete cracking to reinforcement corrosion. The first edition, published in 1995, was principally a response to BRE publications suggesting that cracks in concrete structures could give rise to reinforcement corrosion. Since all concrete structures crack, this implied that reinforcement corrosion was inevitable, and the conclusion was thought to be contrary to practical experience, which suggests that in the vast majority of cases, corrosion damage does not occur during the service life of a structure. The report provided some clarity on the subject and formulated guidelines to help classify crack types based on their potential to give rise to corrosion. In this new edition, the discussion has been reassessed, and where appropriate the text is amended, new text is provided, and references are updated to align with current thinking.

Di Biase, Carolina, ed. 2009. *Il degrado del calcestruzzo nell'architettura del Novecento*. Santarcangelo di Romagna, Italy: Maggioli.

This volume systematically analyzes and describes the deterioration mechanisms of concrete, including concrete mortars, artificial stone, and reinforced concrete. The disciplinary perspective and tools adopted are those of the architectural conservation field as conceived in the Italian context, with the objective to help architects and engineers better understand the relationship between deterioration phenomena, type of construction, materials employed, construction methods, location, and the life of the building. The final aim is to provide tools to help define the conservation approach and orient selection of methods to guarantee longer durability of the repair work. The necessity to intertwine knowledge and disciplinary perspectives of architects and engineers is underlined. The work does not deal with structural issues, but focuses on deterioration starting from observation of exposed surfaces. Although the book is mostly in Italian, the first chapter is translated into English and presents the general concrete conservation context for the book. The extensive and detailed glossary of concrete deterioration is also in both Italian and English and is supported by numerous photographs of deterioration types with technical notes.

Di Biase, Carolina, and Francesca Albani. 2009. "Alterations and Decay in Twentieth-Century Architecture: A Lexicon Proposal." In *Protection of Historical Buildings: PROHITECH 09: Proceedings of the International Conference on Protection of Historical Buildings, PROHITECH 09, Rome, Italy, 21–24 June 2009*, edited by Federico M. Mazzolani, 519–24. Boca Raton, FL: CRC Press.

This paper briefly surveys a few early works on the deterioration of exposed concrete architecture as a means of introducing the need for a standard lexicon or glossary to assist in the identification of deterioration in concrete. The authors began this research in 2003. Their definitions are supplemented by images that illustrate each type of deterioration and descriptions of conditions at specific twentieth-century buildings where they are present. Likely causes of deterioration are also identified.

Dyer, Thomas D. 2017. *Biodeterioration of Concrete*. Boca Raton, FL: CRC Press.

This comprehensive and detailed book presents the different types of organisms that can colonize concrete: bacteria, fungi, plants, and animals. The author discusses how they can cause chemical or mechanical deterioration, sometimes both, but also how they can be harmless or even provide certain protections to concrete. The content also includes prevention and control of biodeterioration while considering the environmental consequences of such measures. Discussions on aesthetic damage are deliberately not included, as the author argues that the perception of what is considered such can vary considerably. Chapter 1 includes a short introduction to the subject and how the book is organized. Chapter 2 focuses on the most common chemical compounds produced by living organisms and their relationship with deterioration processes in concrete. The following three chapters have a similar structure, but each covers a different type of organism: chapter 3 is on bacteria, chapter 4 is on fungi, and chapter 5 is on plants. These chapters start with a general description of the organism type and its life cycle, followed by an analysis of how concrete provides a supportive environment to it, then the consequences of interactions between the organism and concrete, and an evaluation of available methods to control deterioration. Chapter 6 concludes with a focus on deterioration caused by animals, particularly marine animals and birds.

Figueira, R. B., R. Sousa, L. Coelho, M. Azenha, J. M. de Almeida, P. A. S. Jorge, and C. J. R. Silva. 2019. "Alkali-Silica Reaction in Concrete: Mechanisms, Mitigation and Test Methods." *Construction and Building Materials* 222:903–31. https://doi.org/10.1016/j.conbuildmat.2019.07.230.

This review article focused on alkali-silica reaction is a good starting point for professionals looking for a more in-depth understanding of the subject and the current state of research. It starts by discussing the literature available on the various contributing factors, such as reactive aggregate content, and availability of alkalis, soluble calcium, and moisture. The following section presents the current diagnostic methodology to confirm alkali-silica reaction. Most of the section on prevention concerns the construction of new structures, except for measures to control moisture access to the concrete. Some of the prevention methods discussed may be relevant when new materials are being introduced, such as in a concrete repair. The authors also discuss limitations of the available evaluation techniques to assess alkali-silica reaction, developments in modeling, and recommendations for future research.

Hellebois, Armande, Arnaud Launoy, Christian Pierre, Michel De Lanève, and Bernard Espion. 2013. "100-Year-Old Hennebique Concrete, from Composition to Performance." *Construction and Building Materials* 44:149–60. https://doi.org/10.1016/j.conbuildmat.2013.03.017.

This article presents an analysis of concrete samples from a viaduct built in Belgium in 1904, designed by the Hennebique office and built by a licensed contractor. These results are compared to material analyses from eight other Hennebique structures in different European countries built between 1904 and 1909. This is a useful reference for practitioners analyzing the concrete properties and composition of Hennebique structures. The analysis aims at understanding the mechanical properties of the concrete; identification of composition, such as binder, aggregates, cement content, and water-to-cement ratio; and durability indicators, such as carbonation depth, chloride content, and water absorption. The study concludes that the concrete used in Hennebique structures had many similarities in terms of the type of materials employed, but with a lot of variation in compressive strength, which the authors attribute to the limitations of the execution process and tools available at the time. These limitations, they say, can be linked to common deterioration patterns, such as honeycombing and risk of reinforcement corrosion due to displacement of reinforcement bars during pouring. The authors also remark on variations in concrete composition for different element types in the same structure.

Jester, Thomas C. 2014. "Part II: Concrete." In *Twentieth-Century Building Materials: History and Conservation*, 45–86. Los Angeles: Getty Conservation Institute.

See annotation on p. 9.

Loughran, Patrick. 2007. *Failed Stone: Problems and Solutions with Concrete and Masonry*. Basel, Switzerland: Birkhäuser.

This book addresses the many ways in which concrete and masonry buildings fail, and the reasons for and modes of failure. The objective is to inform new design by highlighting past failures and solutions. Eight types of failure are addressed, mostly as a series of case studies. The most relevant sections to historic concrete are as follows: The chapter on efflorescence introduces issues associated with salts in concrete structures. The chapter on surface defects includes discussion of surface finish treatments, various types of concrete, and building techniques, including cast-in-place, precast, self-compacting, and fiber-reinforced concrete. The chapter on discoloration identifies the importance of composition and consistency of the concrete in influencing color, including the importance of the water-to-cement ratio. The chapter on corrosion discusses in detail a product known as Sarabond, a mortar additive that entered the market in 1965 and was responsible for significant corrosion of reinforcements due to its release of chlorides into the pore structure. This chapter also discusses calcium chloride as an additive, alkali-silica reaction, carbonation, and salts. One chapter is dedicated to structural failure. Two of Frank Lloyd Wright's buildings are discussed in the context of seismic performance: the Imperial Hotel, Tokyo (1922), as a success story, and the Ennis-Brown House, Los Angeles (1924), as a failure. Several other pre-1950s case studies are also discussed.

Maierhofer, Christiane, Hans-Wolf Reinhardt, and Gerd Dobmann, eds. 2010. *Non-Destructive Evaluation of Reinforced Concrete Structures*, vol. 1, *Deterioration Processes and Standard Test Methods*. Boca Raton, FL: CRC Press.

See annotation on p. 58.

Marcos, Ignacio, José-Tomás San-José, Leire Garmendia, Amaia Santamaría, and Juan Manuel Manso. 2016. "Central Lessons from the Historical Analysis of 24 Reinforced-Concrete Structures in Northern Spain." *Journal of Cultural Heritage* 20:649–59. https://doi.org/10.1016/j.culher.2016.03.003.

This article presents the results of an analysis of condition assessment reports from twenty-four reinforced concrete structures, including seventeen listed as heritage, located in the Basque Country. These structures date from 1900 to 1937, prior to the adoption of the first Spanish national standard for concrete structures. The analysis aims to reveal common deterioration patterns and compliance with standards adopted by other European countries at the time of construction. The article starts by comparing early-1900s parameters for reinforced concrete adopted in proprietary systems, and in standards from different European countries. This first part also covers concrete mixes and compaction techniques employed in that period. The second part focuses on analysis of the condition assessment reports. These reports included visual inspections, either total or partial, and tests for properties and conditions of concrete and reinforcing steel, although the types of tests included in each report varied. The analysis concludes that most structures followed the specifications of standards from the time of construction. The main deterioration mechanism observed was reinforcement corrosion, due to a combination of low concrete cover prescribed in that period and the common use of chloride-contaminated materials in the analyzed case studies, either in the water or in aggregates. The authors advocate for more thorough investigation of historic concrete structures to guide preventive maintenance measures.

Marie-Victoire, Élisabeth, Emmanuel Cailleux, and Annick Texier. 2006. "Carbonation and Historical Buildings Made of Concrete." *Journal de physique IV (Proceedings)* 136 (1): 305–18.

This paper introduces the issue of carbonation in historic concrete buildings and assesses the potential causes by looking at eight French case studies. Carbonation tests using phenolphthalein as pH indicator were undertaken prior to restoration works at each site. In some cases, additional data was available for comparison, such as microscopy analysis. In this set of case studies, a correlation between the level of carbonation and composition of the concrete was not found. High porosity, often due to the heterogeneity of the material, was seen as a major influence in increased levels of carbonation. The most influential parameter, however, appeared to be the environmental conditions at the site, with wind and humidity being key and connected elements. In this study, the cases with the highest carbonation depths did not have corroded reinforcement. In some cases, carbonation was found to progress from both inner and outer surfaces, influenced in one example by the use of more porous concrete on the hidden inner surface.

Marie-Victoire, Élisabeth, and Annick Texier. 2003. "Alterations in Old Concretes." In *Architectural Culture around 1900: Critical Reappraisal and Heritage Preservation*, edited by Fabio Grementieri, Jorge Francisco Liernur, and Claudia Shmidt, 247–53. Buenos Aires: Editarq.

A research project launched in France in 1993 under the auspices of Le Cercle des Partenaires du Patrimoine sought to understand the causes of visible conditions on concrete buildings and structures. This paper looks

at five key nonstructural mechanisms that trigger deterioration in concrete: carbonation, chloride contamination, sulfate deterioration, freeze-thaw cycles, and alkali-aggregate reactions. In this study, eighteen different types of visible defects or damage were identified and listed. Of these, the conditions found to most frequently affect French historic monuments are spalls related to reinforcement corrosion, cracks, black deposits, and biological growth. The paper proposes a five-stage diagnosis procedure for assessing the type of maintenance or restoration work required where conditions are visible. Trials were undertaken in 1996 and again in 2001 to identify methods to deal with some of the conditions encountered. The results were inconclusive, and a third program, almost entirely devoted to trialing new technologies, was launched in 2002. The preliminary conclusion of this new study was that the new technologies appeared to be promising. Part of the content of this paper was published in more detail in Élisabeth Marie-Victoire, *Les altérations visibles du béton: définitions et aide au diagnostic*, Les Cahiers techniques du Cercle des partenaires du patrimoine 1 (Champs-sur-Marne, France: Cercle des partenaires du Patrimoine, 1996), available online in French at https://www.lrmh.fr/Default/digital-viewer/c-64839.

Mays, Geoff, ed. 1992. *Durability of Concrete Structures: Investigation, Repair, Protection*. London: E & FN Spon.

See annotation on p. 60.

Neff, Delphine, Élisabeth Marie-Victoire, Valérie L'Hostis, Emmanuel Cailleux, Laurent Vincent, Annick Texier, Ludovic Bellot-Gurlet, and Philippe Dillmann. 2007. "Preservation of Historical Buildings: Understanding of Corrosion Mechanisms of Metallic Rebars in Concrete." In *Metal 07: Interim Meeting of the ICOM-CC Metal Working Group, Amsterdam, 17–21 September 2007*, vol. 4, *Study and Conservation of Composite Artefacts*, edited by Christian Degrigny, 30–35. Amsterdam: Rijksmuseum.

This paper presents preliminary results of research aimed at understanding the corrosion mechanism in reinforcement embedded in concrete. The results focus on the characterization of corrosion products found on reinforcement in three case studies in France, ranging from forty-seven to sixty-eight years in age. Analysis of the carbonated concrete environment that surrounded the corroded reinforcements was also conducted. The paper first describes what is known about the corrosion mechanism of reinforcement in concrete. It explains how corrosion products have been found to form two distinct layers around the reinforcement bars: a dense product layer of iron oxyhydroxides and magnetite in contact with the metal, and the transformed medium of iron oxyhydroxides and minerals characteristic of the surrounding material. Next, the paper explains the testing protocol developed for this research. Three types of tests were performed: carbonation with phenolphthalein; on-site electrochemical methods, such as potential mapping, resistivity, and corrosion rate measurements; and laboratory analysis, including scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDS), and Raman microspectroscopy. The focus then shifts to the results of the laboratory analysis of samples collected from the three case studies. These results indicated that multiple types of corrosion products formed from the metallic core to the external zone, and that they could coexist on the same reinforcement bar. The results had yet to be paralleled with results from electrochemical techniques.

Neville, A. M. 2011. *Properties of Concrete*. 5th ed. Harlow, UK: Pearson.

This comprehensive reference book provides knowledge on the properties of concrete, and is an essential base for anyone working with this material, whether or not it is of historic significance. Chapter 1 is dedicated to Portland cement, covering manufacture, chemical composition, hydration process, and influence of fineness and compound composition on properties. Chapter 2 presents the different types of cementitious materials, such as white cement, pozzolanas, and high-alumina cement. Chapter 3 discusses aggregates, mechanical properties, porosity, potentially harmful contamination, testing for reactivity (alkali-silica), and grading. Chapter 4 discusses concrete in its fresh state, including workability and how it is measured, mixing, placing, and potential issues, such as bleeding and segregation. Chapter 5 describes different types of admixtures and their use, such as accelerating, retarding, and water-reducing. Chapter 6 covers properties of hardened concrete

that contribute to its strength. Chapter 7 presents other characteristics of hardened concrete, such as electrical and acoustic properties, and also includes a section on curing. Chapter 8 focuses on effects of temperature in concrete, including influence of extreme temperatures in the concreting phase, thermal properties of hardened concrete, and resistance to fire. Chapter 9 discusses elasticity, shrinkage, and creep. Chapters 10 and 11 are the most relevant to understanding concrete deterioration. Chapter 10 describes processes that influence concrete durability, such as transportation of liquids and gases through concrete, carbonation, acid attack, sulfate attack, efflorescence, effect of sea water, alkali-silica reaction, abrasion, erosion, cavitation, and cracking. Chapter 11 is dedicated to freeze-thaw effects and chlorides, including testing for resistance to these deterioration agents. Chapter 12 presents a comprehensive compilation of destructive and nondestructive tests for mechanical properties, physical properties, and composition. Chapter 13 covers special types of concrete, such as lightweight concrete. And the final chapter discusses selection of concrete mix proportions. This book is in its fifth edition, and it has been translated into twelve languages. The first edition was published in 1963, and the following editions were published in 1973, 1981, and 1995. Each one serves as a snapshot of the state of knowledge on concrete technology at the time of publication.

Neville, A. M., and J. J. Brooks. 2010. *Concrete Technology*. 2nd ed. Harlow, UK: Prentice Hall.

This volume addresses all aspects of concrete technology, including concrete constituents, properties, and behavior, with reference to current national standards and testing methods valid in Britain, Europe, and the United States. It is a valuable reference for both students and professionals of civil engineering and structural engineering. Chapters 1 to 11 address the following topics: concrete as a structural material; cement; normal aggregate; quality of water; fresh concrete; strength of concrete; mixing, handling, placing, and compacting concrete; admixtures; temperature problems in concreting; development of strength; and other strength properties. Chapters 12 to 15 are particularly useful for analyzing deterioration conditions in existing structures related to elasticity and creep, deformation and cracking independent of load, permeability and durability, and resistance to freezing and thawing. Chapter 16 is related to testing, both on-site and in the laboratory. The last chapters, 17 to 19, refer to conformity with specifications; lightweight concrete; and mix design.

Odgers, David, ed. 2012. *Practical Building Conservation: Concrete*. Farnham, UK: English Heritage / Ashgate.

See annotation on p. 70.

Palmisano, F. 2017. "A Preliminary Study on Shear Capacity of Historical Reinforced Concrete Beams." *International Journal of Heritage Architecture* 1 (4): 608–23. https://doi.org/10.2495/HA-V1-N4-608-623.

This article describes the results of a preliminary study on the shear capacity assessment of historic reinforced concrete beams. It is based on the consideration that, before the first technical standards appeared, reinforced concrete structures were designed by applying patents for structural elements, such as the Monnier and Hennebique patents for beams and pillars, which often resulted from experimentation rather than scientific knowledge. Many of these structures may not meet current structural safety standards, and thus the evaluation of shear capacity of reinforced concrete beams from that era is crucial to identify specific needs for structural consolidation interventions. The author argues that current design and construction techniques employed in shear reinforcement are so different from what was used in the early twentieth century that current methods to evaluate shear capacity are not applicable to early twentieth-century reinforced concrete beams without adaptation. The study presented starts by investigating whether the shear formulation from Eurocode 2 would be applicable to the reinforced concrete beams tested in Stuttgart by Emil Mörsch in the early twentieth century. The author then proposes a novel formulation for the transversal shear capacity for historical reinforced concrete beams with U-shaped plates.

Pardo Redondo, Gabriel, Giovanna Franco, Antroula Georgiou, Ioannis Ioannou, Barbara Lubelli, Stefano F. Musso, Silvia Naldini, Cristiana Nunes, and Rita Vecchiattini. 2021. "State of Conservation of Concrete Heritage Buildings: A European Screening." *Infrastructures* 6 (8): article 109. https://doi.org/10.3390/infrastructures6080109.

This article describes the research methodology and main results of the European project CONSECH20 (CONSErvation of 20th century concrete Cultural Heritage in urban changing environments). The project has analyzed a total of forty-eight historic concrete buildings, located in the four different partner countries and selected according to predefined criteria related to age, presence of exposed concrete, and overall current conditions. The methodological approach is described with the support of a flowchart. The project results are presented in three datasets: recurrent damage types and most probable causes; effect of different parameters on the severity of the damages observed; and trends in maintenance, renovation, and reuse in different countries. Results confirmed that the most recurring damages in the case studies are related to the corrosion of reinforcement and moisture-related processes; that the use of plasters and structural facade walls shows a positive effect in protecting concrete; and that the overall state of conservation varies greatly across countries. The presented methodology is expected by the authors to serve as the basis for larger quantitative research involving a representative number of buildings across Europe, to gain a broader understanding of the problems affecting historic concrete.

Pardo Redondo, Gabriel, Barbara Lubelli, and Silvia Naldini. 2019. "State of the Art Report on New Technologies to Monitor, Conserve and Restore the Materiality of Modern Buildings in a Compatible, Durable and Sustainable Way." Report, CONSECH20, Working Package 2–Task (i), Version 03. https://consech20.eu/wp-content/uploads/2022/01/WP2_TUD-SoA_Report_New_Technologies_Restore.pdf.

See annotation on p. 105.

Pardo Redondo, G., S. Naldini, and B. Lubelli. 2021. "Decay Patterns and Damage Processes of Historic Concrete: A Survey in the Netherlands." In *12th International Conference on Structural Analysis of Historical Constructions SAHC 2021*, edited by P. Roca, L. Pelà, and C. Molins, 105–16. Barcelona: International Centre for Numerical Methods in Engineering (CIMNE). http://congress.cimne.com/SAHC2020/frontal/doc/Ebook_SAHC2020.pdf#page=105.

This paper presents a research study regarding the most common types of decay and damage in a set of historic concrete sites in the Netherlands, with a focus on direct and indirect parameters that can hasten or slow down deterioration. The study is developed in the framework of the European research project CONSECH20 (CONSErvation of 20th century concrete Cultural Heritage in urban changing environments). In the first research phase, fifteen case studies from the Netherlands (selected based on age, state of conservation, and type of ownership) were investigated. In the second phase, the history and materials of the buildings were examined. In the third phase, an on-site visual survey was performed on each building to identify types of damage and their extent and severity. The analysis of results shows that most types of damage are related to corrosion, likely induced by carbonation. The factors with a higher impact on concrete durability were the environment, the use and maintenance of the buildings, the existence of a sacrificial plaster on exposed elements, and type of ownership.

Prudon, Theodore H. M. 1981. "Confronting Concrete Realities." *Progressive Architecture* 62 (11): 131–37.

See annotation on p. 22.

Pullar-Strecker, Peter. 1987. *Corrosion Damaged Concrete: Assessment and Repair*. London: Construction Industry Research and Information Association; Boston: Butterworths.

This guide to dealing with common durability problems associated with corrosion-damaged concrete provides a fundamental understanding of corrosion and corrosion-related repairs in reinforced concrete structures. This is not an in-depth publication, but one intended to enlighten owners and nonspecialists. It encourages the hiring of a corrosion expert. Section 2 of the document provides inspection and evaluation procedures to help determine conditions that may lead to failure. Physical and laboratory evaluations, in situ nondestructive evaluation, and destructive evaluation procedures are outlined. Section 3 tackles the question of how to appropriately commission structural inspections and how to determine when repairs are needed. Repair types and advice are provided in section 4. The document emphasizes that lack of sensitivity to the material and incorrect

repairs have been shown to exacerbate corrosion. Surface treatments and cathodic protection are highlighted in the last two sections of the text as treatment options. Given the date of publication, more recent references should be consulted for up-to-date information.

Reed, Peter, Kate Schoonees, and Jeremy Salmond. 2008. *Historic Concrete Structures in New Zealand: Overview, Maintenance and Management*. Wellington, NZ: Science & Technical Pub., Dept. of Conservation. https://www.doc.govt.nz/globalassets/documents/science-and-technical/sap248entire.pdf.

See annotation on p. 84.

Rosato, Vilma G. 2006. "Diversity and Distribution of Lichens on Mortar and Concrete in Buenos Aires Province, Argentina." *Darwiniana* 44 (1): 89–97. https://www.ojs.darwin.edu.ar/index.php/darwiniana/article/view/124.

This study on lichens growing on concrete and cement mortars in different localities of Buenos Aires Province aims to identify which ones are potentially harmful for these types of substrates. The case study typologies include bridges, dams, churches, town halls, a university building, an observatory, private houses, cemeteries, statues, benches, and a few other kinds of artifacts. The author identified thirty-three different species growing on cement mortars and concrete. Lichens were identified utilizing dissecting and optical microscopes. The research results interestingly revealed the first identification of *Staurothele frustulenta* in Argentina, and the first identification of *Acarospora subcastanea* in Buenos Aires Province. Also, a high number of foliose lichens (fifteen species) were registered, and some species previously known only on tree barks were encountered colonizing cement materials.

Sergi, G., and A. Dunster. 2004. *Corrosion of Steel in Concrete: A Review of the Effect of Humidity*. BRE Digest 491. Watford, UK: BRE.

This paper reviews models and data and presents additional information to European Standard EN 206 for the United Kingdom. It deals with the issue that the exposure classes for concrete susceptible to reinforcement corrosion in EN 206 does not adequately describe the major risks from possible environmental changes during the life of the reinforced concrete object, nor does it quantify the risk of reinforcement corrosion for more constant environments. One reason could be the variability of environmental conditions in Europe and the different practices of member states. A more robust environmental classification is therefore needed, and should be based on a better understanding of variations in moisture at different depths under changing external conditions, and the resulting corrosion rate of steel reinforcement.

Skalny, Jan, Jacques Marchand, and Ivan Odler. 2002. *Sulfate Attack on Concrete*. Modern Concrete Technology 10. London: Spon Press.

This volume provides a comprehensive reference to the subject of sulfate attack on concrete. It includes a short history of concrete deterioration due to sulfate attack, and addresses the origin of sulfates in concrete, the importance of appropriate concrete processing, types and physical-chemical mechanisms of concrete deterioration due to sulfates, preventive measures, standardization, and numerous case histories. This publication was conceived as a reference text for both industry practitioners involved in concrete science and engineering, and researchers of materials science and concrete technology.

Szocinski, Michał, Andrzej Miszczyk, and Kazimierz Darowicki. 2019. "Condition of Reinforced Concrete Structures and Their Degradation Mechanism at the Former Auschwitz Concentration and Extermination Camp." *Studies in Conservation* 64 (3): 174–86. https://doi.org/10.1080/00393630.2018.1557937.

See annotation on p. 66.

TNO, TU Delft, and Dutch Rijksdienst voor het Cultureel Erfgoed. 2023. "Concrete Damage Atlas." Monument Diagnosis and Conservation System (MDCS) website. https://mdcs.monumentenkennis.nl/damageatlas/7/material.

This web-based tool offers support in the identification and diagnosis of deterioration in various types of materials present in historic buildings, including concrete. It includes a visual glossary of concrete deterioration, available without the need to create an account. The different types of deterioration are presented in categories and subcategories covering disintegration, cracks, surface changes, biological growth, deformation, mechanical damage, missing parts, and corrosion of reinforcement. Each type is described and illustrated with photos, and possible causes are offered.

Urquhart, Dennis. 2014. *Historic Concrete in Scotland*, part 2, *Investigation and Assessment of Defects*. Short Guide 5. Edinburgh: Historic Scotland. https://www.historicenvironment.scot/archives-and-research/publications/publication/?publicationId=c2a38944-eb81-44e8-bd5e-a59100fb611a.

See annotation on p. 67.

Wilkie, Simeon, and Thomas Dyer. 2021. "Design and Durability of Early 20th Century Concrete Bridges in Scotland: A Review of Historic Test Data." *International Journal of Architectural Heritage* 16 (8): 1131–51. https://doi.org/10.1080/15583058.2020.1870776.

This paper addresses the issue of durability of early twentieth-century concrete bridges in Scotland by carrying out a review of preexisting test data for thirty-six bridges built prior to 1950 to better understand their designs and the implications for their maintenance and preservation as historic resources. Many of these structures were designed when concrete was a relatively new material and there were scant or no standard design criteria. As a result, several suffer from significant durability issues. This research also analyzed changes that have occurred in the design and construction of reinforced concrete bridges by comparing their original designs to current engineering codes. The authors conclude that there appears to be no correlation between year of construction and level of deterioration risk; rather, deterioration risk is dependent on the quality of the concrete, the depth of the concrete cover, and environmental exposure conditions.

CHAPTER 3

# EVALUATION

## Key References

American Concrete Institute. 2019. *Guide for Assessment of Concrete Structures before Rehabilitation: Reported by ACI Committee 364*. ACI 364.1R-19. Farmington Hills, MI: American Concrete Institute.

This publication is a guide to general procedures for the assessment of concrete structures before rehabilitation. It is the updated version of the ACI 364.1R-07 Guide for Evaluation of Concrete Structures before Rehabilitation (2007). After the introduction and a useful set of definitions, the following subjects are covered: investigation, including specifications on preliminary assessment and detailed assessment; document review, which distinguishes between design information, materials information, construction information, service history, and project documents; field investigation, focusing on preparation and planning, field verification of as-built construction, condition survey and visual inspection, exploratory openings, and unsafe or potentially hazardous conditions; sampling and testing, including determination of requirements, testing and evaluation methods, sampling techniques, and test reporting; evaluation, which includes determining causes, evaluating the consequences of damage, structural evaluation, and evaluation of rehabilitation approaches; and report, suggesting the report's contents and structure. An earlier version is included in Mark E. Hughes and Carl R. Bischof, eds., *Concrete Repair Manual* (2013, see annotation on p. 100).

Broomfield, John P. 2007. *Corrosion of Steel in Concrete: Understanding, Investigation and Repair*. 2nd ed. London: Taylor and Francis.

See annotation on p. 27.

Bungey, John H., Stephen G. Millard, and Michael G. Grantham. 2018. *Testing of Concrete in Structures*. 4th ed. Boca Raton, FL: CRC Press.

This book overviews methods for testing concrete structures, and is intended for nonspecialist engineers who are responsible for planning test programs. Despite the publication covering many topics, test procedures are presented at a high level of detail to enable the reader to dialogue with experts in each specific method. Established techniques are outlined together with new techniques and procedures having potential for future development. The publication is organized in the following chapters: "Planning and Interpretation of In Situ Testing," "Surface Hardness Methods," "Ultrasonic Pulse Velocity Methods," "Partially Destructive Strength Tests," "Cores," "Load Testing and Monitoring," "Durability Tests," "Performance and Integrity Tests," and "Chemical Testing and Allied Techniques." The appendices are "Typical Cases of Test Planning and Interpretation of Results," "Examples of Pulse Velocity Corrections for Reinforcement," and "Example of Evaluation of Core Results." Although no specific reference is made to testing concrete on historic structures, readers will find useful information and recommendations. For example, chapter 1 addresses how to increase confidence in results and improve calibration accuracy when deciding on number and location of in situ tests and test combinations. Chapter 5 discusses issues with small cores, and the influence of specimen size on reliability, limitations, and applications.

Harrer, Ann, and Paul Gaudette. 2017. "Practice Points, no. 16: Assessment of Historic Concrete Structures." *APT Bulletin: Journal of Preservation Technology* 48 (4): 29–36. https://www.apti.org/assets/docs/Practice_Point_16.pdf.

This article overviews the assessment process for historic concrete structures, underlining the need for a more careful approach than one would employ for ordinary concrete structures. The whole process of assessment is described, from the research phase to field investigation and evaluation of findings. Practical recommendations are provided for each phase. In the field investigation, attention is focused on the need to analyze modifications or repairs not well documented, use of the structure, environmental conditions, location of the building, and source of construction materials, all of which could contribute to deterioration. Evidence is given also of the need to carefully choose the location of inspection openings, which should be representative of the various conditions and elements but also as unobtrusive as possible. The authors advise that existing damage, such as spalls, may reveal construction and material characteristics, and thus help minimize the need for additional openings. Basic information is provided about materials studies, underlining that their results may also assist in the development of compatible repair materials. Also covered are the need to well understand the causes of deterioration, the owner's perspective on building use and maintenance, and the site's values and significance, in order to meet the owner's needs while preserving the building's historic character.

Macdonald, Susan, ed. 2003. *Concrete: Building Pathology*. Oxford: Blackwell Science.

This comprehensive text focuses on the diagnostics and repair of architectural concrete from the 1890s onward. It begins with a comprehensive history of architectural concrete in Britain, from early typologies, materials, and construction methodologies to advancements and improvements in materials, standards, and construction through the 1970s. Chapters 3 and 4 focus on structural assessments, condition assessments, and survey methodologies to identify and catalogue concrete deterioration. Chapter 4 also overviews the main types of deterioration in concrete and their potential causes. Chapter 5 provides an in-depth discussion of traditional and electrochemical repair options and the requirements for such repairs. As corrosion is one of the most significant modes of deterioration for concrete, much discussion covers this topic. The applicability and impacts of repairs and electrochemical treatments to listed/historic buildings are addressed. Chapter 6 addresses maintenance of concrete buildings and concepts of service life, life-cycle analysis, and whole-life costing. Several maintenance options are discussed with a focus on coatings. The key concept is that by understanding factors affecting concrete durability, one can better plan construction projects. Preventive maintenance and proactive repairs can provide significant cost savings over the life of a building and extend service life for concrete assets. Chapter 7 anticipates changes to concrete in the future. This includes reviewing current standards and past failures, and designing intelligently. Planned maintenance, designing preventive systems, and the use of appropriate materials to increase durability are discussed as conservation approaches. The aim is to shift the industry paradigm from "respond and repair" to "predict and prevent" (p. 259), a necessary approach in heritage conservation.

Odgers, David, ed. 2012. *Practical Building Conservation: Concrete*. Farnham, UK: English Heritage / Ashgate.

See annotation on p. 70.

## General References

Akhurst, Paul, Susan Macdonald, and Trevor Waters. 2005. "Sydney Opera House: Analysis and Cleaning of the Concrete." *Journal of Architectural Conservation* 11 (3): 45–64. https://doi.org/10.1080/13556207.2005.10784952.

See annotation on p. 88.

Alwaal, A. H., S. Barnett, R. Inkpen, and L. Hastewell. 2018. "Monitoring Historic Concrete and Associated Cementitious Repair: A Case Study of Boathouse 4, Portsmouth Historic Dockyard, UK." In *ICDCS 2018: Proceedings of the Sixth International Conference on Durability of Concrete Structures, 18–20*

*July 2018*, edited by P. A. M. Basheer, 723–28. Dunbeath, UK: Whittles. https://docs.lib.purdue.edu/icdcs/2018/ram/1/.

This paper proposes a methodology for monitoring microscale changes and damage to historic concrete surfaces, including repaired areas. The case study selected to test this methodology is Boathouse 4 at Portsmouth Historic Dockyard, England, an iconic building from the 1930s, also used during World War II to build the three-person midget X-Craft submarine. In 2015, the building was the object of a restoration and adaptive reuse program to be converted into a boatbuilding skills training center. The field investigation included analysis and monitoring of three areas showing past patch repairs, which were scanned with a portable laser scanner three times at intervals of up to nine months within a three-year period dedicated to this research study. The laser scanner made it possible to obtain high-resolution 3D images of the concrete surfaces, which were used to detect gradual changes to the micro-topography and appearance of the concrete surface. The investigation results showed slight topographic changes in the concrete surface as well as color change of the cementitious repair materials. For the level of detail of the data obtained, this methodology appears particularly useful in specific circumstances, such as monitoring small-scale concrete artifacts (bas-relief decorations, sculptures, et cetera) and architectural concrete surfaces with a particularly significant texture or painting layer.

American Concrete Institute. 2013. *Report on Nondestructive Test Methods for Evaluation of Concrete in Structures: Reported by ACI Committee 228*. ACI 228.2R-13. Farmington Hills, MI: American Concrete Institute.

This technical report focuses on nondestructive test methods for evaluating the condition of concrete structures. It discusses the different methods available, including visual inspection, stress-wave methods, nuclear methods, methods for measurement of fluid transport properties, magnetic and electrical methods, infrared thermography, and ground-penetrating radar. It describes the principles underlying each nondestructive test method, the instrumentation needed, procedures, and data analysis methods. The report also highlights advantages and limitations of the methods and provides information on planning a nondestructive test program. This technical and practical information is instrumental to all professionals involved in the conservation of cultural heritage made of concrete. Also included in Mark E. Hughes and Carl R. Bischof, eds., *Concrete Repair Manual* (2013, see annotation on p. 100).

Andrei, Viorel, Carmen Virban, Elena Dan, and Marcela Muntean. 2003. “Durability Investigation of Old Concrete Structures.” In *Concrete Solutions: 1st International Conference on Concrete Repair, St.-Malo, France, 15–17 July 2003*, edited by Michael Grantham, 731–38. London: GR Technologie Ltd.

This paper focuses on concrete investigations utilizing laboratory-based physical and chemical techniques, including chemical analysis, X-ray diffraction, and optical microscopy. The laboratory investigation focuses on the quality of the hardened concrete, notably composition, cement content, aggregate type, and water-to-cement ratio. The quality of the material, as expressed through the results of the testing program, can assist with predicting the future behavior of a concrete structure. This combined methodology can be employed to choose repair materials and evaluate risk. Concrete samples examined were taken from four structures between twenty and fifty years old. While none were of cultural significance, the analytical laboratory approach can provide information regarding estimation ratios of original construction materials, chemical attack, and concrete properties.

Australian Concrete Repair Association (ACRA), Commonwealth Scientific and Industrial Research Organisation (CSIRO), and Standards Australia. 2006. *Guide to Concrete Repair and Protection*. 2nd ed. SAA HB 84-2006. Sydney: ACRA / CSIRO / Standards Australia.

See annotation on p. 89.

Ayón, Angel. 2009. “The Guggenheim at Fifty: Notes on Recent Preservation Work.” *DOCOMOMO Journal*, no. 41, 73–79.

This article discusses conservation works undertaken at Frank Lloyd Wright's Solomon R. Guggenheim Museum in New York nearly fifty years after construction. It details the extensive documentation and assessment efforts, structural analysis, materials testing, and conservation treatments and works conducted. It highlights the use of a structural 3D model put together from data collected through laser-surveying technology. This model was used to analyze the structure under different environmental conditions and to identify requirements for structural repairs and/or stabilization. All repairs were undertaken in accordance with the project's conservation approach, which sought to adhere to national and international guidelines and charters. Also highlighted is the extensive analysis undertaken in selecting the most appropriate external surface finish product, which took into consideration both physical characteristics and aesthetics. The rationale for replacing some of the original fenestration and work done to reduce internal and external moisture-related issues is also discussed.

Ban, Matea. 2014. "Wotruba Church and Cologne Opera: Aspects of Concrete Aging." In *Concrete Solutions: Proceedings of Concrete Solutions, 5th International Conference on Concrete Repair, Belfast, Northern Ireland, 1–3 September 2014*, edited by Michael Grantham, P. A. Muhammed Basheer, Bryan Magee, and Mario Soutsos, 619–25. Boca Raton, FL: CRC Press.

This paper discusses current conservation challenges concerning aging concrete. It outlines the testing program, the results, and the rationale behind the selection of the most suitable repair options given the constraints of a heritage structure. Two cases—the Church of the Holy Trinity (Wotruba Church), a sculptural concrete church in Vienna, and the Cologne Opera House—are used to illustrate differences in nondestructive evaluations and conservation treatments for landmark concrete structures. The testing program for the Wotruba Church utilized nondestructive and semi-destructive testing, including water absorption, surface strength, microstructural analysis, carbonation, survey of reinforcement distribution, air permeability, and climate analysis. The Cologne Opera House's assessment program included an extensive site study and more invasive test methods: survey of reinforcement location and cover thickness, petrographic analysis of thin sections, carbonation, adhesion pull-off strength, paint/binder analysis (for coatings), and carbonation resistance of coated areas. The combination of nondestructive and semi-destructive evaluations proved useful in determining the concrete's condition in both cases. At the Wotruba Church, the methodology focused on academic research and less-invasive testing led to the development of a conservation approach. In the case of the Opera, more invasive investigations were used to determine the degree to which the concrete could be restored. Continued research and analysis are needed for understanding localized treatments, protective coatings, and interactions between repair materials and historic concrete.

Berkowski, Piotr, and Grzegorz Dmochowski. 2022. "Structural and Material Assessment of Historic Reinforced Brick Masonry Elevator for Grain: A Study Case." In *Concrete Solutions 2022: 8th International Conference on Concrete Repair, Durability & Technology*, edited by M. G. Grantham, M. Basheer, and R. Mangabhai, art. 01001. MATEC Web of Conferences 361. Les Ulis, France: EDP Sciences. https://doi.org/10.1051/matecconf/202236101001.

This paper focuses on durability and maintenance issues in the case of a grain elevator built around 1940 at an Odra River embankment in Poland, made of reinforced concrete and brick masonry. The aim of the condition assessment was to evaluate the possibility of its adaptive reuse as an apartment building. The structure, comprising seventy-four silo chambers with square plans, shows a rectangular plan perpendicular to the former port wharf. The elements in reinforced concrete are the ground-floor columns and walls, the above floor with the drainage funnels, the inter-story ceilings of the technical route, the roof, and the attic ceiling. The walls of the silo chambers are made of reinforced brick masonry. The publication gathers the results of the diagnostic analysis of the various materials (concrete, brick, steel) and includes comparison of archival documentation and as-built condition, inventory of observed damage and structural elements, geotechnical examinations, concrete and reinforcement strength tests, structural modeling, and calculation. The analysis concludes that the proposed design would be difficult to implement.

Bertolini, Luca, Federica Lollini, and Elena Redaelli. 2009. "Corrosion Assessment of Structural and Decorative Reinforced Concrete of Torre Velasca in Milan." In *Protection of Historical Buildings: PROHITECH 09: Proceedings of the International Conference on Protection of Historical Buildings, PROHITECH 09, Rome, Italy, 21–24 June 2009*, edited by Federico M. Mazzolani, 495–500. Boca Raton, FL: CRC Press, Inc.

The subject of this paper is the holistic diagnostic approach applied at Torre Velasca (1956–58), a significant brutalist reinforced concrete building in Milan, with information on testing and methodologies for assessing corrosion risk. Conservation methodology, condition analysis, and diagnosis were needed to develop a repair approach to deal with corrosion in the structure. Both nondestructive and semi-destructive testing were carried out, with in situ tests including half-cell potential, resistivity, and cover testing. Laboratory testing included X-ray diffraction analysis (XRD), thermo-gravimetric analysis (TGA), Fourier-transform-infrared spectroscopy (FTIR), and scanning electron microscopy (SEM). After preliminary research, the authors identified previous repairs but could not visually determine the areas patched. Only sealed cracks were visually noted. Laboratory and core testing indicated that the concrete had three layers—structural, mortar, and plaster—and that the surface coating was acrylic-based and most likely applied in a 1978 repair campaign. The key tests here indicate that conditions differ between the structural concrete and the decorative elements. Correlations between cover thickness, carbonation depth, potential, and resistivity provide evidence that the upper levels of the exposed concrete building and precast elements are at higher risk than the structural concrete. Previously repaired cracks in the plaster layer were not found to be caused by corrosion.

Borg, Ruben Paul. 2020. "Concrete Heritage: Challenges in Conservation." *Symposia Melitensia* 16:35–52. https://www.um.edu.mt/library/oar/handle/123456789/53475.

Methodological aspects of concrete diagnosis are the focus of discussion here, from documentation and mapping of degradation to materials, structural, and environmental assessment. This methodology is applied to understand and report the current conditions of six case studies. The case studies consist of military and industrial concrete structures built in the Maltese islands between the 1890s and the second half of the twentieth century, most of them in aggressive coastal environments. The paper includes a preliminary discussion about conservation principles for concrete heritage, influencing factors and degradation processes in concrete, and current European design codes on durability of reinforced concrete structures, including exposure classes related to different environmental conditions and detail design. All the case studies show distinctive geometrical and constructive features, depending on their function. Most present severe deterioration depending on whether they were long in a state of abandonment.

Bouichou, Myriam, Élisabeth Marie-Victoire, Héloïse Jourdan, Benoit Thauvin, Ronan Queguiner, Roberto Olmi, and Cristiano Riminesi. 2018. "Measurement of Water Content and Salinity Index in Concrete by Evanescent Field Dielectrometry." *Journal of Cultural Heritage* 34:237–46. https://doi.org/10.1016/j.culher.2018.07.003.

This paper describes the application on reinforced concrete of the SUSI-R© system, a noninvasive microwave system based on evanescent field dielectrometry to determine water and chloride content. This technique was developed for use in wall paintings, while here it is applied to reinforced concrete elements. Water and chloride ions are important risk factors for reinforcement corrosion, which is a major cause of deterioration in reinforced concrete. Thus, the development of nondestructive techniques able to detect the presence of water and chloride ions represents an interesting alternative to existing diagnostic techniques for concrete architectural heritage. The system was tested on twelve reinforced concrete slabs made of two different types of cement, which were semi-immersed in water or in a sodium chloride solution. Measurements with the SUSI-R© system were taken before and during the rise of the capillary absorption front. Then the system was calibrated in the laboratory using prisms made of the same types of cement. Research results show that the SUSI-R© system enables detection of hydric changes, estimation of water content, identification of capillary absorption solution (plain water or salted water), and, finally, identification of differences in capillary absorption kinetics and in the evolution of the salinity index, depending on the cement type.

Breysse, Denys, ed. 2012. *Non-Destructive Assessment of Concrete Structures: Reliability and Limits of Single and Combined Techniques: State-of-the-Art Report of the RILEM Technical Committee 207-INR*. Dordrecht, the Netherlands: Springer Netherlands. https://doi.org/10.1007/978-94-007-2736-6.

This book reports on the RILEM Technical Committee 207-INR findings on nondestructive assessment of concrete structures. It is guided by the premise that nondestructive assessment and evaluation methods can be effectively applied to infer material conditions and properties if their use is based on sound knowledge of how the method interacts with concrete, how to properly employ the method, and how to interpret the results. The goal of this book is to cover that necessary knowledge base, and how to combine the different techniques to obtain more accurate assessments. Chapter 1 describes the basic concepts and challenges, and introduces different ways techniques can be combined. Chapter 2 explains the principles behind the different types of methods, equipment, data processing, limitations, and references. The following methods are covered: ultrasound through transmission; ultrasonic echo; surface waves; impact-echo; impulse response; acoustic emission; ground-penetrating radar; capacitive technique; electrical resistivity measurement; infrared thermography; radiography; rebound hammer; and pullout testing. Chapters 3 through 7 explain specific applications of the methods; for example, chapter 3 is focused on estimation of compressive strength, and chapter 5 focuses on assessment of bonding and delamination. Chapter 8 further discusses combinations of different types of nondestructive evaluation methods.

British Cement Association. 1992. *The Diagnosis of Alkali-Silica Reaction*. 2nd ed. Berkshire, UK: British Cement Association.

This report by the British Cement Association provides advice and guidance on approaches to concrete buildings in which alkali-silica reaction is suspected. It details the types of site investigation and testing that should be undertaken, outlines requirements for site survey, specifies sampling procedures, discusses in detail the available laboratory tests for the identification of alkali-silica reaction, and looks at the possible risk of future reaction. The publication makes clear that no single observation can positively identify the presence of alkali-silica reaction and associated damage. The results of any investigation, incorporating site and laboratory observations, must be assessed as a whole before the level of probability that alkali-silica reaction is present and causing damage can be determined. Throughout the text, it is observed that the presence of alkali-silica reaction does not necessarily mean that it has caused damage, and that other potential damage factors should not be ruled out. The text is well illustrated with diagrams, photographs, flowcharts, graphs, and tables to aid understanding of the processes involved. Detailed appendices provide additional information on some of the processes described. Appendix D provides a list of aggregate types that may be sensitive to alkali-silica reaction. Given the date of publication, more recent references should be consulted for up-to-date information on investigation techniques.

Broomfield, John P. 2013. "Concrete Preservation Plan for Reinforced Concrete University Campus Buildings." In *Forensic Engineering: Informing the Future with Lessons from the Past: Proceedings of the Fifth International Conference on Forensic Engineering*, edited by John Carpenter, 401–13. London: Institution of Civil Engineers Publishing.

This paper addresses measures taken to minimize corrosion damage and deterioration of the brutalist concrete structures designed by Denys Lasdun at the University of East Anglia, which are grade II and II* listed. As part of the project's scope, the university buildings were investigated, diagnosed, and treated in accordance with the concrete repair standard BS EN 1504. The specification of works was written to be as fully compliant with 1504 as possible given the additional needs stemming from its heritage listing. Investigation and predictive analysis were used in various locations to determine time to damage through carbonation and chloride profiles. The paper makes a case for various levels of intervention in accordance with BS EN 1504, while keeping landmark status and minimal concrete removal in mind. Different treatments were applied in three phases of work to the three structures, based on variations in corrosion conditions. The paper emphasizes the importance of understanding the original concrete and its durability, and the use of trials for treatment options. Due to the complexities of the facade on the Biotower and the presence of low cover, cast-in chlorides, and carbonation, impressed current cathodic protection was used on the interior elevations. Where previous repairs had weathered, creating a different appearance, architectural coatings were applied. The Library Walkway received galvanic anodes, coatings, and waterproofing treatments. Testing procedures utilized to ensure quality are outlined, though some of the work preceded the publication of BS EN 1504. The author concludes that the methodology set forth in BS EN 1504 can be successfully applied to guide repairs to historic concrete when requirements are modified to meet the specific needs of the structure's heritage status.

Building Research Establishment. 2000. *Corrosion of Steel in Concrete: Investigation and Assessment*. BRE Digest 444, part 2. Garston, UK: BRE.

This document is the second of a three-part series on corrosion of steel reinforcement in concrete. It describes assessment techniques and diagnosis of reinforcement corrosion. It starts by describing the different types of inspection, and the purpose of testing and monitoring. The following section describes a methodology for site inspection. It advocates targeted testing of critical areas based on initial research on the structure. The methodology presented is not different from investigation of any other type of deterioration, but it mentions specific signs of reinforcement corrosion that could be noticed in a visual inspection and key contributing factors that must be evaluated, such as carbonation and chloride contamination. The following section briefly describes the types of testing that can be used in diagnosing reinforcement corrosion. Then the document explains how data collected in a site inspection can be used to assess risk of future reinforcement corrosion. The last section discusses how reinforcement corrosion can affect structural performance. Part 1 (see annotation on p. 31) focuses on describing the deterioration mechanism of corrosion in reinforced concrete and the factors that contribute to it, and part 3 (see annotation on p. 91) covers repair and preventive treatment options for this type of deterioration. Also included in Mark E. Hughes and Carl R. Bischof, eds., *Concrete Repair Manual* (2013, see annotation on p. 100).

Carmona-Quiroga, P. M., A. Pachón-Montaño, J. Queipo-de-Llano, J. A. Martín-Caro, D. López, I. Paniagua, I. Martínez et al. 2021. "Characterisation and Diagnosis of Heritage Concrete: Case Studies at the Eduardo Torroja Institute, Madrid, Spain." *Materiales de construcción* 71 (344): art. e262. https://doi.org/10.3989/mc.2021.11021.

The study presented in this article aimed to characterize the current conditions of a series of concrete elements forming part of the Instituto de Ciencias de la Construcción Eduardo Torroja in Madrid, a modernist architectural complex listed and protected by the city as a cultural heritage asset. The results of this diagnosis, involving both in situ nondestructive and laboratory techniques, revealed that the core of the concrete elements was in good condition, despite surfaces showing signs of deterioration. The latter required conservation interventions compatible with the preservation of the integrity and authenticity of the heritage asset. Strategies for maintenance for each analyzed element are outlined in the conclusions. The study was developed within the framework of the international research project InnovaConcrete on twentieth-century concrete-based cultural heritage.

Chae, Yena, and Sean Hay Kim. 2022. "Interstitial Hygrothermal Analysis for Retrofitting Exterior Concrete Wall of Modern Heritage Building in Korea." *Case Studies in Construction Materials* 16:art. e00797. https://doi.org/10.1016/j.cscm.2021.e00797.

This publication focuses on issues related to hygrothermal performance and condensation that can occur with installation of insulation in exterior concrete walls. The authors selected as case studies three modern heritage buildings with concrete structures in Seoul. The measurement of moisture content and temperature on the concrete wall surface, as well as the measurement of indoor temperature and humidity, were used as the initial conditions for selecting the most adequate insulation. These measurements were also used for hygrothermal analysis aimed at understanding whether a vapor retarder should be installed. One of the case studies, a school building, was chosen for retrofit, and a series of analysis were undertaken (mock-up test, ISO 13788 steady-state analysis, and dynamic simulations by WUFI Pro) to evaluate the risk of interstitial condensation in the exterior wall, referring to the initial moisture content measured.

Cohen, James S. 2013. "Evaluation of a Historic High-Rise Reinforced Concrete Building." In *Forensic Engineering 2012: Gateway to a Better Tomorrow: Proceedings of the Sixth Congress on Forensic Engineering, October 31–November 3, 2012, San Francisco, California*, edited by Anthony M. Dolhon, Michael J. Drerup, Alicia Díaz de León, Joshue B. Kardon, Derrick S. Hancock, and Shen-en Chen, 1198–207. Reston, VA: American Society of Civil Engineers.

The subject of this paper is a high-rise concrete-frame building from 1914 in Newark, New Jersey. The building is on the National Register of Historic Places and therefore subject to landmark compliance, but it has been derelict for many years. A neighborhood revitalization effort required a survey to determine its condition and salvageability, with follow-up necessary after an earthquake in 2011. The testing program for the building outlines nondestructive evaluation procedures in conjunction with a core sampling program. The report identifies challenges in dealing with early concrete structures and the need to alter testing protocols when actual site conditions and safety limit access to the structure. The testing program included compressive strength, sounding survey to detect delaminations, rebound hammer, and cover and carbonation depths. Visual indicators of deterioration, crack surveys, and water penetration were noted. The paper provides a summary of conditions, but limited conclusions.

Collette, Quentin. 2017. "Investigation of the Reinforced-Concrete Construction of the Dotremont House in Brussels." *APT Bulletin: Journal of Preservation Technology* 48 (1): 40–48. https://www.jstor.org/stable/26291034.

This paper presents the analysis and intervention carried out at the Dotremont house in Brussels, designed by Louis Herman De Koninck and built in 1932–34. Investigations focused on the general context at the time of construction, with reference to the use of patented systems, the intense technology transfer in Belgium, and the profile of the architect, who had a strong interest in structural design efficiency. This detailed survey enabled a comprehensive understanding of the structural design concept for this three-story house, characterized by two load-bearing systems: the exterior one made of thin cast-in-place reinforced concrete walls on the front and rear facades, built with non-standardized formworks and finished with bush hammering and chiseling, and the interior one consisting of a beam-and-column concrete frame structure supported by piers, with floors supported by continuous double T-beams running throughout the length of the house. The house was renovated in 2011. Three structural interventions were carried out: stabilization of the foundation system, reinforcement of the concrete porch roof, and strengthening of a thin cantilevered slab on the rear wall. In addition, some minor concrete repairs were performed on the exterior concrete walls, based on petrographic and aggregate size analysis for matching the original concrete.

The Concrete Society. 2000. *Diagnosis of Deterioration in Concrete Structures: Identification of Defects, Evaluation and Development of Remedial Action*. Technical Report 54. Crowthorne, UK: Concrete Society.

See annotation on p. 33.

The Concrete Society. 2014. *Analysis of Hardened Concrete: A Guide to Tests, Procedures and Interpretation of Results*. 2nd ed. Technical Report 32. Surrey, UK: Concrete Society.

This technical report aims to assist all professionals involved in the chemical analysis of hardened concrete. To a lesser extent, microscopic examination techniques are also discussed. Following the introduction, the report describes sampling and specimen preparation. The two following chapters provide guidance on available techniques for determining concrete constituents and concrete properties. The final chapter discusses future research needs identified by the working group. The report is enriched with a series of appendices covering a glossary of terms, health and safety, micrometric determination of mix proportions, and the findings of the Concrete Society laboratory trial. An earlier version is included in Mark E. Hughes and Carl R. Bischof, eds., *Concrete Repair Manual* (2013, see annotation on p. 100).

Courard, Luc, Benoît Bissonette, Alexander M. Vaysburd, Normand Bélair, and François Lebeau. 2012. "Comparison of Destructive Methods to Appraise the Mechanical Integrity of a Concrete Surface." *Concrete Repair Bulletin* 25 (4): 22–30.

This article describes research to determine whether any of the three main methods used for establishing the strength and integrity of a concrete surface—the Schmidt rebound hammer test, pullout tests (two trialed: Capo pullout test and accelerated cohesion test), and the pull-off test—could also be used for assessing a surface that has been prepared to receive a patch repair following concrete removal. The procedures and necessary considerations for each of these methods are described. As part of this investigation, each method was first trialed on a series of untreated concrete slabs to establish the significance and sensitivity of the procedure. Following this, tests were undertaken to establish the success of each of the methods for identifying surface integrity on prepared surfaces. Concrete blocks were used for this trial; control surfaces were left untreated, and other surfaces were prepared by removing the concrete cover by sandblasting or using handheld concrete breakers of three different weights. The Capo pullout test was left out of this trial because it had been found to only work on flat surfaces. The investigation concluded that the best method for identifying surface integrity was a combination of the Schmidt hammer test and either the pull-off test, for horizontal surfaces, or the accelerated cohesion test, which was found to be suitable for all surfaces.

Courard, Luc, Anne Gillard, Anne Darimont, Jean-Marie Bleus, and Pierre Paquet. 2012. "Pathologies of Concrete in Saint-Vincent Neo-Byzantine Church and Pauchot Reinforced Artificial Stone." *Construction and Building Materials* 34:201–10. https://doi.org/10.1016/j.conbuildmat.2012.02.070.

This article documents the investigation undertaken to understand concrete deterioration at Saint Vincent Church in Liège, Belgium. This is part of a larger research project documenting and characterizing concrete churches internationally, identifying defects and proposing potential conservation solutions. The article gives a brief history, an architectural description, and a structural description of the building, which was designed by Robert Toussaint in 1928–30. The structure is in reinforced concrete, and the outer finish in many areas uses a material known as Pauchot, a reinforced artificial stone. The authors recommend a two-stage investigative approach in which visual assessment and selective sampling in deteriorated areas is followed by a detailed diagnostic survey, including destructive and nondestructive analysis techniques. Three types of potential deterioration are identified—cracking, spalling, and corrosion of reinforcements—and the presence of each is described in relation to the church. Bombing during World War II, an earthquake that occurred in 1983, and the effects of a local stream causing subsidence are identified as potential causes of the deterioration, particularly the cracking. Spalling has mainly been attributed to the corrosion of reinforcements as a result of carbonation of the thin concrete cover. The article includes a section on the analysis of the Pauchot reinforced artificial stone. In conclusion, the authors identify the removal of carbonated concrete, treatment of corroded reinforcement, and replacement using a less porous mortar as a potential approach to the repair work.

Crevello, Gina. 2015. "Practice Points, no. 13: Data Interpretation and Early Corrosion Test Program for Historic Concrete Buildings." *APT Bulletin: Journal of Preservation Technology* 46 (1): 1–8. https://www.apti.org/assets/docs/PracticePoints13.pdf.

This article addresses misinterpretation in data analysis and material aspects affecting results of diagnostic tests on corrosion. The author includes many examples and practical recommendations to interpret test data correctly, starting from the consideration that test results on historic concrete buildings may often fall outside the thresholds established in current standards. A first example is of half-cell potential testing values obtained in carbonated concretes that may not be indicative of the real corrosion conditions. Also, since corrosion rate is influenced by temperature and relative humidity, data taken on a hot day will differ from readings taken in mild weather. The author also underlines the necessity to understand all construction materials and be aware of past repairs. Indeed, structural elements such as prestressed or post-tensioned rods may not be tested easily, variations in concrete mix may affect potential readings, and high-quality concrete may provide false resistivity readings. The use of low-quality repair materials may accelerate corrosion, while the use of migrating corrosion inhibitors may act as pore blockers and impact electrochemical tests. The author, therefore, stresses the importance of approaching corrosion in a preventive manner, and that test procedures should be carried out by a multidisciplinary team of experts in materials science, corrosion science, and structural engineering, able to provide a holistic interpretation of test results.

Crevello, Gina L., Nancy Hudson, and Paul A. Noyce. 2014. "Corrosion Condition Evaluations of Historic Concrete Icons." In *Concrete Solutions: Proceedings of Concrete Solutions, 5th International Conference on Concrete Repair, Belfast, Northern Ireland, 1–3 September 2014*, edited by Michael Grantham, P. A. Muhammed Basheer, Bryan Magee, and Mario Soutsos, 627–35. Boca Raton, FL: CRC Press.

This paper focuses on the challenges of assessing historic concrete buildings. It emphasizes preserving material integrity and being proactive through durability assessments. A holistic approach and assessment procedure performed by a well-versed group of professionals who understand the historic value of a structure can lead to a better understanding of long-term performance. Deterioration mechanisms, such as corrosion, have a time frame for initiation and propagation. As corrosion is a measurable electrochemical reaction, its behavior can be predicted. Combined in situ testing and laboratory analysis can help determine the corrosion condition of a structure prior to large-scale aesthetic and structural failures. When the aim of the repair is to preserve the historic integrity of the concrete material, a durability analysis with failure predictions can help guide the process. Four case studies of historic structures in the United States are presented. A corrosion testing program was integrated with an overall condition evaluation, and durability modeling was performed from the data collected. The case studies illustrate the complexity of historic concrete structures. In all instances, there were limitations in material sampling, invasive testing, and probe openings. The paper emphasizes that by understanding the conditions that lead to corrosion, where the structure is within its life cycle and when it may experience damages, time frames for micro-cracking can be established and appropriate treatments that address long-term corrosion mitigation can be considered.

de Jonge, Wessel, and Arjan Doolaar, eds. 1998. *The Fair Face of Concrete: Conservation and Repair of Exposed Concrete*. Preservation Technology Dossier 2. Eindhoven, the Netherlands: DOCOMOMO International / Eindhoven University of Technology.

See annotation on p. 15.

De Luca, Flavia, Gerardo M. Verderame, and Gaetano Manfredi. 2014. "Eurocode-Based Seismic Assessment of Modern Heritage RC Structures: The Case of the Tower of the Nations in Naples (Italy)." *Engineering Structures* 74:96–110. https://doi.org/10.1016/j.engstruct.2014.05.015.

This paper describes the seismic analysis of the Tower of the Nations in Naples, according to the seismic assessment criteria of Eurocode 8 for ordinary reinforced concrete structures. Designed in 1938 and completed in 1940, the tower is a remarkable example of modern architecture in southern Italy. It is characterized by two glazed facades and two opaque facades infilled with tuff masonry and covered with travertine sheets. All the input data for the seismic assessment is described in detail. These include the structural system's geometry, details, and material properties. This data was gathered from original design documentation and building codes and regulations at the time of construction, as well as through structural survey, in situ and laboratory tests, and a simulated design procedure aimed at determining steel reinforcements in beams and columns. Two nonlinear models of the structure were developed to simulate the hypotheses of taking and not taking into consideration the tuff infills' stiffness and strength contributions. Assessment was carried out for the so-called limit states of Significant Damage and Damage Limitation by means of nonlinear dynamic analyses. The assessment results show that tuff infills play a significant role by increasing the stiffness and strength of the building, as long as the seismic demand does not exceed the deformation capacity, and by providing a regularization of the demand along the height of the building.

Di Re, Paolo, Egidio Lofrano, Jacopo Ciambella, and Francesco Romeo. 2021. "Structural Analysis and Health Monitoring of Twentieth-Century Cultural Heritage: The Flaminio Stadium in Rome." *Smart Structures and Systems* 27 (2): 285–303. https://doi.org/10.12989/sss.2021.27.2.285.

This paper presents the methodology and main results of the structural analysis and health monitoring of the Stadio Flaminio in Rome, designed by Pier Luigi Nervi for the 1960 Olympic Games. The focus is on the main grandstand canopy, one of the most interesting structural elements due to its geometry, but unfortunately one that is in a critical state of conservation. The study was carried out as part of the development of a conservation management plan for the stadium financed by the Keeping It Modern initiative by the Getty Foundation. The preliminary analysis, including a detailed evaluation of the mechanical properties of construction materials, was aimed at studying the structural response under different modeling hypotheses and at developing a 3D finite element model. Results show that the canopy plays a crucial role in the stadium's response to seismic actions. To validate the model results and further investigate the dynamic interplay of the canopy with the supporting reinforced concrete frames, the authors carried out dynamic tests under operating conditions. Ultimately, the authors propose a low-cost sensor network for structural health monitoring and address the data management through a heritage building information modeling (HBIM) model that includes degradation mapping and structural health monitoring.

Eden, M. A. 2010. *SR2: A Code of Practice for the Petrographic Examination of Concrete*. London: Applied Petrography Group.

This code of practice aims to provide guidance on the minimum requirements for a full petrographic report on concrete samples and other cementitious materials. It describes suggested procedures for the preparation of thin sections and examination with a petrological microscope. In particular, it includes a description of concrete sampling via diamond core drilling, the equipment for thin section preparation, the preliminary macroscopic examination of polished surfaces and thin sections, microscopic examination of broken surfaces, composition measurements, and detailed recommendations concerning the recording and reporting of results. The appendix provides a brief glossary of terms used in the petrographic analysis of concrete.

Faggiano, Beatrice, Roberta Fonti, and Raffaele Landolfo. 2019. "The Structural Assessment of the Travertine Façade of the Banco di Napoli Palace in Via Toledo in Naples: An Example of a Mixed Concrete-Steel-Masonry Monumental Building in the Decade 1930–1940 in Italy." *International Journal of Architectural Heritage* 13 (1): 58–75. https://doi.org/10.1080/15583058.2018.1497227.

This article presents the analysis carried out at the Banco di Napoli Palace in Naples, designed by the architect Marcello Piacentini. Concrete is used in various forms in the building: with reinforcing bars in the pillars, with reinforcing metal lattice in the beams, and as block elements in the infill masonry walls. The study focuses on the top part of the stone-clad monumental facade, supported by an architrave composed of three parallel iron lattice girders connected by metal stirrups and embedded in a pumice-cement conglomerate. The stone cladding, after cleaning operations, revealed atypical cracks, making a deep investigation necessary. Information about the original design was found in the historic construction codes. Analysis included visual inspections, cracking layout survey, cover meter survey, ultrasonic tests, endoscopies, hygrometric tests, jack tests, and laboratory tests on concrete specimens. The porous pumice cement conglomerate revealed a high carbonation and complete imbibition, which explained the advanced corrosion of the lattice girders, which showed a reduced cross section and were deformed both in plane and out of plane. The structural analysis, following European and national standards, was aimed at determining the necessary retrofitting interventions, complying with the UNESCO conservation criteria for the World Heritage Site of Naples historical center and in line with Italian guidelines for the reduction of the seismic risk of built cultural heritage.

Farny, James A., and Beatrix Kerkhoff. 2007. *Diagnosis and Control of Alkali-Aggregate Reactions in Concrete*. Concrete Technology. Skokie, IL: Portland Cement Association.

This technical report focuses on alkali-aggregate reactions in concrete, and their diagnosis and control. The reactivity of certain aggregate constituents to alkali hydroxides present in the pore solution of concrete is potentially harmful when it produces significant expansion. This reaction has two forms: alkali-silica reaction (more common) and alkali-carbonate reaction (less common). Alkali-silica reaction has been recognized as a potential source of distress in concrete since the late 1930s. Alkali-carbonate reaction in concrete was not documented until the 1950s. The report briefly reviews the mechanisms, visual distress symptoms of expansion, test methods for identification, and control measures. In the final part, the document includes two useful tables: "Test Methods for Alkali-Silica Reactivity" and "Test Methods for Alkali-Carbonate Reactivity."

Ferreira, Teresa Cunha, Nuno Mendes, Rui Fernandes Póvoas, and Paulo B. Lourenço. 2024. "Assessment Methodology for Conservation Planning of Concrete Buildings: Ocean Swimming Pool (1960–2021) by Álvaro Siza in Portugal." *International Journal of Architectural Heritage* 18 (2): 333–55. https://doi.org/10.1080/15583058.2022.2147877.

This paper proposes a methodology for the condition assessment of historic concrete buildings, a preparatory step in the definition of conservation planning measures, risk assessment, and maintenance. The case study presented is the Piscina das Marés in Portugal, designed by the architect Álvaro Siza, which is listed as a national monument and included in the World Heritage Tentative List. The assessment methodology, supported by the cross analysis of documentary and physical evidence, allows for an integrated approach to conservation planning. The authors describe the building chronology and construction features, as well as the diagnostic techniques employed, including in-situ nondestructive testing and laboratory analysis on collected samples. Moreover, the article presents a pilot concrete repair intervention. The case study shows the advantages of integrating conservation principles and methods used for traditional buildings in the conservation of modern heritage made of concrete.

Frens, Dale H. 2002. "Restoration of the Concrete Roof of the Mercer Museum in Doylestown, Pennsylvania." *APT Bulletin: Journal of Preservation Technology* 33 (1): 13–19. https://doi.org/10.2307/1504784.

See annotation on p. 97.

Garmendia Arrieta, Leire, Ignacio Marcos Rodríguez, Natalia Lasarte Arlanzón, and Estibaliz Briz Blanco. 2018. "Damage Assessment and Conservation Strategy for the Largest Covered Market in Europe: The Ribera Market (Bilbao)." *International Journal of Architectural Heritage* 12 (6): 997–1018. https://doi.org/10.1080/15583058.2018.1431728.

The Ribera Market in Bilbao, Spain, is the largest covered market in Europe, commissioned from Pedro Ispizua in 1927. The load-bearing structure is made of reinforced concrete. In 1984, the building underwent rehabilitation works due to flooding from the previous year, and then major renovation took place between 2009 and 2012. The objective of this paper is to report on the assessment work developed for this structure, underlining common challenges in conservation of early concrete buildings. Field investigation and laboratory studies included analysis of forms and extent of deterioration, determination of the constructive section and steel ratio, measurement of carbonation depth, inspection of reinforcement, definition of chloride profiles, petrographic and mineralogical characterization of concrete, and structural evaluation. The main sources of deterioration were found to be the presence of chlorides as part of the concrete mass and the periodic flooding of the semi-basement. Finally, the paper includes a discussion of alternative strategies of intervention, underlining that available technologies for concrete conservation and repair are not always applicable in historic buildings.

Gaudette, Paul E., and Harry J. Hunderman. 1997. "Repair of Mies van der Rohe's Promontory: A Multiphased Approach to Facade Restoration." *APT Bulletin: Journal of Preservation Technology* 28 (2–3): 45–50. https://doi.org/10.2307/1504593.

See annotation on p. 98.

Georgiou, Antroula V., Maria M. Hadjimichael, and Ioannis Ioannou. 2021. "Conservation of 20th Century Concrete Heritage Structures in Cyprus: Research and Practice." In *12th International Conference on Structural Analysis of Historical Constructions SAHC 2021*, edited by P. Roca, L. Pelà, and C. Molins, 82–93. Barcelona: International Centre for Numerical Methods in Engineering (CIMNE). http://congress.cimne.com/SAHC2020/frontal/doc/Ebook_SAHC2020.pdf#page=82.

This paper was developed by the Cyprus working group within the European project CONSECH20 (CONSErvation of 20th century concrete Cultural Heritage in urban changing environments). The authors focus on a structural assessment of two concrete heritage buildings in Nicosia, following the methodologies described by modern codes for the assessment and retrofit of existing concrete structures. A new analysis approach is described and compared to the force-control approach of the pushover analysis established in Eurocode 8, which significantly overestimates demands for seismic upgrading. The results obtained for the two case studies are compared. Useful information is also provided regarding listing and conserving reinforced concrete heritage in Cyprus and in relation to the selection process behind the concrete heritage case studies for the CONSECH20 research project.

Gillard, Anne, Luc Courard, and Pierre Paquet. 2011. "Churches and Concrete in Liège District: History, Architecture and Pathologies." *Restoration of Buildings and Monuments* 17 (1): 3–13. https://doi.org/10.1515/rbm-2011-6421.

This article documents the findings of a project characterizing the condition of nine churches constructed primarily of reinforced concrete. Located in the Liège district of Belgium, the churches were completed between 1930 and 1991. The article opens with a brief history of concrete and its use in the construction of religious buildings. It then sets out the investigation process for this project and identifies the necessary considerations for this type of survey. The study follows the approach outlined in EN 1504–9, where investigation, analysis, and root cause and damage identification are conducted prior to choosing a repair method. Damage identified through visual inspection of the churches falls into three main categories: concrete damage, structural damage, and miscellaneous degradations. Corrosion of the reinforcements due to carbonation was determined to be the most prevalent cause of deterioration. Cracks were present in almost all of the structures. Each was classified according to its general condition: "bad" if the structure or its occupants' safety was in danger; "satisfactory" if further investigation was urgent but the damage did not appear to affect the structural performance or pose safety concerns; and "good" if any deterioration was mainly aesthetic. Five of the churches in the survey were categorized as bad, two satisfactory, and two good. The article concludes that further investigation to understand and remedy the causes of damage is needed.

Goins, Elizabeth S. 2004. *Standard Practice for Determining the Components of Historic Cementitious Materials*. 2002–20. Natchitoches, LA: National Center for Preservation Technology and Training, National Park Service, US Department of the Interior. https://web.archive.org/web/20220628115644/https://www.ncptt.nps.gov/blog/standard-practice-for-determining-the-components-of-historic-cementitious-materials-2002-20/.

This document reviews and discusses different standards and protocols used to analyze and determine the components of historic cementitious materials. Tests are typically based on the acid digestion of a sample to determine the ratios of original components. A number of instrumental techniques typically used are described: X-ray diffraction analysis (XRD), scanning electron microscopy (SEM), porosimetric measurements, Fourier-transform-infrared spectroscopy (FTIR), identification of granulometric fractions, and thin section analysis. The thorough comparison and critical review developed with respect to various existing methods within the area of historic mortar analysis can constitute a useful reference for all professionals involved in the condition assessment of historic concrete structures.

Golež, Mateja, Vesna Zalar Serjun, Mateja Štefančič, Darja Rant, and Sabina Dolenec. 2023. "Characterisation of 20th Century Cementitious Materials from Selected Cultural Heritage Structures in Slovenia." *Materials* 16 (18): art. 6206. https://doi.org/10.3390/ma16186206.

This paper gathers the results of a research study aimed at the characterization of cementitious materials from a selection of heritage sites in Slovenia. The case studies represent different architectural types, periods, and geographic areas. A range of laboratory tests were conducted on specimens. Electron microscopy and X-ray powder diffraction were used to study the mineralogical-petrographic compositions of aggregates, and to identify the type of binder and secondary minerals. The porosity and pore network were analyzed with a mercury porosimeter. Test results showed that the investigated samples of historic cementitious materials were heterogeneous mixtures prepared with different aggregates (limestone, dolomite, quartz, feldspar, and mica) and binders, and in some cases, with some pozzolanic additives like granulated ground blast furnace slag. Based on the examined specimens, the authors concluded that it was possible to hypothesize some trends in the cement composition according to the geographical location of the site, but acknowledged the need for further systematic study of these materials to better identify the geographical trend according to the origin of the cement clinker. This investigation contributes to a better understanding of the technologies and materials used to prepare historic cementitious and cement-lime mixtures in the Slovenian territory during the twentieth century.

Grantham, Michael, ed. 2011. *Concrete Repair: A Practical Guide*. London: Routledge / Taylor and Francis.

See annotation on p. 88.

Griffin, Isobel, and Jim Tate. 2012. "Conserving Our Wartime Heritage: A Reinforced Concrete Air Raid Shelter in East Lothian, Scotland." *Journal of Architectural Conservation* 18 (1): 81–100. https://doi.org/10.1080/13556207.2012.10785105.

This article describes scientific research and investigation into the deterioration of a 1941 reinforced concrete air raid shelter located at the military airfield at East Fortune, East Lothian, Scotland. The aims were to characterize the methods and materials used in the construction, record the condition, investigate the movement of moisture through the structure, understand the deterioration process at work, and assess conservation options. Corrosion of the reinforcement was found to be the most common form of deterioration. Moisture movement was investigated using both infrared thermography and electrical resistivity. The results indicated that the main source of moisture was rising damp, although further tests indicated that this may be less significant than rainwater entering from above. It was determined that corrosion was caused by the presence of chlorides in the concrete rather than carbonation. Although a conservation method was not selected for this site, BS EN 1504 is discussed and a summary table provides various conservation options, along with assessments of their advantages and disadvantages.

Harrer, Ann, Paul Gaudette, and Deborah Slaton. 2020. "Approach to Preservation of Historic Concrete." *Concrete Repair Bulletin* 33 (2): 12–17. https://cdn.ymaws.com/icri.site-ym.com/resource/resmgr/crb/2020marapr/ICRI-CRB-Mar-Apr2020-web.pdf#page=14.

See annotation on p. 79.

Ibarrondo, Iratxe, Urko Balziskueta, Irantzu Martínez-Arkarazo, Cristina García-Florentino, Gorka Arana, Agustín Azkarate, and Juan Manuel Madariaga. 2021. "Portable Raman Can Be the New Hammer for Architects Restoring 20th-Century Built Heritage Elements Made of Reinforced Concrete." *Journal of Raman Spectroscopy* 52 (1): 109–22. https://doi.org/10.1002/jrs.5959.

The authors of this paper investigated the use of a portable Raman spectrometer to characterize the original material and to identify deterioration agents on two different buildings having a reinforced concrete structure built with Portland cement. The buildings are in the province of Biscay, in northern Spain: the Punta Begoña Galleries, Getxo (1918) is located in the aggressive marine and industrial environment of Bilbao's commercial harbor, and the library of the University of the Basque Country, Campus of Leioa (1968), is located in metropolitan Bilbao. For both cases, portable Raman spectroscopy (with 785 and 532 nm lasers) was used to characterize original and decayed compounds in raw materials and overlaying efflorescence salts. In both buildings, the main deterioration agents were atmospheric gases (direct in the galleries, diffuse in the library) and percolation waters charged with reactive ions. The only—albeit substantial—difference in the sources of deterioration between the two buildings was the presence of carboxylic acids at the galleries, probably from exhaust gases produced by ship engines and carried by the marine aerosol. This research work demonstrates how portable Raman spectroscopy can identify the source of deterioration agents within a wider approach where the building is seen as a complex system characterized by various chemical reactions between original compounds and chemicals from the surrounding environment.

Ingham, Jeremy P. 2011. *Geomaterials under the Microscope: A Colour Guide*. London: Manson.

This book represents the first comprehensive guide to the petrography of geomaterials intended for a broad audience, including architects, engineers, conservators, and materials scientists. It includes more than 350 high-quality color photomicrographs of geomaterials under normal conditions and deterioration conditions, accompanied by descriptions of their petrographic properties. The introduction chapter includes an overview of geomaterials practice and a state-of-the-art review of petrographic techniques. Each of the following chapters is dedicated to a different type of construction material and includes details on its history, manufacture, and use, plus helpful references to British, European, and US standards on petrographic examinations. Every chapter includes a description of the material's deterioration types and the principal applications of petrographic examination. Of particular interest are chapter 4 (aggregates), chapter 5 (concrete), and chapter 6 (concrete products). For example, petrography can be used in the examination of aggregates to assess the potential for alkali-aggregate reactivity, to diagnose the causes of in-service deterioration, and to match aggregate types for restoration of mortar in historic buildings. For concrete, petrography is helpful in identifying mix ingredients, determining mix proportions and air void content, assessing the quality of workmanship, and diagnosing the causes, severity, and extent of defects and deterioration. As for concrete products, petrography can be used to identify the ingredients used and the manufacturing process, identify the presence of hazardous materials such as asbestos, and diagnose the causes and significance of decay and deterioration.

Jerome, Pamela. 2013. "Conserving Frank Lloyd Wright's Solomon R. Guggenheim Museum." *Historic Environment* 25 (1): 62–70. https://australia.icomos.org/wp-content/uploads/Conserving-Frank-Lloyd-Wrights-Solomon-R.-Guggenheim-Museum-vol-25-no-1.pdf.

See annotation on p. 81.

König, G., B. Novák, and G. Schenk. 2001. "Investigation and Recalculation on the 'Hyparschale' in Magdeburg." In *Structural Studies, Repairs, and Maintenance of Historical Buildings VII*, edited by C. A. Brebbia, 451–60. WIT Transactions on the Built Environment 55. Southampton, UK: WIT Press. https://www.witpress.com/elibrary/wit-transactions-on-the-built-environment/55/3308.

This paper summarizes the main results of the investigation analysis developed on the Hyparschale in Magdeburg, Germany, a reinforced concrete shell structure designed by engineer Ulrich Müther and built in 1969 to serve as a multifunctional space for concerts, exhibitions, and other events. The shell, which is only seven centimeters thick, consists of four sub-portions shaped as hyperbolic paraboloids supported by concrete girders and columns, covering altogether an area of forty-eight square meters. In 1990, the Hyparschale was left unused, and its condition started to deteriorate. In a first on-site investigation in 1998, the authors observed that the structure was affected by longitudinal cracks on the sloped columns and some inner beams, loss of concrete cover on many columns, defects and damage in the roof's drainage system and waterproofing, and deterioration of the glazed facades. A range of material investigation analyses were thus conducted: determination of concrete cover; identification of carbonation depth with the phenolphthalein test; inspection for micro-cracks in prestressing steel with the magneto-optical method; and evaluation of the loss of prestressing force. A structural recalculation was then developed using the finite elements method and considering two different situations—the shell structure with and without defects and damages. This recalculation showed that the standard requirements of the ultimate limit state are fulfilled in both cases.

Krill, Alfred. 2017. "Recalculation of German Concrete Bridges Considering the Code 'Nachrechnungsrichtlinie.'" *Proceedings of the ICE – Engineering History and Heritage* 170 (3): 125–33. https://doi.org/10.1680/jenhh.16.00022.

This paper deals with the structural safety of old concrete bridges in the German context. In 2011, the German government published the *Nachrechnungsrichtlinie*, a code for the recalculation of old bridges based on current Eurocodes and the DIN-Fachberichte, aiming to ensure that all old bridges in Germany can be recalculated in a comparable way to identify any necessary work to prolong their use, or if some of them must be rebuilt. For this reason, the author's office team recalculated more than fifty concrete bridges in Germany for different clients, and the paper discusses the experience acquired in this extensive work. A statistical analysis of numerical results shows that changes in design criteria over time is a crucial aspect in the recalculation of old concrete bridges. The main reason for the observed deficits is not increased traffic loads, but formulas that changed from the past to the current codes. The author, therefore, emphasizes the importance of having a deep knowledge of historic codes, construction practices, and calculation methods to identify the design possibilities to preserve these relevant historic structures while assuring their structural safety. The paper, moreover, shows that it is necessary to have reliable information not only on the construction process, but on the entire history of the bridge, including all interventions carried out since its completion.

Lenticchia, Erica, Gaetano Miraglia, Antonino Quattrone, and Rosario Ceravolo. 2023. "Condition Assessment of an Early Thin Reinforced Concrete Vaulted System." *International Journal of Architectural Heritage* 17 (2): 343–61. https://doi.org/10.1080/15583058.2021.1922784.

This paper presents the results of an extensive structural assessment campaign aimed at understanding the conditions of a paraboloid structure in Casale Monferrato, Italy, built in 1922 as a clinker warehouse for the Italcementi factory. This investigation was part of an evaluation of the structure's compatibility with its proposed new use as a cultural center. The case study is characterized by an apparently simple geometric shape and composition, which hides a high structural complexity revealed through the assessment methodology adopted. The investigation included both mechanical and dynamic tests. The authors describe the results of in situ investigations and laboratory tests carried out to analyze the mechanical properties of the structural elements and materials, as well as the modal response of the structure. Further analysis was made through corroboration of numerical models and behavior observed during the tests. The conclusion was that in this kind of structure, non-monolithic behavior and material dislocations lead to appreciable stiffness reductions. Future research developments will focus on nonlinear analysis aimed to investigate the potential effects of the collapse of the tie-rod elements on the static and the dynamic global behavior. This case study is a useful reference for researchers and practitioners dealing with this structural typology, which is particularly widespread among industrial heritage.

Linton, Linnea M. 2005. "Delaminations in Concrete: A Comparison of Two Common Nondestructive Testing Methods." *APT Bulletin: Journal of Preservation Technology* 36 (2–3): 21–27. https://www.jstor.org/stable/40004701.

This article summarizes a research project comparing the usefulness of hammer and impact-echo tests in searching for delamination in concrete slabs. The two methods are introduced, and details are given of the laboratory investigation carried out to identify which method is most accurate. The experiment was conducted on concrete test slabs prepared with delaminations in known positions; the control slab had no delaminations. It was intended that the tests should be performed in twenty locations for each of the two methods. Several factors resulted in the impact-echo tests being reduced to five locations per slab. The hammer test produces only a "yes" or "no" result, so a numerical scale was created to quantify the data. The success of these techniques was assessed through a statistical analysis of their accuracy and a comparison of the applicability of both methods. The study concluded that the hammer test was best suited for locating general areas of delamination. If time and money are available, the impact-echo test should be performed in areas determined to be delaminated to find the depth of the delamination. Use of the impact-echo test alone is not recommended because it was shown to have a higher percentage of error in locating delaminated areas.

Macdonald, Susan, and New South Wales Heritage Office. 2003. *The Investigation and Repair of Historic Concrete*. Parramatta, Australia: NSW Heritage Office. https://www.environment.nsw.gov.au/-/media/OEH/Corporate-Site/Documents/Heritage/investigation-repair-historic-concrete-0303.pdf.

This guide addresses the history and use of architectural concrete in Australia. It was one of the early texts establishing a conservation methodology for the repair of historic concrete construction, diagnostics, and understanding the impact of a repair. The text stresses the importance of understanding construction, materials, and environment in order to diagnose deterioration mechanisms and identify repair options; an inappropriate approach, it emphasizes, can lead to a failed repair. A number of reference charts are provided for ease of diagnosing concrete deterioration, material and design issues that impact degradation, issues related to workmanship, inherent material problems, environmental issues impacting curing and durability, and problems caused by lack of maintenance. Corrosion as a deterioration mechanism is discussed at length. A repair approach that provides a protocol for understanding significance, deterioration, and life cycle is outlined. A brief guide to assessment and investigation, and the proper interpretation of results, is provided. A thoughtful section on repair and rehabilitation highlights the process of making decisions based on heritage values. This is a valuable guide for anyone working on historic concrete.

Maierhofer, Christiane, Hans-Wolf Reinhardt, and Gerd Dobmann, eds. 2010. *Non-Destructive Evaluation of Reinforced Concrete Structures*, vol. 1, *Deterioration Processes and Standard Test Methods*. Boca Raton, FL: CRC Press.

This is the first of a two-volume publication dedicated to nondestructive testing on reinforced concrete. The goal is to inform engineers about applicability, reliability, and limitations of available methods. Volume 1 covers applicability of nondestructive testing; deterioration mechanisms and traditional assessment techniques, including visual survey; and laboratory-based sample analysis. Chapters 1 and 2 discuss the role of nondestructive testing in assessing concrete structures. Chapter 3 offers an overview of deterioration processes, which are broken down into physical and mechanical processes, and chemico-physical processes. Chapter 4 focuses on modeling processes affecting concrete durability, in particular reinforcement corrosion. Chapter 5 describes how concrete constituents affect durability. Chapter 6 discusses service-life management. Chapter 7 describes the traditional approach for assessing concrete, with a focus on German highways. Chapter 8 is dedicated to petrographic analysis. Chapter 9 describes the analysis of concrete composition. Chapter 10 describes chloride content measurement. Chapter 11 is on water content investigation.

Maierhofer, Christiane, Hans-Wolf Reinhardt, and Gerd Dobmann, eds. 2010. *Non-Destructive Evaluation of Reinforced Concrete Structures*, vol. 2, *Non-Destructive Testing Methods*. Boca Raton, FL: CRC Press.

This is the second of a two-volume publication dedicated to nondestructive testing in reinforced concrete. The goal is to inform engineers about applicability, reliability, and limitations of available methods. Volume 2 covers planning and implementation of assessments utilizing nondestructive testing methods. Chapter 1 discusses the planning of a program. Chapter 2 presents the state of the art and future trends in building diagnosis using nondestructive testing. Chapter 3 describes the use of automated nondestructive evaluation systems. Chapter 4 focuses on monitoring. Chapter 5 discusses combinations of multiple types of nondestructive testing and presents a method for data analysis. Chapters 6 to 22 are dedicated to specific tests: wireless monitoring, electromagnetic and acoustic-elastic waves, laser-induced breakdown spectroscopy, acoustic emission, magnetic flux leakage, electrical resistivity, capacimetry, polarization resistance and corrosion potential, ground-penetrating radar, radar tomography, active thermography, nuclear magnetic resonance, stress wave propagation, surface wave techniques, impact-echo, and ultrasonic techniques. Chapters 23 to 25 present case studies utilizing ground-penetrating radar, acoustic emission, and impact-echo.

Malhotra, V. M., and N. J. Carino, eds. 2004. *Handbook on Nondestructive Testing of Concrete*. 2nd ed. Boca Raton, FL: CRC Press.

This book offers practical information on a comprehensive list of nondestructive test methods for concrete structures. Each chapter describes a different type of nondestructive test: surface hardness, penetration resistance, pullout, break-off, maturity, pull-off, permeation, resonant frequency, pulse velocity, magnetic, electrical, radioactive, nuclear, radar, stress wave propagation, infrared thermography, and acoustic emission. For each technique, the chapter author describes principles, applicability, operation, limitations, factors that can affect readings, standardization, and interpretation of results. The book was written for practicing engineers working in quality control or assessment of concrete structures. It is worth mentioning that not all techniques presented in this book would be considered nondestructive in the conservation field, since they cause low to moderate damage to the tested material.

Marie-Victoire, Élisabeth, Véronique Bouteiller, Jean-Luc Garciaz, Jean François Cherrier, Jean Dauthuille, F. Marzin, and Jonas Schneider. 2012. "On-Site Instantaneous Corrosion Rate Measurements on a Historical Building." *European Journal of Environmental and Civil Engineering* 16 (3–4): 505–23. https://doi.org/10.1080/19648189.2012.668013.

This article examines electrochemical evaluation methods in chloride-contaminated and carbonated concrete at Notre-Dame de Royan (1954–58), a historic landmark concrete church in France. Prior to electrochemical evaluation, the program identified carbonation depth, chloride profiles, concrete cover, and reinforcement distribution. In order to measure reinforcement corrosion, electrochemical measurements were taken using three different tests: half-cell potential, resistivity, and corrosion rates. The on-site testing program was carried out over a nine-month period to determine temperature and humidity influences on the corrosion rate readings. It was determined that seasonal fluctuations did not impact the corrosion, but that the presence of moisture (for example from rain events) appeared to be leading to higher corrosion activity. Additionally, the testing program, which compared two commercial corrosion rate meters, identified significant discrepancies between them in terms of readings. The testing program also indicated that both devices overestimated and underestimated corrosion activity in passive or carbonated conditions. According to the authors, to overcome the unreliable results produced by these two devices, correction factors should be added or different devices used. They also advocate for long-term monitoring over spot-testing programs for historic concretes.

Marie-Victoire, Élisabeth, Emmanuel Cailleux, and Annick Texier. 2006. "Carbonation and Historical Buildings Made of Concrete." *Journal de physique IV (Proceedings)* 136 (1): 305–18.

See annotation on p. 36.

Marie-Victoire, Élisabeth, Alain Proust, Valérie L'Hostis, and F. Vallot. 2012. "Comparative Study of Techniques to Evaluate the Corrosion Activity of Rebars Embedded in Concrete." In *Concrete Solutions: Proceedings of Concrete Solutions, 4th International Conference on Concrete Repair, Dresden, Germany, 26–28 September 2011*, edited by Michael Grantham, Viktor Mechtcherine, and Ulrich Schneck, 377–86. Boca Raton, FL: CRC Press.

This study evaluates the feasibility of using acoustic emissions to monitor reinforcement corrosion on carbonated concrete versus the more traditional use of linear polarization resistance. The measurements were performed in controlled conditions favorable to corrosion, and the slabs were autopsied after the testing to validate the conclusions. A description of the general decay mechanism related to carbonation and its effect on historical monuments is provided. Panels used in the first phase of testing were taken from the Church of Notre-Dame du Raincy (1921–23), and for the second phase, new concrete slabs were cast and artificially carbonated. When compared, both methods indicated low rates of activity, and variations in corrosion activity were distinguished. Linear polarization resistance readings were instantaneous, while acoustic emissions testing took about an hour. The paper concludes that acoustic emissions testing can detect corrosion in carbonated concrete and may be able to pick up the signals of corrosion activity earlier than electrochemical techniques, but acknowledges that the data was difficult to interpret. The authors also note that linear polarization resistance testing provided consistent and accurate data when compared to the autopsied samples.

Matthews, Stuart. 2012. *Structural Appraisal of Existing Buildings for Change of Use*. BRE Digest 366. Watford, UK: BRE.

This is an expanded and updated version of a BRE Digest originally published in 1991. Directed at engineers, it is a guide to undertaking structural appraisals when a change of use is proposed for an existing building.

The document has been expanded to four sections. Part 1, “Requirements for a Structural Appraisal,” considers overall regulatory requirements, with an emphasis on collapse issues. Part 2, “Preparing for Structural Appraisal,” introduces the concept of structural appraisal and examines the various factors that can influence the process, including cultural heritage issues. Part 3, “Structural Appraisal Procedures,” outlines the structural appraisal process. Part 4, “Additional Considerations and Information Sources,” examines in more detail potential deterioration mechanisms and other issues such as climate change. It also includes an extensive bibliography of related building standards, codes, and guidelines.

Mays, Geoff, ed. 1992. *Durability of Concrete Structures: Investigation, Repair, Protection*. London: E & FN Spon.

This book addresses the long-term durability of concrete, including in-depth case studies on specific building and structure typologies. It is divided into two parts. The first, “Theories and Solutions,” includes the chapters “The Behaviour of Concrete,” “Deterioration Mechanisms,” “Structural Investigations,” “Repair Materials and Techniques,” “Protection,” and “Conclusions.” The second part, “Case Studies,” contains chapters on specific structural typologies: “High-Rise Buildings,” “Highway Bridges,” “Railway Structures,” “Concrete Pavements,” and “Marine Structures.” Chapter 3 includes preliminary considerations regarding how to plan a structural investigation and details on in situ sampling and testing, determination of structural integrity, determination of concrete quality, steel serviceability and condition, laboratory testing and sample analysis, visual examination, physical testing of concrete to determine quality, chemical analysis, petrographic examination, and guidance on the interpretation of condition surveys. Detailed information on investigation activities specific to different structural typologies is provided through the case studies. For example, in the case of high-rise buildings, the book describes a five-year tall block inspection program; for highway bridges, it distinguishes among different structural elements (decks, substructures, retaining walls); for railway structures, it refers to chloride problems, carbonation, frost attack, alkali-silica reactions, and surface appearance; for concrete pavements, it refers to their unique types of defects; for marine structures, it distinguishes between the underwater and above-water zones. This book is particularly useful for understanding that depending on the structure’s morphology and function, it can be affected by specific deterioration problems that will require specific testing programs.

Mehta, P. Kumar, and Paulo J. M. Monteiro. 2014. *Concrete: Microstructure, Properties, and Materials*. 4th ed. New York: McGraw-Hill Education.

See annotation on p. 28.

Merzoug, Wissam, Samia Chergui, and Mustapha Cheikh Zouaoui. 2020. “The Impact of Reinforced Concrete on the Modern-Day Architectural Heritage of Algeria.” *Journal of Building Engineering* 30:art. 101210. https://doi.org/10.1016/j.jobe.2020.101210.

This paper presents an analysis carried out on the Cathédrale du Sacré-Coeur d’Alger in Algiers. Recognized as a remarkable work of modern architecture, it was designed by Paul Herbé and Jean Le Couteur with the collaboration of the engineer M. Sarger and built in 1956 by the Perret Freres company. The structure is characterized by a large nave measuring fifty-two by thirty-five meters, covered by a thirty-five-meter-high hyperbolic tower and enclosed within V-shaped walls measuring ten centimeters thick. The design is described in detail, from the structural concept to the spatial organization, materials, and thermal and acoustic parameters. In-depth analysis of archival documentation, geometrical data, and on-site inspections allowed the development of a structural model according to the finite element method, followed by a campaign of nondestructive evaluation using dynamic ultrasonic testing and a sclerometer. The structural model proved that the structural concept and geometry of the church contribute to its good seismic response, which satisfies all the requirements of the current Algerian seismic code. Moreover, the SonReb test, which combines ultrasound propagation speed and sclerometer results, showed the high quality of the concrete, which had a higher compressive strength than ordinary concrete. Information on past local seismic activity is provided to underline that despite the seismic events that have occurred, the structure has sustained no significant damage.

Neff, Delphine, Élisabeth Marie-Victoire, Valérie L'Hostis, Emmanuel Cailleux, Laurent Vincent, Annick Texier, Ludovic Bellot-Gurlet, and Philippe Dillmann. 2007. "Preservation of Historical Buildings: Understanding of Corrosion Mechanisms of Metallic Rebars in Concrete." In *Metal 07: Interim Meeting of the ICOM-CC Metal Working Group, Amsterdam, 17–21 September 2007*, vol. 4, *Study and Conservation of Composite Artefacts*, edited by Christian Degrigny, 30–35. Amsterdam: Rijksmuseum.

See annotation on p. 37.

Neville, A. M. 2011. *Properties of Concrete*. 5th ed. Harlow, UK: Pearson.

See annotation on p. 37.

Noyce, Paul A., and Gina L. Crevello. 2013. "Early Concrete Testing and Interpretation for Long-Term Preventive Measures." *Materials Performance* 52 (11): 54–57.

The premise of this paper is that if a concrete structure is assessed for corrosion early enough in its life cycle, a dramatically different approach can be taken for maintenance and repair. Preventive maintenance and proactive assessments can avert large-scale loss of material, which is preferable to a reactive repair. Early testing and data interpretation, and an understanding of the complexity of the results, are key to diagnosing concrete and corrosion-related failures. This article identifies numerous test methods used to assess concrete deterioration and highlights the complexities of understanding the data generated from electrochemical test methods. It emphasizes having qualified testing professionals determine whether the data acquired has been affected by construction conditions, is accurate, or is influenced by other factors. This is a shortened version of a National Association of Corrosion Engineers conference paper.

Onton, Heiki. 2007. "Estimation of Residual Carrying Capacity and Restoration of the Historic Reinforced Concrete Shells and Frames Erected in Estonia." In *Structural Studies, Repairs and Maintenance of Heritage Architecture X*, edited by C. A. Brebbia, 407–17. WIT Transactions on the Built Environment 95. Southampton, UK: WIT Press. https://doi.org/10.2495/STR070381.

This paper describes an investigation developed on two hangars in Tallinn and Saaremaa, Estonia, designed and built between 1915 and 1917 as part of the Russian fortification system for the Baltic Sea. The hangar in Tallinn is of particular interest because it is a reinforced concrete shell structure composed of three spherical shells placed next to each other, connected to seven cylindrical shells on the borders and four two-story towers in the corners. Unfortunately, in both hangars, a lack of maintenance and repair, and the absence of doors and windows, caused extensive water-related damage, including corrosion of reinforcement, washing out of the cement binder, and frost damage. Moreover, the top surface of the Tallinn hangar showed many long cracks caused by temperature and humidity changes (there are no expansion joints in the hundred-meter-long structure) and circular cracks caused by cold joints formed during construction between different pouring phases. The material research involved analysis of compression strength, frost resistance, mineralogical composition, carbonation depth, porosity, and water absorption. The structural finite elements analysis attested that axial and shear forces and bending moments were relatively small, which allowed the badly damaged structure to survive. Finally, it describes the urgent restoration works that started in 2001, which included stitching of cracks, reinforcement with anchor bars, application of biological repellent, and styrene-butadiene-styrene roof covering.

Papayianni, I., V. Pachta, and A. Milosi. 2016. "The Survey of a Historical Building from the Beginning of the Previous Century: Evaluation of Mechanical Characteristics of the Load Bearing System." In *Concrete Solutions: Proceedings of Concrete Solutions, 6th International Conference on Concrete Repair, Thessaloniki, Greece, 20–23 June 2016*, edited by Michael G. Grantham, Ioanna Papayianni, and Kosmas Sideris, 353–60. Leiden, the Netherlands: CRC Press / Balkema.

The authors address the condition assessment of an art deco building from the interwar period in northern Greece, the Library of Florina, which is still in use. The load-bearing system is partly made of stone masonry and partly of concrete elements. Since there was no archival documentation regarding the architecture or construction system of the building, the investigation aimed to determine the structural system and the physical-mechanical characteristics of the building materials (concrete, mortars, plasters, stones, bricks). The on-site survey and investigations were used to produce the necessary technical drawings to map damages and identify the structural members to determine the residual bearing capacity. The investigation included in situ tests, small-scale excavations to analyze the foundations, as well as collection and examination of samples of masonry and concrete. The residual bearing capacity of the structural system was investigated in order to proceed with future interventions.

Pardo Redondo, Gabriel, Barbara Lubelli, and Silvia Naldini. 2019. "State of the Art Report on New Technologies to Monitor, Conserve and Restore the Materiality of Modern Buildings in a Compatible, Durable and Sustainable Way." Report, CONSECH20, Working Package 2–Task (i), Version 03. https://consech20.eu/wp-content/uploads/2022/01/WP2_TUD-SoA_Report_New_Technologies_Restore.pdf.

See annotation on p. 105.

Pepi, Raymond M., Laura N. Buchner, and Christopher Gembinski. 2014. "Conservation of Dalle de Verre at the New York Hall of Science." *APT Bulletin: Journal of Preservation Technology* 45 (4): 3–12.

See annotation on p. 106.

Petrini, Lorenza, Marco Antico, Luigi Zanzi, and Luigia Binda. 2011. "Integrated Non Destructive Techniques Applied for the Diagnosis of a Sixty Years Old R.C. Building." In *Art '11: 10th International Conference on Non-Destructive Investigations and Microanalysis for the Diagnostics and Conservation of Cultural and Environmental Heritage = Convegno internazionale sulle prove non distruttive per la salvaguardia del patrimonio artistico*. Brescia, Italy: Associazione Italiana Prove non Distruttive Monitoraggio Diagnostica.

This paper explains an integrated approach to studying the behavior of a five-story concrete structure built shortly after World War II. The building has projecting balconies and bow windows, where 45-degree cracks had formed on the vertical piers. Since original drawings and documentation were lost and limited funding was available, a nondestructive evaluation program assisted in determining construction history and condition without extensive invasive investigations. Ground-penetrating radar was used to locate the embedded steel in structural elements, and 3D radar scanning allowed the investigators to determine reinforcement patterns and beam elements. Long-term crack monitoring was undertaken to understand movement patterns, and provided evidence that the structure had both seasonal movements and diurnal fluctuations. The study helped investigators form a hypothesis for crack formation, led to a broader understanding of the condition of the structure, and informed the repair approach. Though limited in nondestructive evaluation techniques, the article indicates the usefulness of integrated nondestructive evaluation testing programs to determine building construction and behavior.

Poole, Alan B., and Ian Sims. 2016. *Concrete Petrography: A Handbook of Investigative Techniques*. 2nd ed. Boca Raton, FL: CRC Press.

This handbook offers a comprehensive guide to petrographic analysis of concrete and complementary techniques. Though the main audience is the professional petrographer, it may be useful to other professionals who need to commission petrographic analysis and interpret the results as part of an investigation. Chapter 1 introduces the subject of the book and offers an overview of the methodology for a petrographic study. Chapter 2 describes the use of the polarizing microscope, which the authors consider fundamental to an in-depth investigation of concrete, and other complementary techniques, such as scanning electron microscopy, X-ray powder diffraction, Fourier-transform-infrared spectroscopy, thermal and chemical analysis methods, and computer-aided image analysis. Chapter 3 covers sampling, selection of sampled location, and specimen preparation, such as thin sections and polished surfaces. Chapters 4 and 5 describe concrete composition and features that can be observed through microscopy. Chapter 6 focuses on concrete deterioration and diagnosis. Chapter 7 covers special types of concrete, including precast and fiber-reinforced products. Chapter 8

discusses Portland cement mortars, terrazzo, and repair materials. Chapter 9 presents non-Portland cementitious materials, such as lime and gypsum.

Prudon, Theodore H. M. 1981. "Confronting Concrete Realities." *Progressive Architecture* 62 (11): 131–37.

See annotation on p. 22.

Pullar-Strecker, Peter. 1987. *Corrosion Damaged Concrete: Assessment and Repair*. London: Construction Industry Research and Information Association; Boston: Butterworths.

See annotation on p. 39.

Reed, Peter, Kate Schoonees, and Jeremy Salmond. 2008. *Historic Concrete Structures in New Zealand: Overview, Maintenance and Management*. Wellington, NZ: Science & Technical Pub., Dept. of Conservation. https://www.doc.govt.nz/globalassets/documents/science-and-technical/sap248entire.pdf.

See annotation on p. 84.

Riminesi, Cristiano, Oana Adriana Cuzman, Mateusz Moczko, and Krzysztof Raszczuk. 2022. "Comparative Interpretation of Results after Application of Different Non-Destructive and Portable Techniques on Historic Concrete in the Centennial Hall in Wrocław." *Case Studies in Construction Materials* 17:art. e01409. https://doi.org/10.1016/j.cscm.2022.e01409.

The paper presents a research study about the Centennial Hall exhibition center in Wrocław, Poland, developed within the InnovaConcrete research project. The authors address a key aspect of the conservation of concrete buildings, which is the development of a diagnostic and monitoring approach based on nondestructive and portable techniques. In this case study, the physical and mechanical characteristics of the cementitious materials were estimated through indirect methods. In particular, ultrasonic pulse velocity and rebound tests were undertaken to evaluate the hardness and compactness of the material, the sponge test method was used to evaluate surface permeability, evanescent field dielectrometry was used to evaluate water and salts content, and, finally, colorimetric measurements were taken to evaluate change of color. All of these tests (except for evanescent field dielectrometry) were repeated two times by different teams of researchers using different instruments but following a similar protocol. The results were compared, showing good repeatability. This demonstrated the capability of the combined use of nondestructive and portable techniques in supporting decision-making processes for the conservation of historic concrete buildings.

Riminesi, Cristiano, and Roberto Olmi. 2017. "Diagnostics and Monitoring of Moisture and Salt in Porous Materials by Evanescent Field Dielectrometry." In *Proceedings of SWBSS 2017: Fourth International Conference on Salt Weathering of Buildings and Stone Sculptures, University of Applied Sciences, Potsdam, Germany, 20–22 September 2017*, edited by Steffen Laue, 49–56. Potsdam, Germany: Verlag der Fachhochschule Potsdam. https://repository.hawk-hhg.de/images/4/41/SWBSS_2017_Proceedings_49-56_Riminesi_Olmi.pdf.

This paper presents a noninvasive microwave system based on evanescent field dielectrometry, called SUSI©, for detection of water content and presence of soluble salts in porous materials, such as wall paintings, stones, plasters, and cement-based artifacts. This system can be used to map the moisture content and the salinity index up to two centimeters in depth. The dielectric contrast between the wet and dry material enables detection of moisture, while the ionic conductivity reveals the presence of salts. Narrow-bandwidth resonant dielectrometry allows for portable and low-weight tools. The system consists of a two-port resonant probe connected to a scalar network analyzer for measuring the sensor's response and is completed by a numerical code running on a computer, which allows calculation in real time of the moisture content and salinity index of the material in contact with the probe. The system, moreover, enables a better understanding of the absorption dynamics of water-based products in treated areas and the ability to monitor the effectiveness of restoration interventions by comparing moisture content and salinity index before and after the treatment. This

also allows for comparison of different types of products. The calibration procedure of the SUSI© system is described for cement mortar samples as an example. Two applications for diagnostics and monitoring for wall paintings are also briefly described.

Secco, Michele. 2012. "Characterization Studies on Cement Conglomerates from Historic Reinforced Concrete Structures." PhD diss., Università degli Studi di Padova. https://hdl.handle.net/11577/3422111.

This dissertation analyzes cement conglomerates from five reinforced concrete structures built in Italy between the late nineteenth and mid-twentieth century. The first phase of the research applied petrographic analysis, X-ray diffraction (XRD), and scanning electron microscopy with energy-dispersive X-ray microfluorescence (SEM-EDS) to characterize the texture and composition of the materials. The second phase developed a protocol to obtain a quantitative reconstruction of mix design through multi-scale image analysis. This protocol obtained comparable results to the multi-analytical characterization conducted in the first phase. The protocol established included sample preparation, image acquisition, and analysis. The third part of the research focused on condition assessment through laboratory analysis, with a focus on degradation by combined sulfate-phosphate attack.

Sena-Cruz, José, Rui Miguel Ferreira, Luís F. Ramos, Francisco Fernandes, Tiago Miranda, and Fernando Castro. 2013. "Luiz Bandeira Bridge: Assessment of a Historical Reinforced Concrete (RC) Bridge." *International Journal of Architectural Heritage* 7 (6): 628–52. https://doi.org/10.1080/15583058.2012.654895.

The article presents an analysis of the Luiz Bandeira Bridge, built in 1907 on the Vouga River—the oldest reinforced concrete bridge still in use in Portugal. It was constructed by engineers and builders Moreira de Sá and Malevez using the Hennebique system. Forty-four meters long and four and a half meters wide, it is composed of two parallel arches with a rectangular section, connected by a set of cross beams with a square section, and a deck supported by two longitudinal beams placed on a mesh of beams and columns. Over the decades, increased traffic had led to the rapid degradation of the bridge, which underwent a major rehabilitation in 1951. This intervention paid careful attention to preserve the original shapes. The comprehensive study presented includes geometrical and damage surveys, physical and chemical characterization of structural materials, assessment of reinforcement detailing, dynamic characterization, and safety level analysis developed according to current national and European Standards. Concrete characterization was based on twenty core samples, representing all types of structural elements. Reinforcements were analyzed through reinforcement detector, geo-radar, and inspection openings allowing direct observation. The safety analysis showed that the bridge did not present special concerns.

Shirai, Kazutaka, Masaru Kikuchi, Tomoaki Ito, and Ken Ishii. 2019. "Earthquake Response Analysis of the Historic Reinforced Concrete Temple Otaniha Hakodate Betsuin after Seismic Retrofitting with Friction Dampers." *International Journal of Architectural Heritage* 13 (1): 47–57. https://doi.org/10.1080/15583058.2018.1497222.

This article addresses the earthquake response analysis of the Otaniha Hakodate Betsuin temple in Hakodate, Japan, dated 1915. The structure is made of reinforced concrete except for the roof frame, which is of structural steel. In the nave of the main hall, the axes of the girders do not match the axes of the columns because the temple reproduced the architectural style of traditional Japanese timber temples using concrete elements. Technologies and steel materials used in the Kahn and Floretyle systems adopted for the construction of the reinforced concrete elements in the temple were imported from the United States. The authors developed a nonlinear response analysis using two numerical 3D frame models subjected to strong input motions, with the aim to predict the aseismic performance of the temple without retrofitting and after retrofitting with supplemental vibration control devices, namely friction dampers. The analysis results show that the installation of such devices would enhance the aseismic performance of the temple by improving energy dissipation, stiffness, and seismic capacity. However, the increase in the seismic capacity of the main story achieved by incorporating these dampers would increase the response acceleration at the roof level. The retrofitting of the roof level, as well as the main story, should therefore be considered.

Silman, Robert. 2000. "The Plan to Save Fallingwater." *Scientific American* 283 (3): 70–77. https://www.jstor.org/stable/26058864.

This article, written from an engineering perspective, deals with the structural investigation begun in 1995 at Frank Lloyd Wright's Fallingwater in Mill Run, Pennsylvania (1939), and was written prior to repairs being undertaken. This article gives details of the architectural design, which incorporated a large number of cantilevered, steel-reinforced concrete beams. Structural issues were apparent as early as the building's construction. These historic issues are discussed, along with the structural problems identified during this investigation. Predominantly nondestructive investigation was undertaken, but some in situ strength tests on the concrete and laboratory tests on a small piece of reinforcing steel were carried out. Fallingwater's supporting structure was not well understood prior to this study. It was not clear where the support for each floor originated, nor was the relative structural importance of each element of the building well understood. To improve this understanding, a computer model was produced based on survey and analysis data, and three hypotheses were tested. One of these hypotheses was confirmed by the data, which indicated that the stresses in Fallingwater's main cantilever beams were sufficient to raise questions about the safety of the building. A decision was made to shore up the ends of the main beams overhanging the river (undertaken in 1997). The study determined that three of the four cantilever beams underneath the living room required reinforcement. Post-tensioning was identified as the only method that would not affect the building's outward appearance. The proposed repairs are described and illustrated. Repairs were scheduled for the winter of 2001–2 as part of a larger restoration project.

Sorace, Stefano, and Gloria Terenzi. 2013. "Structural Assessment of a Modern Heritage Building." *Engineering Structures* 49:743–55. https://doi.org/10.1016/j.engstruct.2012.12.012.

This article describes the seismic analysis of the Palazzo del Lavoro in Turin, Italy, a masterpiece by Pier Luigi Nervi designed in 1959 and completed in 1961. The analysis was conducted according to the Italian Technical Standards on construction. Based on the original design documentation (no on-site inspections were developed), the paper provides a detailed description of the structure, characterized by sixteen reinforced concrete monumental columns with variable sections supporting a steel mushroom-type roof, a perimeter gallery made of reinforced concrete ribbed slabs, and a glazing envelope. Original design documentation was also used to determine all necessary input data for the numerical analysis, aimed at understanding the original design concept of the different elements and at evaluating their current seismic safety conditions. The steps of the linear and nonlinear analysis included: buckling analysis of the steel roof beams; "integral" seismic pushover analysis of the monumental columns; and seismic analysis of the ribbed reinforced concrete gallery slabs and of the glazed facades. The results highlight the general good performance of the structure (in particular, a remarkably high performance of the columns) but also some criticisms: the roof beams didn't pass the verifications on panel flexural-torsional buckling, some gallery floor beams showed poor shear resistance, and the glazed facade proved to be the structure's most vulnerable element.

Spanò, Antonia, Giacomo Patrucco, Giulia Sammartano, Stefano Perri, Marco Avena, Edoardo Fillia, and Stefano Milan. 2023. "Digital Twinning for 20th Century Concrete Heritage: HBIM Cognitive Model for Torino Esposizioni Halls." *Sensors* 23 (10): art. 4791. https://doi.org/10.3390/s23104791.

This paper presents an integrated approach adopted for digital documentation of the Torino Esposizioni Halls by Pier Luigi Nervi, within the process of development of the conservation management plan financed by the Keeping It Modern initiative by the Getty Foundation. The focus of the conservation project was on structural and seismic vulnerability, but its aim was also to serve as a reference case study for digitization of a twentieth-century heritage site through integrated survey technologies. The documentation approach is based on the construction of a multi-scale and multi-content digital model, also called a "digital twin," able to support holistic knowledge of the structure's geometry with particular attention to the slimness of ferro-cement thin shells, the curved shapes, and control of the wide and complex spaces with partially visible objects. In addition, the digital model includes information on the mechanical deterioration and surface degradation of the structure's various elements. The authors underline the challenges of creating this type of digital model for a reinforced concrete heritage building due to innovative geometries where structure and architecture often coincide. The issue is harmonizing geometric and radiometric data in a single system according to a classification that is significant for structural purposes, and layering them with the results of diagnostic tests, with the final aim of assessing the state of the building's conservation and structural health. The use of a heritage building information modeling (HBIM) system is explored to fulfill the multi-source data requirements and adapt the consolidated reverse modeling processes based on scan-to-BIM solutions.

Szocinski, Michał, Andrzej Miszczyk, and Kazimierz Darowicki. 2019. "Condition of Reinforced Concrete Structures and Their Degradation Mechanism at the Former Auschwitz Concentration and Extermination Camp." *Studies in Conservation* 64 (3): 174–86. https://doi.org/10.1080/00393630.2018.1557937.

This article presents the results of investigations on reinforced concrete structures at the former Auschwitz I and Auschwitz II-Birkenau concentration camp. Nondestructive methods of reinforcement potential measurement, followed by laboratory investigations performed on samples, allowed for assessment of the actual conditions. Electrochemical potential measurements allowed mapping of the regions characterized by enhanced reinforcement corrosion risk. The concrete composition, water absorbency, salt content, and degree and profile of carbonation as well as mechanical properties were evaluated. Results revealed carbonation as the most common mechanism responsible for degradation of the reinforced concrete structures.

Terenzi, Gloria, Elena Fuso, and Stefano Sorace. 2024. "Structural Performance Study and Improvement of Artemio Franchi Stadium in Florence." *Engineering Structures* 298:art. 117068. https://doi.org/10.1016/j.engstruct.2023.117068.

In this article, the authors present the seismic assessment and proposed seismic retrofit of Stadio Artemio Franchi, designed by Pier Luigi Nervi and built in 1932 in Florence. The stadium is composed of twenty-four independent blocks separated by joints, one of which exhibits a tower fifty-three meters tall. This project was developed in preparation for the rehabilitation of the stadium to meet current requirements for a sports complex while respecting the site's architectural and engineering significance. The seismic assessment included careful examination of original design documentation, field surveys, sampling, testing, and modeling. Methodology and results of dynamic characterization tests performed using radar interferometric technique are presented. The article describes how the finite element model was developed and calibrated using testing results. Seismic assessment revealed eighty-seven sections in slightly unsafe conditions in flexure and compression flexure. The proposed seismic retrofit consisted of the installation of dissipative braces with pressurized fluid viscous spring dampers in several blocks and pressurized fluid viscous pure dampers in most joints. This solution, described in detail, aimed to improve seismic safety while minimizing impact on significance.

Turk, Tilen, Petra Štukovnik, Marjan Marinšek, and Violeta Bokan Bosiljkov. 2022. "Characterisation of Concrete from the Rupnik Military Line." *Materials and Technology* 56 (5): 579–86. https://doi.org/10.17222/mit.2022.608.

This article addresses the characterization of concrete used to build the bunkers of the Rupnik military line in Slovenia, established around 1935 in the Kingdom of Yugoslavia as a defense system against the Kingdom of Italy. The Rupnik line includes more than four thousand reinforced concrete bunkers of various sizes and purposes. The concrete walls were often rendered with a unique cementitious mixture to protect them from environmental factors. The authors used different nondestructive techniques to characterize the concrete of a set of bunkers selected as case studies. In addition, samples were collected for laboratory tests to gain more detailed data on the material characteristics. The results of nondestructive and laboratory tests showed that widely varying concrete compositions were used to build the bunkers. Results also showed extensive variation in properties for each composition due to heterogeneity and entrapped air voids in the concrete. The average Schmidt hammer reading provided for a given position the estimate of compressive strength and enabled an estimation of the secant modulus of elasticity using the Model Code 2010 approach. Samples drilled from one case study provided additional information about petrographic characteristics, physical and mechanical properties, and durability.

Urquhart, Dennis. 2014. *Historic Concrete in Scotland*, part 2, *Investigation and Assessment of Defects*. Short Guide 5. Edinburgh: Historic Scotland. https://www.historicenvironment.scot/archives-and-research/publications/publication/?publicationId=c2a38944-eb81-44e8-bd5e-a59100fb611a.

This is the second volume of a three-part Short Guide produced by Historic Scotland. Part 1 (see annotation on p. 25) introduces the history and development of pre-1945 concrete, and part 2 addresses concrete defects and deterioration, and site and materials investigation and assessment. The investigation and assessment techniques addressed in this publication are intended as an overview. The concrete deterioration discussed is ascribed to many different factors, including poor workmanship, the use of poor-quality materials, poor detailing, excess free lime, high alumina cement, alkali-silica reaction, and environmental factors such as acid rain and climate conditions. Deterioration specific to reinforced concrete is also described, such as the effect of concrete carbonation on reinforcements. A wide range of investigation techniques are described, and the importance of undertaking a review of existing documentation and conducting a visual assessment of the structure is emphasized. The most commonly utilized techniques for the investigation and analysis of historic concrete are described, providing the reader with an overview of both nondestructive and destructive techniques. The third volume in the series (see annotation on p. 109) deals with the maintenance and repair of historic concrete.

Weiss, Norman, Pamela Jerome, and Stephen Gottlieb. 2001. "Fallingwater Part 1: Materials-Conservation Efforts at Frank Lloyd Wright's Masterpiece." *APT Bulletin: Journal of Preservation Technology* 32 (4): 44–55. https://doi.org/10.2307/1504772.

This is the first of two articles (see annotation on p. 101 for the other) addressing conservation works undertaken at the start of the twenty-first century at Frank Lloyd Wright's Fallingwater in Mill Run, Pennsylvania (1939). This article was written as the conservation works were getting under way, and it introduces the site and the main material conservation issues. Moisture penetration is identified as the key cause of concrete deterioration. The authors detail the primary locations where this problem was found. It was determined that the detailing of the concrete on the parapet walls was poorly executed. The parapet's rounded top had separated from its body at a cold joint, and this, combined with cracking at the corners due to a lack of expansion joints, allowed moisture penetration behind the surface's stucco layer. Another area of deterioration described in detail is a set of stairs suspended beneath the living room that go down to the stream, which suffered from spalling concrete and corrosion of the embedded steel. Other building elements, including stone, windows, doors, roofs, terraces, paints and coatings, and interiors, are described, as are maintenance histories and condition assessments undertaken by Wank Adams Slavin Associates starting in 1988. From 1989 to 1993, various concrete patching materials were trialed following removal of the deteriorated concrete and treatment of the corroding reinforcements. An attempt was made to reattach part of the rounded top of the parapet using stainless steel anchors to retain the original material. Small patch repairs were trialed on the stairs to the stream, and it was decided that a greater intervention was required due to the level of corrosion present.

Wiles, Andrew. 2009. "St John and St Mary Magdalene, Goldthorpe: The Conservation of an Early Concrete Building." *Transactions (Association for Studies in the Conservation of Historic Buildings)* 32:40–50. https://www.aschb.org.uk/wp-content/uploads/2022/01/Vol-32.pdf#page=41.

See annotation on p. 110.

Wilkie, Simeon. 2018. "Evaluation of Cement and other Constituents in Historically-Significant Concrete Structures in Scotland." PhD diss., University of Dundee. https://discovery.dundee.ac.uk/en/studentTheses/evaluation-of-cement-and-other-constituents-in-historically-signi.

This PhD dissertation is aimed at advancing knowledge on cement and other constituents in historically significant concrete structures in Scotland. It is based on the premise that properties of Portland cement and concrete are influenced by local raw materials and manufacturing processes, and that at present there is very limited data regarding Portland cement and other constituents in historic concrete structures in the United

Kingdom. The research produced a database of compositions of cement in concrete structures throughout Scotland, including information about construction date, architectural type, production source, and physical characteristics. Furthermore, the dissertation discusses the limitations of available methods for the analysis of concrete and questions the extent to which it is possible to use such methods to accurately evaluate historic concrete.

Wilkie, Simeon, Ana Paula Arato Gonçalves, Susan Macdonald, Élisabeth Marie-Victoire, Myriam Bouichou, Jean Ducasse-Lapeyrusse, Nicki Lauder et al. 2023. "Performance Evaluation of Patch Repairs on Historic Concrete Structures (PEPS): An Overview of the Project Methodology." In *Conservation and Restoration of Historic Mortars and Masonry Structures: HMC 2022*, edited by Violeta Bokan Bosiljkov, Andreja Padovnik, and Tilen Turk, 288–99. RILEM Bookseries 42. Cham, Switzerland: Springer. https://doi.org/10.1007/978-3-031-31472-8_22.

This paper overviews the background and methodology for the international research project Performance Evaluation of Patch Repairs on Historic Concrete Structures (PEPS). Up to ten case studies were identified in each partner country, and the specific criteria for selection are described. The project methodology was developed to answer the following questions: What materials and protection systems were used in the repair and adjacent substrate? How was the repair area prepared, and how has this impacted the repair bond? How is the repair performing technically? How is the repair performing aesthetically? The methodology includes the application of diverse traditional and nontraditional diagnostic techniques, and both nondestructive and destructive methods, aimed at identifying the mechanical, chemical, and electrochemical characteristics of the original concrete and repair materials. In addition, a shared procedure for recording results was developed to ensure that data was collected consistently and could be used for further comparative analysis. Final results of the project will be presented in future publications.

Wilkie, Simeon, and Thomas Dyer. 2022. "Challenges in the Analysis of Historic Concrete: Understanding the Limitations of Techniques, the Variability of the Material and the Importance of Representative Samples." *International Journal of Architectural Heritage* 16 (1): 33–48. https://doi.org/10.1080/15583058.2020.1749728.

This paper describes in detail an experimental research study that started from the premise that the mix proportions and water-to-cement ratio of the original concrete must be established to create like-for-like repair materials. The research evaluated the main issues and challenges of applying current concrete analysis standards to historic concrete samples. For this purpose, nine concrete samples were produced using Portland cement with proportions based on mix designs used in early twentieth-century concrete buildings. The research results and literature review led the authors to express concern regarding the accuracy of existing methods and standards used for the analysis of historic concrete given the frequent lack of sufficient material and adequate samples. In the case of historic concrete buildings, samples are usually much smaller than the minimum standard representative sample, or are taken from areas of the structure that are not representative due to heterogeneity of the material resulting from the construction process. The authors, therefore, underline the limitations of available techniques, the variability of concrete in historic structures, and the crucial importance of samples that are as representative as possible.

CHAPTER 4

# CONSERVATION APPROACH

## Key References

Croft, Catherine, Susan Macdonald, and Gail Ostergren, eds. 2018. *Concrete: Case Studies in Conservation Practice*. Los Angeles: Getty Conservation Institute.

This book presents a collection of fourteen case studies on the conservation of twentieth-century concrete heritage structures. The development of this book followed an international meeting of conservation professionals, held in 2014 at the Getty Center, where a need clearly emerged for gathering and making available current knowledge on best practices in conserving concrete heritage. The selected case studies include a wide range of building typologies built over six decades as well as a variety of environmental contexts, economic conditions, and legislative frameworks. The case studies presented are: listening mirrors in Denge, Kent, England; Halles du Boulingrin, Reims, France; Villa Girasole, Verona, Italy; Dudley Zoo Gardens, England; São Francisco de Assis Church, Belo Horizonte, Brazil; Magliana Pavillion, Rome; Gänsehäufel swimming facility, Vienna; Unité d'Habitation, Marseille, France; First Christian Lower Technical School Patrimonium, Amsterdam; the Morse and Ezra Stiles Colleges of Yale University, New Haven, Connecticut; the New York Hall of Science; the National Theatre, London; Brion Cemetery, San Vito D'Altivole, Italy; and an outdoor sculpture by Donald Judd in the southwest of England. Despite the clear differences in terms of typologies and conditions, all the case studies share a rigorous approach that starts with in-depth investigations to identify the causes and extent of damage, with the final aim of defining proper conservation solutions able to preserve cultural significance. A very practical and useful aspect is that, for many case studies, the authors explain what worked and what didn't, as well as the compromises that the project team had to make. Numerous illustrations and technical drawings help the reader comprehend the physical conditions of the structures pre- and post-intervention, and the types of diagnostic activities, trials, and conservation work carried out.

Gaudette, Paul E., and Deborah Slaton. 2007. *Preservation of Historic Concrete*. Preservation Briefs 15. Washington, DC: National Park Service, Heritage Preservation Services. https://www.nps.gov/orgs/1739/upload/preservation-brief-15-concrete.pdf.

This publication provides an introduction to the conservation of historic concrete. It overviews historic uses of concrete and its manufacture, illustrated with many examples, in the United States. The characteristics of concrete are briefly discussed. The text details the mechanisms and causes of deterioration of concrete, and evaluates their impacts on concrete structures. A section on planning for concrete conservation highlights the importance of investigation and analysis prior to undertaking any repair work. A section covers methods of maintenance and repair. Fieldwork and site issues that may impact the repair process—including surface preparation, formwork, selection of repair materials, and repair techniques—are also discussed.

Harboe, Gunny, Fernando Espinosa de los Monteros, Stefania Landi, and Kyle Normandin. 2021. *The Cádiz Document: InnovaConcrete Guidelines for Conservation of Concrete Heritage*. Paris: ICOMOS International. https://openarchive.icomos.org/id/eprint/2578/.

This document, developed within the InnovaConcrete project, aims to provide guidance for the conservation of concrete heritage with respect to its cultural, historical, aesthetic, social, and technological values. It is conceived as an aid to conservation practitioners and other professionals, including architects, engineers, and conservators as well as contractors, craftspeople, public agencies, and private owners dealing with the preservation of concrete heritage structures. The document is based on the concepts expressed in the Approaches to the Conservation of Cultural Heritage of the Twentieth Century (also known as the Madrid–New Delhi Document), which ICOMOS-ISC20C published in 2017. After introductory considerations on different typologies and scales of concrete structures, the combination of concrete with other building materials, sustainability of repair practice, goals of a proper repair, and special aspects to be considered in an approach to concrete conservation, the document proposes eight steps to guide the development of any such conservation project: develop understanding and assess significance; identify an experienced interdisciplinary project team; develop preliminary knowledge of site-specific issues; perform a detailed condition assessment; develop sustainable repair approaches and policies; implement the repair program; establish maintenance programs and monitoring; and promote and celebrate concrete heritage.

Macdonald, Susan, and Ana Paula Arato Gonçalves. 2020. *Conservation Principles for Concrete of Cultural Significance*. Los Angeles: Getty Conservation Institute. http://hdl.handle.net/10020/gci_pubs/conservation_principles_concrete.

The principles outlined in this publication intend to remedy the limited availability of guiding resources in the field of conservation of concrete heritage. It is based on the premise that much knowledge can be drawn from best practices in general concrete repair, but historic buildings and structures need additional care to retain their cultural significance. The publication was conceived as a tool for architects, engineers, conservators, contractors, and stewards to develop a sound and informed decision-making process for conserving concrete of cultural significance. Referring to both international concrete repair guidelines and conservation principles, the document provides an approach starting from the understanding and investigation of the concrete object, to the development and implementation of conservation strategies, and, finally, to maintenance and monitoring. A flowchart summarizes the principles and illustrates the cyclic path of the methodology, highlighting the key decision-making steps. This publication is an outcome of the Concrete Conservation project, part of the Conserving Modern Architecture Initiative of the Getty Conservation Institute. It is also available in Spanish and French.

Odgers, David, ed. 2012. *Practical Building Conservation: Concrete*. Farnham, UK: English Heritage / Ashgate.

This volume on the conservation of concrete is part of the English Heritage Practical Building Conservation series. It addresses all major concerns regarding the deterioration and assessment of concrete structures, and best practices for the conservation of this complex material, in a manner that will be useful and accessible to beginning and seasoned professionals alike. The book draws on evidence from the past and looks at the history of concrete-based materials, from mass concrete to early reinforcing systems, precast mosaic panels, and post-tension construction. Materials, aggregates, architectural finishes, and coatings are addressed in relation to their aesthetic and functional performance. Curing and placement issues that may impact performance, appearance, and durability are touched upon. The section on deterioration and damage addresses structural problems, inherent problems, and the various mechanisms of chemical failure, among other causes of decay. Testing, inspection, and evaluation procedures for concrete assessments, including specialist inspections, results analysis, and how these methods can be utilized on-site, are discussed. Repair options and treatment methods are explained, and guidance in selecting appropriate options is provided. Where applicable, each chapter cross-references other texts from the Practical Building Conservation series. A recommended reading list appears at the end of each chapter. Through a collection of eight case studies, a wide variety of treatments and approaches are examined, from traditional repair to proprietary systems, combined traditional and innovative repairs, large-scale repairs to mass concrete, cathodic protection of reinforced concrete, repairs to concrete in marine environments, repairs using precast panels, and repairs to concrete mosaic finishes. The book closes with a brief overview of care and maintenance.

## General References

Akhurst, Paul, Susan Macdonald, and Trevor Waters. 2005. "Sydney Opera House: Analysis and Cleaning of the Concrete." *Journal of Architectural Conservation* 11 (3): 45–64. https://doi.org/10.1080/13556207.2005.10784952.

See annotation on p. 88.

Albani, Francesca. 2016. "The Durability of Restoration of Exposed Concrete: Case Histories Compared." In *First International Workshop on Durability and Sustainability of Concrete Structures: Bologna, Italy, 1–3 October 2015*, edited by Mario Alberto Chiorino, Luigi Coppola, Claudio Mazzotti, Roberto Realfonzo, and Paolo Riva, 3.1–3.10. ACI Special Publication 305. Farmington Hills, MI: American Concrete Institute. https://doi.org/10.14359/51688563.

This paper describes and compares conservation approaches and techniques used in different interventions on buildings where exposed concrete surfaces play a key role in architectural value. The case studies analyzed are the Church of Notre-Dame du Raincy, France, by Gustave and Auguste Perret (1922–23); the second Goetheanum in Dornach, Switzerland, by Rudolf Steiner (1924–28); a housing complex in Milan by Luigi Figini and Gino Pollini (1963–69); and the Olivetti Factory in Crema, Italy, by Marco Zanuso (1968–71). Through a comparative analysis, the author discusses the different factors influencing intervention choices, and strengths and weaknesses of the various conservation methods implemented over time. The various construction periods represented in the case studies also enable a reflection on the variety of construction methods and types of concrete employed over the century. The need for a case-by-case approach clearly emerges, for example, in the application of different conservation techniques on different portions of the same building in response to the results of a careful diagnostic campaign.

Arato Gonçalves, Ana Paula. 2021. "Conservation Principles for Concrete: Multidisciplinary Context." In *The 16th International DOCOMOMO Conference Tokyo Japan 2020 + 1: Inheritable Resilience-Sharing Values of Global Modernities*, edited by Ana Tostões and Yoshiyuki Yamana, 430–34. Tokyo: Docomomo Japan.

This paper compares the Conservation Principles for Concrete of Cultural Significance proposed by the Getty Conservation Institute with current literature and standards in concrete repair, highlighting the points of divergence and convergence, with the aim of establishing better dialogue between these fields. The organization of the paper is based on the steps defined in the document: project planning; understanding the building and conservation needs; developing conservation strategies; implementation; maintenance; and monitoring. The Conservation Principles for Concrete of Cultural Significance advocate for an approach that merges well-established methodologies in the fields of conservation and concrete repair. It recognizes that there might be instances where conservation and concrete repair practices conflict, but that solutions that balance both are ultimately the most effective in achieving the goal of conserving cultural significance of sites where concrete plays an important role.

Ayón, Angel. 2009. "The Guggenheim at Fifty: Notes on Recent Preservation Work." *DOCOMOMO Journal*, no. 41, 73–79.

See annotation on p. 44.

Balletta, Michael. 2018. "Conservation vs Durability in Heritage Protection." *Heritage and Traditional Building Magazine*, no. 1, 25–27.

This article focuses on the challenge of balancing the need for a structurally sound and long-lasting repair with the need for "like for like" repairs aimed at ensuring an "invisible mend." After briefly describing procedures for assessing damage, causes of failure, and past repair performance, the discussion focuses on repair choices. Different issues are pointed out, for instance that fully complying with European Standard EN 1504 is often not possible when using like-for-like repairs. In addition, different portions of the same building may show different surface colors and textures due to variations during construction, or weathering. This constitutes a technical challenge in color matching, and also increases time and cost needed for a project. The National Theatre in London is used as an example to discuss the following issues associated with repairs: long-term color matching, since repair and original materials weather differently; and repair durability, especially in areas of reinforced concrete with low concrete cover. The author concludes that there is no absolute right solution. An array of repair methods might be correct depending on the structure's characteristics and the objectives defined.

Bertolini, Luca, Maddalena Carsana, and Elena Redaelli. 2008. "Conservation of Historical Reinforced Concrete Structures Damaged by Carbonation Induced Corrosion by Means of Electrochemical Realkalisation." *Journal of Cultural Heritage* 9 (4): 376–85. https://doi.org/10.1016/j.culher.2008.01.006.

See annotation on p. 89.

Blain, Catherine. 2016. "Living a Manifesto: The Second Life of EDF's Housing Towers in Ivry-sur-Seine (Atelier de Montrouge, 1963–67)." In *Adaptive Reuse: The Modern Movement Towards the Future, 14th International DOCOMOMO Conference Proceedings, 6–9 September 2016, Calouste Gulbenkian Foundation, Lisbon, Portugal*, edited by Ana Tostões and Zara Ferreira, 817–23. Lisbon: DOCOMOMO International.

This paper focuses on the conservation process of two small reinforced concrete housing towers in the former industrial area of Ivry-sur-Seine, France. The towers were designed by Atelier de Montrouge between 1963 and 1967 and rehabilitated by the Atelier AUA Paul Chemetov between 2011 and 2016. They originally comprised eleven housing units, one per floor, intended for the executives of the national electricity company (Electricité de France) assigned to the thermal power plant on the Seine riverbanks. Since their construction, thanks to their sculptural and brutalist aesthetics, they have been recognized as a manifesto of the modern movement. Left unused since the end of the 1990s, they underwent serious degradation before being rescued thanks to their inscription on the national list of historic monuments in 2003, putting them among the few examples of postwar housing projects protected in France, and facilitating rehabilitation as part of the vast urban renewal project Ivry Confluences by a private developer. The author overviews the rehabilitation process, focusing on the respectful approach adopted, which aimed to preserve the original appearance of the towers despite the need to change the layout of the apartments (they were split in two to obtain smaller and more affordable units) and the need to improve insulation (which was inserted from the inside).

Boothby, Thomas E., M. Kevin Parfitt, and Charlene K. Roise. 2005. "Case Studies in Diagnosis and Repair of Historic Thin-Shell Concrete Structures." *APT Bulletin: Journal of Preservation Technology* 36 (2–3): 3–11. https://www.jstor.org/stable/40004699.

This article introduces thin-shell concrete structures and demonstrates some issues associated with this form of architectural design using two case studies: Kresge Auditorium in Cambridge, Massachusetts, and Loring Air Force Base in Limestone, Maine. Although their forms of deterioration may recall those of other concrete structures, the authors discuss how thin-shell concrete structures may deteriorate thanks to additional factors. Several references to further sources of information on the diagnosis and repair of such buildings are given. The case studies focus on issues inherent to the roof coverings, as well as the solutions identified for improving their performance. According to the authors, solutions must take into account shell type and condition, expansion and contraction characteristics, the building's internal and external environments, aesthetics, and modern safety and performance requirements.

Busse, Felix, Christa Heidrich, Markus Kleine, Christoph Sander, and Murat Ünal. 2015. "BEGLARES II Protection and Restoration of Monumental Concrete-Glazing with Cathodic Protection Systems." In *Le vitrail comment prendre soin d'un patrimoine fragile? 9e Forum sur la conservation et la technologie du vitrail. Paris, 8–10 juillet 2015 = Stained-Glass: How to Take Care of a Fragile Heritage? 9th Forum for the Conservation and Technology of Historic Stained-Glass, Paris, 8–10 July 2015*, edited by Claudine Loisel and Isabelle Pallot-Frossard, 83–90. Paris: International Council on Monuments and Sites, section française.

This paper focuses on decay processes and conservation challenges associated with monumental concrete glazing, and also presents the premises and main objectives of the BEGLARES II research project. This project addresses carbonation-induced corrosion of reinforcements and experiments with the use of cathodic protection in the conservation of concrete glazing, based on the existing wide experience in the use of this technique on concrete structures. The authors describe the historical evolution of concrete glazing, followed by a brief reference to the previous research project, BEGLARES I. They then describe deterioration mechanisms, approaches to conservation and planning of interventions, and the methodology for the application of a cathodic protection system. Finally, they trace the main objectives of the project, referring to visual/aesthetic requirements and to the different parameters that may influence the mode of application (for instance element position, surface ratio of concrete and glass, and surface texture).

Bussell, Michael N. 2007. "Conservation of Concrete and Reinforced Concrete." In *Structures and Construction in Historic Building Conservation*, edited by Michael Forsyth, 192–210. Historic Building Conservation. Oxford: Blackwell.

See annotation on p. 13.

Calder, Barnabas, Susan Macdonald, Claudia Devaux, Paul Gaudette, Rosa Lowinger, and Ana Paula Arato Gonçalves. 2020. "Conserving Concrete: Live Roundtable Discussion for the Launch of *Conservation Principles for Concrete of Cultural Significance*." December 9, 2020, YouTube, 1:28:42 min. https://www.youtube.com/watch?v=pAItU49c708&ab_channel=GettyConservationInstitute.

This is the recording of a webinar that took place on December 9, 2020, to celebrate the launch of the publication *Conservation Principles for Concrete of Cultural Significance* by the Getty Conservation Institute. The discussion topic was the importance of conserving historic concrete and using sound conservation methodologies to guide practice. It includes a ten-minute presentation by Barnabas Calder on the significance of concrete and the importance of preserving it; a ten-minute presentation by Susan Macdonald on the approach to concrete conservation presented in *Conservation Principles for Concrete of Cultural Significance*; seven-minute presentations by Claudia Devaux, Paul Gaudette, and Rosa Lowinger, each presenting a case study to illustrate how they approach concrete conservation in their own work; a twenty-minute roundtable discussion; and questions from the audience.

Ceravolo, R., G. De Lucia, E. Lenticchia, G. Miraglia, A. Quattrone, F. Tondolo, E. Matta et al. 2021. "Challenges in the Reuse and Upgrade of Pier Luigi Nervi's Structures." In *12th International Conference on Structural Analysis of Historical Constructions SAHC 2021*, edited by P. Roca, L. Pelà, and C. Molins, 71–81. Barcelona: International Centre for Numerical Methods in Engineering (CIMNE). http://congress.cimne.com/SAHC2020/frontal/doc/Ebook_SAHC2020.pdf#page=71.

This paper presents the project to develop a conservation plan for the two halls of the Torino Esposizioni, designed by Pier Luigi Nervi and built between 1948 and 1950 to host Turin's annual automobile show. The exhibition center's two main pavilions are outstanding examples of a pioneering use of reinforced concrete. The conservation plan is expected to stimulate and contribute to the preservation of this masterpiece, with special emphasis on structural and seismic vulnerability aspects according to the current Italian standards, to guarantee a new extended service life. The paper provides details on the work plan, including historical analysis, with a particular focus on technological features; 3D dense-cloud modeling derived from 3D sensing technologies; structural analysis premised on vibration-based dynamic tests carried out to investigate the global behavior and health state; analysis of the materials and their durability by means of experimental investigations on structural elements and laboratory mock-ups; and definition of the overall conservation and management plan for the future renovation of the halls. This project was funded by the Getty Foundation's Keeping It Modern initiative.

Chiorino, Cristiana. 2006. "Structural Concrete Architectural Heritage, Problems and Strategies for Documentation and Conservation: The Case Study of Turin." In *Proceedings of the 2nd FIB Congress: June 5–8, 2006, Naples, Italy*. Naples: FIB Italia.

Through case studies on the repair and reuse of four significant landmark exposition halls built between 1949 and 1960 in Turin, this paper addresses the need to create an inventory and history of concrete structures designed by engineers rather than architects. Both good and poor examples of repair and reuse are illustrated. The paper also provides a philosophical approach addressing the cultural values of engineering landmarks and emphasizes an integration of science, engineering, art, and culture. The author explores how values are assessed when a structure has moved away from the realm of iconic architecture, yet the engineered result is structural art. The qualities that make a structure worthy of landmark status are discussed, and a section is dedicated to the history of documenting engineering landmarks by international organizations, including the Institution of Civil Engineers, the US National Park Service, and DOCOMOMO. Criteria for landmark listings are provided. The four case studies on the reuse of functionally obsolete, oversize, engineer- and/or builder-designed concrete structures highlight the challenges of addressing technical fragility, functional inadequacy, and economic and market constraints while also attempting to retain social and cultural values.

Chusid, Jeffrey M. 2011. *Preserving the Textile Block at Florida Southern College*. New York: World Monuments Fund. https://www.wmf.org/publication/preserving-textile-block-florida-southern-college.

This report was produced following an April 2009 meeting of conservation professionals at Florida Southern College, the site of a collection of twelve Frank Lloyd Wright–designed buildings constructed between 1938 and 1959. The meeting topic was the conservation of these buildings and others constructed using Wright's experimental concrete textile block system, involving individual, hand-molded, interlocking concrete blocks. Three groups of conservation challenges are identified: "problems with the individual blocks; problems with the system: the grout tube and steel reinforcing; and problems arising from use or location" (p. 20). The author notes that, as with any conservation work, the first goal is to try to save as much original material as possible, but where replacement is necessary, to preserve the fundamental characteristics of the block system. To do this, the original composition and production method of the blocks must be replicated. Due to the potentially short lifespan of the system, the owner must accept the ongoing task of conservation and, where necessary, replacement over the lifetime of the building. Replacing blocks is particularly tricky due to their interlocking nature. The author suggests creating a publication that can be used by people undertaking repairs to these buildings, but this does not eliminate the need for a good understanding of the processes that have led to each specific area of deterioration. A set of recommendations provides a guiding structure for future conservation work.

Conte, Lisa, Joe Graham-Felsen, and Amanda Trienens. 2020. "The Slurry Wall: Past, Present, and Future." *Studies in Conservation* 65 (suppl. 1): P44–P50. https://doi.org/10.1080/00393630.2020.1765644.

This paper describes conservation issues concerning a quite special reinforced concrete artifact: the slurry wall of the 9/11 Memorial Museum, a remnant of the World Trade Center preserved under Section 106 of the National Historic Preservation Act. It is a twenty-meter-long section of the subterranean wall that surrounded the World Trade Center site, a marvel of engineering conceived to hold back the waters of the Hudson River. It was built following a construction method patented in Italy in the late 1940s and used in the United States in the 1960s. The wall acquired high symbolic meaning after resisting the 9/11 attack. Currently there is a new load-bearing structure behind it; the original perimeter wall was reengineered after 9/11 to address the damages to existing structures and to allow the museum's realization. It does not perform its original work, but it is still in contact with soil and water, and so it is affected by the corrosion of steel, revealed also by rust staining on the concrete surface and salt formation. The complex nature of such an artifact and core element of the museum has required the assembly of a diverse group of experts to take care of it. The authors describe their research process and methods used to analyze the wall's technical and physical characteristics and the approach to preservation, which is not guided by aesthetics, but rather focuses on maintenance and mitigation of future deterioration.

Croatto, Giorgio, Umberto Turrini, and Angelo Bertolazzi. 2016. "Criteria and Guidelines about Structural Reversibility for Reinforced Concrete Historical Buildings Refurbishment: The Excelsior Cinema in Milan

(1926–30).” *Journal of Architectural Conservation* 22 (3): 189–98. https://doi.org/10.1080/13556207.2017.1279866.

This paper describes a project proposal for the refurbishment of the former Cinema Excelsior in Milan (1926–30). The authors present the case study as an experiment in finding project-specific solutions based on in-depth surveys, diagnostic analysis, and study of the building's history and transformations. Until the 1950s, construction practice in Italy maintained a traditional character, even though modern techniques and materials were experimented with. This produced many hybrid constructions, of which the Cinema Excelsior is an emblematic example, combining as it does a reinforced concrete structure with traditional brickwork. The rehabilitation project's approach consisted of blending together the requirements of the building's new use and the preservation of its historical value, operating as far as possible in a reversible way, especially from a structural point of view. The project proposed to keep the iconic facades unaltered while redefining the function and structure of the huge interior volume, adapting it to host two retail spaces occupying two basement floors and five aboveground floors. The authors present a technical solution for joining the existing, variously sized reinforced concrete pillars and the new floor slabs, making them act as independent structures with regard to the vertical strains and as collaborating structures with regard to horizontal ones.

Custance-Baker, Alice, and Susan Macdonald. 2015. *Conserving Concrete Heritage Experts Meeting: The Getty Center, Los Angeles, California, June 9–11, 2014*. Los Angeles: Getty Conservation Institute. http://hdl.handle.net/10020/gci_pubs/conserving_concrete_heritage.

This report documents discussions that occurred during a 2014 experts meeting organized by the Getty Conservation Institute, which convened a multidisciplinary group of professionals in the field of concrete conservation. It was organized under the auspices of the GCI's Conserving Modern Architecture Initiative. The report summarizes the meeting's presentations, discussions, and outcomes as well as a proposed plan of action. Three key areas were addressed: potential research to advance the conservation of concrete; possibilities for creating and disseminating information to fill knowledge gaps; and areas for potential education and training activities. Research priorities were divided into three categories: investigation, diagnostics, and analysis; conservation and repair methodologies; and process, repair materials, and case studies. This publication also includes a background paper by Susan Macdonald focused on reinforced concrete and aimed at stimulating discussion in the meeting. According to Macdonald, the GCI hoped to identify areas of conflict between existing repair options and conservation needs, as well as the actions needed to remove barriers to improving current methods of repair, thereby improving the state of concrete conservation. This paper addresses challenges to conserving concrete, the status of concrete conservation, potential actions to improve the status quo, and research that would advance the conservation of concrete.

de Jonge, Wessel. 1997. “Concrete Repair and Material Authenticity: Electrochemical Preservation Techniques.” *APT Bulletin: Journal of Preservation Technology* 28 (4): 51–57. https://doi.org/10.2307/1504594.

The overarching theme of this article is the conservation of the Zonnestraal sanatorium in Hilversum, the Netherlands. The ideology of the avant-garde and the transitory nature of the modern movement are discussed in relation to its original design intent. The discussion includes physical and philosophical approaches to repair that may alter the authenticity of the original structure. A less-obtrusive stabilization and/or intervention is preferred. By assessing successful realkalization on four concrete structures, three being landmark buildings, the author makes a case for its applicability as a concrete conservation methodology. According to this article, realkalization has less visual impact on the concrete surface, while preserving and extending service life; thus, the article demonstrates its potential benefits as a complementary treatment to traditional repairs. It includes a brief description of concrete deterioration and a technical description of electrochemical treatments. It concludes by emphasizing that while electrochemical treatments are promising, the team must be fully versed in their application, advantages, and challenges. An alternate version of this article can be found in Wessel de Jonge and Arjan Doolaar, eds., *The Fair Face of Concrete: Conservation and Repair of Exposed Concrete* (see annotation on p. 15).

de Jonge, Wessel. 2021. "Concrete Heritage in the Netherlands: Valuation and Conservation of Concrete and Reinforced Concrete Structures." *Architectus* 2 (66). https://doi.org/10.37190/arc210204.

This paper focuses on the history and conservation challenges of concrete heritage structures built in the Netherlands during the interwar period. The author describes changes in the use of reinforced concrete over time, referring also to some specific aspects, such as the introduction of light concrete products for the construction of light curtain walls, the evolution of structural elements such as the introduction of mushroom floors, and changes in reinforced concrete codes that regulate calculation methods. The author discusses conservation issues affecting reinforced concrete, using as representative examples the Sint Jobsveem in Rotterdam, the Zonnestraal sanatorium in Hilversum, and the Van Nelle Factory in Rotterdam, referring to his direct experience in the conservation and rehabilitation of these structures. The approach to the interventions is described for the three case studies. The final section discusses the challenge of determining a conservation approach based on which specific characteristics of the concrete structure contribute to its cultural value; for example, an approach aiming to conserve concrete used in load-bearing elements and rendered with other materials will be different from an approach to conserve concrete used for aesthetic characteristics.

de Jonge, Wessel, and Arjan Doolaar, eds. 1998. *The Fair Face of Concrete: Conservation and Repair of Exposed Concrete*. Preservation Technology Dossier 2. Eindhoven, the Netherlands: DOCOMOMO International / Eindhoven University of Technology.

See annotation on p. 15.

Donofrio, Greg, and Meghan Elliott. 2013. "Understanding the 'World's Largest' All-Reinforced-Concrete Office Building." *APT Bulletin: Journal of Preservation Technology* 44 (2/3): 23–33. https://www.jstor.org/stable/41982402.

This article presents the methodology used to determine significance based on construction and engineering history through the case study of a reinforced concrete building from 1909–10 in Minneapolis. It also discusses the challenges in establishing engineering significance, for example the lack of scholarship describing historical context, and the biases of the preservation field toward visible significance and superlatives (the "first," the "tallest," et cetera). The methodology presented started by gathering evidence from primary sources, such as news articles on the construction and existing archival documentation. The information gathered was checked against physical evidence that could be observed upon inspection of the building. This resulted in a set of questions regarding the significance of the structural design, the type of reinforcement used, the building's engineer, and construction methods. These questions guided a historical context research involving secondary sources on construction history. The article concludes with a series of recommendations that would facilitate recognition of engineering significance, such as the inclusion of engineering history in the curriculum of engineering schools and changes in the National Register form to encourage the same level of attention that is given to investigating architectural significance.

Douglas, Stephen A. 2014. "Maintenance and Preservation of the Royal National Theatre, London." In *Concrete Solutions: Proceedings of Concrete Solutions, 5th International Conference on Concrete Repair, Belfast, Northern Ireland, 1–3 September 2014*, edited by Michael Grantham, P. A. Muhammed Basheer, Bryan Magee, and Mario Soutsos, 715–18. Boca Raton, FL: CRC Press.

This paper focuses on the conservation of the exposed concrete at London's Royal National Theatre, designed by Denys Lasdun and built between 1969 and 1976. This building is a major British postwar structure and an internationally significant example of theater architecture. Though initially condemned by critics and royals alike, it is currently a Grade II* listed site. The National is a cast-in-place exposed concrete building with fiberglass molded "diagrid" soffits and a distinct Douglas fir board-form finish. The board marking is used for intentionality of space, routing of pedestrian access, and expression of space. Despite being constructed to robust standards and with an extremely high level of workmanship, the author reports that the National was at the time of writing beginning to show signs of deterioration, exacerbated by damage from previous proprietary repairs, which might have been avoided with higher-quality concrete. As a result, a project team was undertaking a proactive concrete conservation program to prolong the life of the structure and minimize future repairs. The lack of skilled conservators able to repair concrete had introduced some challenges related to removal of unwanted marks, highlighting the board finish, and proper cleaning techniques. Additionally, as this theater is in almost constant use, it was difficult to find windows of time during which the work could be performed. This case study illustrates both a growing public appreciation of concrete structures from this era and the challenges of their conservation.

Ferreira, Teresa Cunha, and Eduardo Fernandes. 2021. "Álvaro Siza's Tectonic Shift in Leça da Palmeira: From Design to Conservation." In *The 16th International DOCOMOMO Conference Tokyo Japan 2020+1: Inheritable Resilience- Sharing Values of Global Modernities*, edited by Ana Tostões and Yoshiyuki Yamana, 430–34. Tokyo: Docomomo Japan.

This paper focuses on two paradigmatic works designed by Álvaro Siza between 1958 and 1966 in Leça da Palmeira, near Porto, Portugal: the Boa Nova Tea House (1958–63) and the Piscina das Marés (1959–66), both listed as national monuments in 2011 and included in the World Heritage Tentative List in 2017. In the Boa Nova Tea House, Siza mixed traditional materials with modern ones, combining vernacular elements with modern technologies; in the Piscina das Marés, he adopted a modern technology, namely reinforced concrete, with a neoplastic language. Both have been subjected to recent conservation interventions by Siza himself. The authors focus their analysis on the life cycles of these buildings, from their original design and construction to their aging, transformations, and the recent conservation works, including specific considerations on the different approaches adopted for concrete repair in each case and maintenance over time.

Ford, Mike, Paul E. Gaudette, and Deborah Slaton. 2021. "Restoring Serenity: Conservation of Minoru Yamasaki's North Shore Congregation Israel." *Journal of Architectural Conservation* 27 (1–2): 104–16. https://doi.org/10.1080/13556207.2021.1933341.

This paper focuses on the North Shore Congregation Israel complex in Glencoe, Illinois, by Minoru Yamasaki, completed in 1964. The complex exemplifies the interest of the architect in the design potential of precast and cast-in-place concrete and its versatility as both a structural and a decorative material. The main deterioration observed after several decades was spalling along the edge of the precast panels. Previous patch repairs were visually apparent, and many of them were no longer sound. The paper illustrates the approach and process for developing the necessary conservation work, including cleaning procedures to address soiling and biological growth, and finishing techniques to blend the repairs with the existing concrete. The authors describe the condition assessment of the precast concrete, laboratory analysis, approach to repair strategy, development of repair procedure, and repair implementation.

Frens, Dale H. 2002. "Restoration of the Concrete Roof of the Mercer Museum in Doylestown, Pennsylvania." *APT Bulletin: Journal of Preservation Technology* 33 (1): 13–19. https://doi.org/10.2307/1504784.

See annotation on p. 97.

Fu, Chao-Ching. 1995. "Problems of Historicity in the Conservation of the Pioneering Reinforced Concrete Buildings in Taiwan." In *Structural Studies of Historical Buildings IV*, vol. 1, *Architectural Studies, Materials and Analysis*, edited by C. A. Brebbia and B. Leftheris, 53–60. Southampton, UK: Computational Mechanics Publications.

Written from an architectural historian's point of view, this paper explores the issues faced by professionals involved in the conservation of Taiwan's pioneering reinforced concrete buildings. Following the colonization of Taiwan by Japan in 1895, Japanese architectural professionals brought new architectural materials and building types there. These works are considered of great importance, as they mark the arrival of the "real modern development of Taiwanese architecture" (p. 54). Key factors in their deterioration include improper restoration works, destructive alterations, and environmental conditions that include high humidity, abundant rainfall, and location within a seismically active region. The paper discusses the requirement for the retention of a building's

historicity once it has been designated as a Taiwanese national cultural property and the three key problems that result from this requirement: potential discrepancies between historicity and durability; lack of availability of original building drawings and documents; and conflicts between the requirements of preservationists versus building owners.

Gaudette, Paul E. 2000. "Special Considerations in Repair of Historic Concrete." *Concrete Repair Bulletin* (January/February): 12–13.

This brief article discusses the key differences in repairing contemporary versus historic concrete buildings and highlights the special considerations required when dealing with historic concrete. As the author notes, "All of the rules of good concrete repair practice apply, as well as some others" (p. 12). Aesthetics, although sometimes a consideration with new construction, are more crucial when dealing with historic buildings in order to preserve appearance and design intent. The aim of regular concrete repairs is to remove and replace defective material, but with historic buildings, the aim is to preserve as much of the original fabric as possible. In order to properly understand the original materials and construction of a historic concrete building, investigation and analysis stages are generally longer and more in-depth than with a non-historic building. This is also the case when selecting and preparing repair materials, and when conducting laboratory investigations and on-site trials. It is noted that in some cases, repairs with a shorter lifespan may be selected for historic concrete structures where this enables a less-visible intervention.

Getty Conservation Institute. 2019. "Conservation of Concrete." Special issue, *Conservation Perspectives: GCI Newsletter* 34 (2). https://www.getty.edu/conservation/publications_resources/newsletters/pdf/v34n2.pdf.

This edition of the Getty Conservation Institute's newsletter is dedicated to the field of concrete conservation. The introductory essay by Susan Macdonald focuses on the crucial role of concrete as a protagonist of modern architecture, recalling the use of reinforced concrete for consolidating historic buildings and underlining the multiple challenges raised by its conservation. In the following essay, Adrian Forty brings attention to the early phases of diffusion of reinforced concrete around the world, reflecting on its role, together with steel construction, as a symbol of modernity. An essay by Ana Paula Arato Gonçalves details the aims and scope of the Concrete Conservation project launched in 2017 as part of the Getty Conservation Institute's Conserving Modern Architecture Initiative, which was specifically conceived to fill knowledge gaps in the concrete conservation field by creating and disseminating information, and to improve practice through research on specific topics, such as the study of past repairs on concrete. Paola Pesaresi focuses on the use of reinforced concrete for structural consolidation of archaeological sites, underlining the challenges of dealing with the conservation of both the concrete and the archaeological remains. The final entry features Élisabeth Marie-Victoire, Arun Menon, and Ruth Verde Zein in a roundtable discussion about the conservation of concrete heritage.

Graves, Kiernan, and Katey Corda. 2016. "Conserving a Boundary: The Conservation and Management of a Berlin Wall Mural." *Studies in Conservation* 61 (2, suppl. 2): 61–66. https://doi.org/10.1080/00393630.2016.1190996.

This paper focuses on the conservation of five segments of the Berlin Wall painted by artists Thierry Noir and Kiddy Citny. Their association with the Berlin Wall, their place in the history of contemporary street art, and their symbolic role in the fight against oppression define the cultural significance of the paintings. In the early 1990s, these five segments were bought at auction, shipped to the United States, and installed in an outdoor environment (the small courtyard of a skyscraper in Manhattan) accessible to the public. Following an aesthetic motivation, they were positioned in front of a waterfall, with water falling directly on the wall's base. This condition, together with the harsh climate, led to cracking and delamination, corrosion of the reinforcement bars, and flaking and loss of paint layers. Moreover, accessibility to the public resulted in vandalism and mechanical damage. The conservation strategy, articulated by a multidisciplinary team involving conservators, concrete specialists, architects, and engineers, was based on careful consideration of the object's cultural value. The

decision-making process, involving the evaluation of different options for reinstallation, is clearly described. The final choice was to intervene at a minimal level (meaning stabilization, rather than reconstruction, of deteriorated areas) and reinstallation of the segments indoors.

Grignolo, Roberta. 2015. "The Couvent de La Tourette from 1960 to the Present Day: Future Discernibility of Past Interventions." *DOCOMOMO Journal*, no. 53, 64–73. https://doi.org/10.52200/53.A.1IG880RF.

This paper presents a critical analysis of interventions on Couvent de La Tourette (1953–60) by Le Corbusier in Éveux, France, and their discernibility. Until 1964, interventions were overseen by Le Corbusier's collaborator F. Gardien, and the first one included repairs to the rooftop. Other interventions, such as additional repair work on the rooftop parapet cracks, were undertaken in the period before the complex was listed in 1979, but limited documentation is available. Then came a restoration campaign led by J.-G. Mortamet, whose approach was based on the completion of Le Corbusier's work, following his original drawings, in which new insulation layers were installed on the rooftop, raising the floor level by more than forty centimeters. The most recent campaign (2006–13) was overseen by D. Repellin, who aimed at returning the building to its original state and found clever solutions to comply with current standards, especially for fire safety. In this intervention, the original roof level was restored and the entire glazing system, in a serious state of disrepair, was replaced. The author advocates for better cooperation between the French Ministry of Culture, which holds legal responsibility for the site's protection, and the Le Corbusier Foundation, as heir to Le Corbusier's copyrights, which includes all the buildings he designed.

Hamada, Keizo. 2015. "Efforts to Improve the Earthquake Resistance of the Kagawa Prefectural Government Office East Building." *DOCOMOMO Journal*, no. 52, 72–79. https://doi.org/10.52200/52.A.BDI24625.

The Kagawa Prefectural Government Office East Building, designed by Kenzo Tange and completed in 1958, is recognized as culturally valuable for being a masterwork in the use of public spaces, cooperation with artists, and expression of traditional Japanese architectural ideas. Since it has been designated a disaster-prevention base facility, the building is required to comply with strict earthquake resistance standards. The Kagawa Prefecture, in order to evaluate different seismic retrofitting strategies, formed a special committee that included experts on earthquake engineering, the history of design and architecture, culture, economics, and mass communications. Different possibilities were discussed and compared, including reconstruction, seismic isolation retrofitting, and seismic strengthening. Considering the building's function, its cultural value, and the costs involved, the chosen approach was to preserve the building and improve its earthquake resistance through base isolation retrofitting methods. This method ensures the desired seismic resistance, avoids dividing the office spaces with anti-seismic walls, incurs a smaller life-cycle cost than the reconstruction proposal, does not require temporary offices during construction, does not alter the inner or outer appearance of the building, and produces the lowest level of disturbance, noise, and waste during construction.

Harrer, Ann, Paul Gaudette, and Deborah Slaton. 2020. "Approach to Preservation of Historic Concrete." *Concrete Repair Bulletin* 33 (2): 12–17. https://cdn.ymaws.com/icri.site-ym.com/resource/resmgr/crb/2020marapr/ICRI-CRB-Mar-Apr2020-web.pdf#page=14.

This paper describes the main issues to be considered and steps to be undertaken in the conservation of cultural heritage built in concrete, from historic analysis and assessment procedures to the selection of a conservation approach and repair implementation. After mentioning the primary causes of deterioration and other influencing factors, the text briefly introduces the history and development of reinforced concrete. The authors then proceed to describe the phases of the conservation process. The first step includes assessment of the significance of the artifact, including the way concrete is employed, and the collection of information about previous uses and repairs. This step also includes a visual survey aimed at comparing the as-built object with historical information, and the analysis of placement techniques, finishing procedures, construction deficiencies, deterioration, and defects. Operational information is given about types of nondestructive testing, inspection openings, and removal of samples for laboratory analysis. The second step, the definition of a conservation approach, should take into consideration the owner's project goals while solving deterioration problems and preserving the historic fabric with durable solutions. In the third and last step, the authors describe operational aspects regarding trials and mock-ups, which are considered indispensable to verifying and refining the conservation approach before the repair implementation. Finally, the authors highlight the importance of maintaining a high level of craftsmanship and quality control during implementation of repairs.

Heinemann, Herdis A. 2013. "Historic Concrete: From Concrete Repair to Concrete Conservation." PhD diss., Technische Universiteit Delft.

This PhD dissertation aims to achieve a dedicated conservation strategy for historic concrete and aid the field's transition from concrete repair to concrete conservation. The author asks three main research questions: How can historic concrete be preserved with its ascribed heritage values? How can a proposed conservation strategy be evaluated for its impact on values and technical performance? And how to balance technical demands with the preservation of heritage values when heritage values and durability issues originate in the same material properties? The dissertation is organized in three sections. Part 1, "Understanding and Characterization of Historic Concrete," provides a history of concrete in the Netherlands and in-depth description of constituent materials of historic concretes and their influence on concrete durability. Part 2, "Interpretation and Evaluation of Historic Concrete," explores relationships between heritage values, historic concrete, and the state of conservation using three case studies in the Netherlands. This part also discusses the potential impact of repairs and treatments on durability and heritage values. Part 3, "Development and Evaluation of a Dedicated Conservation Strategy," outlines the development of conservation goals and defines criteria for a conservation strategy. The text concludes by stating that no known repair techniques can guarantee the perpetual service life of historic concrete. Each concrete building should be approached with the best possible repair that will extend its service life while protecting its material and cultural values. All treatments must be trialed, and a conservation ethic must be applied to concrete buildings.

Heinemann, Herdis A., Rob P. J. van Hees, and Timo G. Nijland. 2008. "Concrete: Too Young for Conservation?." In *Structural Analysis of Historic Constructions: Proceedings of the VI International Conference on Structural Analysis of Historical Constructions, SAHC08, 2–4 July 2008, Bath, United Kingdom*, edited by Dina D'Ayala and Enrico Fodde, 151–59. London: Taylor and Francis.

This paper presents the case study of Fort Bezuiden Spaarndam, part of the Defense Line of Amsterdam UNESCO World Heritage Site. In 1996, the same year that its World Heritage designation was received, a three-year conservation project began. This paper is an evaluation of the works undertaken. It breaks down each phase and identifies where things could have been approached differently. The main failing seems to be that the work was undertaken with a repair (rather than a conservation) approach that did not consider the heritage values of the structure; the concrete was primarily understood as structural, not historic. The authors note that the general lack of expertise in the conservation of historic concrete must be addressed.

Heinemann, Herdis A., Hanna Zijlstra, Rob P. J. van Hees, and Timo G. Nijland. 2012. "From Concrete Repair to Concrete Conservation: How to Preserve the Heritage Values of Historic Concrete." In *Concrete Solutions: Proceedings of Concrete Solutions, 4th International Conference on Concrete Repair, Dresden, Germany, 26–28 September 2011*, edited by Michael Grantham, Viktor Mechtcherine, and Ulrich Schneck, 55–67. Boca Raton, FL: CRC Press.

This paper is a detailed and comprehensive review of the differences between concrete conservation and concrete repair. It includes sections on the properties of historic concrete, durability and threats, and concrete conservation. Dilemmas and possible solutions are explored in two Dutch case studies. Rather than focusing on specific methodologies for the conservation of concrete, the paper discusses the philosophical considerations that should be part of any concrete conservation project. The gaps between repair and conservation are clearly defined, one of the most important of these being the aim of concrete conservation to preserve the heritage values of a building or structure, which is not a consideration in concrete repair. One of the key obstacles highlighted is the limited number of experts in this field—not only those who consider and understand the conservation of the material, but also those versed in "the related disciplines, such as construction history, conservation philosophy, concrete durability and concrete repair" (p. 66).

Hinz, Elisabeth, and Andreas W. Putz. 2024. "Two Looks Back to Move Forward: Today's Evaluation of Opposite Approaches of Concrete Repair in Heritage Preservation." In *Structural Analysis of Historical Constructions SAHC 2023*, edited by Yohei Endo and Toshikazu Hanazato, 824–37. RILEM Bookseries 46. Cham, Switzerland: Springer. https://doi.org/10.1007/978-3-031-39450-8_67.

This paper compares two approaches to concrete heritage conservation adopted in German-speaking countries since the 1980s, which are opposed in terms of conservation of original material and visual appearance, and also differ in terms of reparability, reversibility, and monitoring. The cases at hand are the Antoniuskirche in Basel, Switzerland (repair 1987–91) and the Liederhalle in Stuttgart, Germany (repair 1991–93). The first was considered an exemplary case for matching the original surface appearance with full surface re-cast of certain areas and replacement of precast elements; the second was acknowledged as a best-practice example for minimal repair intervention. After about thirty years, in light of the contemporary debate on this topic, the authors reevaluated these two cases with regard to long-term performance and the appropriateness and suitability of the approaches. The paper presents innovative methods of photographic survey and color measurement aimed at the examination of repaired concrete surfaces, which are deemed useful for their future assessment, monitoring, and for decision making. This research study was developed within the research project entitled "How to Deal with Historic Concrete Repairs? Evaluating and Managing Past Repairs to Exposed Concrete Buildings from the High Modern Period" funded by the German Research Foundation and developed at the Technical University of Munich's School of Engineering and Design, Professorship of Recent Building Heritage Conservation.

Jerome, Pamela. 2013. "Conserving Frank Lloyd Wright's Solomon R. Guggenheim Museum." *Historic Environment* 25 (1): 62–70. https://australia.icomos.org/wp-content/uploads/Conserving-Frank-Lloyd-Wrights-Solomon-R.-Guggenheim-Museum-vol-25-no-1.pdf.

The author describes the process for establishing the conservation approach for the first comprehensive exterior restoration of the Guggenheim Museum in New York, and the results of this work, completed in 2008. Conservation works included concrete repairs, repainting, structural reinforcement, skylight and window replacement, and mechanical upgrades. Brief notes on the building's history and its structural characteristics provide the background for intervention choices and the decision-making process that led the project team to them. Direct references to key figures and documents in the conservation field, such as the Venice Charter, allow the reader to comprehend the theoretical premises that were brought to define "a progressive authenticity approach, retaining changes that have occurred over time so that a building reads as a timeline of its history" (p. 66), following principles of minimum intervention and maximum reversibility. Investigations included archival research, crack mapping, paint samples, shotcrete samples and mock-ups, structural and environmental monitoring, laser scanning, nondestructive tests, and exploratory probes. Interventions included structural reinforcement of the sixth-floor ramp walls with carbon-fiber-reinforced polymer applied to the interior surface, concrete repair leaving evidence of the original workmanship, and painting with the original color (a buff light yellow). The two latter choices divided the preservation community.

Joshi, Kiran, ed. 2005. *Corbusier's Concrete: Challenges of Conserving Modern Heritage*. Chandigarh, India: Chandigarh Perspectives.

This book contains the proceedings of the seminar "Conservation of Le Corbusier's Work in Concrete," which took place in Chandigarh, India, in 2002. A small, invited group was present. Discussions focused on the conservation of exposed concrete modern heritage and a possible future liaison between the Chandigarh Administration and the Le Corbusier Foundation. The book includes an introduction to the use of reinforced concrete, and to Le Corbusier's use of this material, particularly in the context of Chandigarh. Eight papers are reproduced, along with transcripts of the discussions that followed their presentation during the seminar. The specific paper topics include an introduction to Le Corbusier's work in Chandigarh and restoration work completed; discussion and assessment of the restoration work undertaken at two of Le Corbusier's buildings in France and two in Ahmedabad; a detailed look at concrete production, composition, deterioration, and repair principles; a discussion of a specific process for inhibiting corrosion using a monofluorophosphate-based system; and a discussion of Le Corbusier's use of concrete and his philosophical approach to the material and his designs.

Macdonald, Susan. 1997. "Authenticity Is More Than Skin Deep: Conserving Britain's Postwar Concrete Architecture." *APT Bulletin: Journal of Preservation Technology* 28 (4): 37–44. https://doi.org/10.2307/1504592.

This article focuses on the conservation of Britain's postwar concrete architectural heritage. Of the building materials and systems that came into use in Britain in the twentieth century, reinforced concrete was the most widespread and poses some of the most urgent conservation problems. The author addresses the history and technical development of postwar concrete as well as the physical, philosophical, and aesthetic challenges of its conservation. The article illustrates the importance of challenging technical barriers while also acknowledging the need to retain authenticity. Examples of material and physical failures are given, and the reconciliation of authenticity with repair is emphasized. A great challenge to the practicing conservator is that the concrete surface is inextricably linked to the conceptual and structural intent of the designer, as well as the detail of the structure; in other words, material and aesthetic authenticity are interwoven. The only method of securing a future for these works is to determine the most appropriate repair, following the same approach as is used on any other heritage building. Case studies illustrate various problems and solutions.

Macdonald, Susan, and New South Wales Heritage Office. 2003. *The Investigation and Repair of Historic Concrete*. Parramatta, Australia: NSW Heritage Office. https://www.environment.nsw.gov.au/-/media/OEH/Corporate-Site/Documents/Heritage/investigation-repair-historic-concrete-0303.pdf.

See annotation on p. 57.

Mändel, Maris, and Karl Õiger. 2016. "Conservation of Tallinn Seaplane Hangars." *Proceedings of the ICE – Engineering History and Heritage* 169 (1): 3–10. https://doi.org/10.1680/jenhh.15.00011.

The paper focuses on the conservation process for the seaplane hangars in Tallinn, Estonia, built in 1916–17. The roof shells, which are among the first and still-existing examples of large reinforced concrete shells in the world, are composed of three semispherical shells 36.4 meters in diameter and seven cylindrical shells adjacent to them measuring 36.4 by 6.8 meters. The whole structure is carried by twenty-four columns and twelve angled braces. An overview of the building history and original documentation analysis helps to underline the uniqueness of the Tallinn seaplane hangars in construction history. During the twentieth century, lack of maintenance and rainwater caused extensive spalling of the concrete, corrosion of reinforcements, cracks, and deformations of the shells. Some first repair works, undertaken in 2001, included the reinforcement of deformed areas, stitching and injection of cracks, and installation of a roof cover. Then between 2010 and 2012, the hangars underwent a full conservation process to be reused as the new Estonian Maritime Museum. In 2013, the conservation work received the Europa Nostra Grand Prix award due to its high quality. The paper provides a comprehensive overview of the conservation process and approach, combining the engineering and heritage protection perspectives.

Matthews, Stuart, and Agnieszka Bigaj-van Vliet. 2013. "Conservation of Concrete Structures According to *fib* Model Code 2010." *Structural Concrete* 14 (4): 362–77. https://doi.org/10.1002/suco.201300046.

This paper focuses on chapter 9 of the International Federation for Structural Concrete (*fib*)'s Model Code for Concrete Structures 2010, which is dedicated to conservation of concrete structures (chapter 8 in the 2020 edition), addressing conservation strategies, conservation management, condition surveys, condition assessment, condition evaluation and decision making, interventions, and the recording of information for through-life management. This chapter clearly adopts the overall philosophy of fib Model Code 2010, which introduces a new integrated life cycle perspective into the design of concrete structures. Different condition control categories are defined depending on factors such as the importance of the structure, its function, design service life, impact on third parties, environmental conditions, ease of maintenance, and cost. A through-life management process provides feedback for service life design and allows the associated theoretical model employed to be updated, in turn facilitating the assessment of compliance with the original design objectives. An example of concrete structure conservation according to the fib Model Code 2010 concept is also presented.

Meurs, Paul, and Maria Theresia van Thoor, eds. 2010. *Sanatorium Zonnestraal: History and Restoration of a Modern Monument*. Rotterdam: NAi.

This book comprehensively overviews the conservation process of the Sanatorium Zonnestraal in Hilversum, the Netherlands, designed in 1926 by the architects Jan Duiker and Bernard Bijvoet with the collaboration of engineer Jan Gerko Wiebenga. The restoration project was developed by the architects Hubert-Jan Henket and Wessel de Jonge. The volume describes the origins of the commission to Duiker, the struggle for recognition of Zonnestraal's cultural value, and the social debate about the renovation. It details the conservation approach and interventions, including architectural, technical, landscape, and management aspects. The conservation of Sanatorium Zonnestraal is an important reference in the field for its careful balancing of conservation and change. The numerous illustrations include historical drawings, sketches, and photographs that describe the different stages the Zonnestraal has undergone, from its original use, to its abandonment, to its current appearance after the conservation process.

Paupério, Esmeralda, Xavier Romão, Rui Silva, and Susana Moreira. 2024. "Challenges in the Preventive Maintenance of Early 20th-Century Reinforced Concrete Architectural Sculptures." In *Structural Analysis of Historical Constructions SAHC 2023*, edited by Yohei Endo and Toshikazu Hanazato, 1242–55. RILEM Bookseries 46. Cham, Switzerland: Springer. https://doi.org/10.1007/978-3-031-39450-8_101.

The authors of this paper propose a two-step approach to conservation of sculptural elements in concrete, balancing the constraints that must be considered to safeguard the cultural value of concrete heritage artifacts with constraints related to safety, durability, and budget. The proposed approach is illustrated with the case study of the São João National Theatre in Porto, Portugal, which during the early 2000s began to exhibit severe deterioration linked to weathering, loss of pieces of mortar, and corrosion of steel reinforcement. The first step in the proposed approach consists of determining an intervention index for each case. This index is based on seven qualitative and quantitative criteria graded according to the characteristics of the cultural heritage element under analysis. The second step aims to prioritize maintenance actions by assigning an indicator based on the significance of facades (how many decorative elements are present) and the extent of deterioration observed. Detailed considerations are included about the advantages that might come from implementing the proposed procedure to develop a sustainable conservation plan. The analyzed case study had a total number of 170 and 193 conservation interventions carried out in 2019 and 2022, respectively. A preliminary analysis of the maintenance indicators confirmed the adequacy of the interventions carried out in 2019, while a clear decrease is shown by some types of interventions in 2022.

Piffaretti, Paola, and Giacinta Jean, ed. 2018. *Conservazione del calcestruzzo a vista: dal minimo intervento alla ricostruzione: analisi di casi studio = Conservation of Fair-Faced Concrete: From Minimum Intervention to Reconstruction: Examination of Case Studies*. Atlanti della conservazione. Florence: Nardini editore.

This book presents a selection of executed conservation projects on buildings in northern Italy and Switzerland characterized by architectural concrete: Antoniuskirche in Basel; the Church of St. Josef am Maihof in Lucerne; the Giardini of the Venice Biennale; the University of St. Gallen; Brunnmatt school in Basel; Heiligkreuzkirche in Chur; Church of the Conversion of St. Paul at Azzano San Paolo; and the Middle School of Morbio Inferiore. The collection of these case studies is part of the research project Critical Encyclopaedia of Restoration and Reuse of Twentieth-Century Architecture (2009–12), developed by the Architecture Academy of Università della Svizzera Italiana, the Lausanne Polytechnic, the Zurich Polytechnic, and the Istituto Materiali e Costruzioni of Scuola Universitaria Professionale della Svizzera Italiana in Lugano. The goal of this publication is to provide professionals who work with twentieth-century concrete heritage with background information that can be helpful in decision making. It describes how the various steps of the project led to the development of conservation strategies that were considered appropriate in each context to conserve the aesthetic value of the concrete. Each case study illustrates a different challenge, various levels of intervention, and various levels of success. The description of each includes basic background information, scope of work for the project, deterioration, preliminary diagnostic, intervention, and conclusions. Description of the intervention phase includes issues faced and, if the intervention was concluded at the time of analysis, observations on performance and maintenance. The repair techniques and materials described often rely more on proprietary mortars, coatings, and aggressive replacement of original materials than would be appropriate conservation solutions in many cases. It is also worth observing that the book includes a chapter by Eugen Brühwiler that contains a definition of "noninvasive intervention" that is contrary to what the conservation field commonly adopts. This book is in Italian and English.

Prudon, Theodore H. M. 1981. "Confronting Concrete Realities." *Progressive Architecture* 62 (11): 131–37.

See annotation on p. 22.

Reed, Peter, Kate Schoonees, and Jeremy Salmond. 2008. *Historic Concrete Structures in New Zealand: Overview, Maintenance and Management*. Wellington, NZ: Science & Technical Pub., Dept. of Conservation. https://www.doc.govt.nz/globalassets/documents/science-and-technical/sap248entire.pdf.

This handbook for the maintenance and management of historic concrete structures in New Zealand is intended to support decision making by those responsible for their administration, care, and maintenance. Considering that early concrete structures form an important part of New Zealand's national cultural heritage, the handbook starts with a description of the historical development and properties of concrete in that country, from its early use as a building material up to the 1940s. It then identifies the causes and types of defects and deterioration in concrete and provides a set of investigation procedures and conservation strategies for conservation and repair. The volume is organized in the following chapters: "History of Concrete," "Concrete Components and Mixes," "Properties of Concrete," "Causes of Defects and Deterioration in Historic Concrete," "Types of Defects and Deterioration in Historic Concrete," "Investigation and Evaluation of Historic Concrete," "Repairs to Defective and Deteriorating Concrete," "Conservation Strategies," and "Field Guidelines." It concludes with a list of references, additional readings, a glossary of technical terms, and a case study illustrating all phases, from analysis to recommended repair strategies.

Schrag, Zachary M. 2022. "'Things That Should Look Permanent Forever': The Challenges of Preserving the Washington Metro." *APT Bulletin: Journal of Preservation Technology* 53 (1): 19–28. https://www.jstor.org/stable/48680409.

This paper presents the interesting case of the Washington Metro, starting from an intervention that coated the monumental concrete vaults with white paint in 2017, which raised a strong wave of criticism for interfering with the character of the stations while creating an additional maintenance requirement. The Metro is appreciated for being simultaneously a work of architecture, civil engineering, mechanical engineering, city planning, and even graphic design. Since the opening of its first station, it has been recognized as a symbol of Washington, DC. Its stations are characterized by spacious train rooms, indirect lighting, consistency across the stations, and a distinct palette of materials. Concrete was used as "basic material," with bronze and granite as "foreground material" for the elements that riders would touch. The author, while reflecting on the several interventions that the Metro has undergone over the decades (including changes in color palette and the installation of canopies), shows very clearly the challenge to carefully combine preservation with innovation in a large-scale complex infrastructure that is also recognized as architecturally significant.

Simpson, Lorne, Paul Gaudette, and Deborah Slaton. 2001. "Centre Street Bridge Lions: Rehabilitation and Replication of Historic Concrete Sculpture." *APT Bulletin: Journal of Preservation Technology* 32 (2–3): 13–20. https://doi.org/10.2307/1504734.

This article addresses the history and decision making behind the conservation of the four cast concrete lions on the Centre Street Bridge in Calgary, Canada. Each lion sits atop a kiosk at a corner of the bridge, which was constructed circa 1915. Investigation works to assess the condition of the lions and identify the mode of construction and the materials used began in 1999. Each lion was found to have been cast in five pieces, then put together following masonry techniques with mortar construction joints. Each section was reinforced, but with no structural reinforcement or frame to link the pieces. The concrete was found to be composed of two layers: an inner porous concrete composed of a fine aggregate and low cement content, and a thin, dense outer layer. The article discusses at some length repairs undertaken in the 1970s and 1980s. The lions were found to be in poor condition, with high levels of cracking, delamination, and corrosion of the reinforcement. This was attributed to environmental conditions, high porosity, and unsuccessful previous interventions. The article details the conservation trials and the six different conservation approaches considered. Ultimately, it was decided that the condition of the lions was too poor for any of them to remain in place. The process of taking a rubber mold of the best one and creating four replicas is described. Three of the original lions were restored and are on display elsewhere. The fourth lion was in very poor condition and is being retained for research purposes. Conservation works included full documentation, removal of surface coatings, and application of a new facing mortar to redefine lost details using materials developed to match the original concrete.

Ueda, Tamon, and Koji Takewaka. 2007. "Performance-Based Standard Specifications for Maintenance and Repair of Concrete Structures in Japan." *Structural Engineering International* 17 (4): 359–66. https://doi.org/10.2749/101686607782359119.

This paper introduces the Japan Society of Civil Engineers (JSCE) Standard Specifications for Concrete Structures–2001 "Maintenance," the first comprehensive code for maintenance and repair of concrete structures. The standard uses a performance-based approach and defines performance according to the following criteria: safety; serviceability, including prevention of hazard to third parties and preservation of aesthetic appearance/landscape; maintainability, including restorability; constructability; environmental friendliness; and cost effectiveness. The standard is divided into two parts. Part 1, "Maintenance," includes required performance, basic principles for maintenance, inspection, identification of deterioration mechanism, evaluation of structural performance, and remedial measures, together with a flowchart outlining the overall maintenance activities, from initial inspection to execution of remedial measures. Part 2, "Standards for Maintenance," provides information on deterioration prediction, inspection methods, evaluation, and remedial measures for different deterioration mechanisms. Finally, the paper includes some application examples illustrating maintenance plans for the superstructure of an open-type wharf.

Vaysburd, Alexander M., and Benoit Bissonnette. 2021. "The Battle for Survival of Our Concrete Infrastructure." *Concrete International* 43 (9): 33–37.

This paper focuses on the condition evaluation process for existing concrete structures as well as on durability planning, repair design issues, and project specifications. Durability issues considered include the function and type of structure, performance requirements, loads, environmental effects, internal conditions, overall design approach, and evaluation of alternative solutions. In relation to each of these issues, a series of factors are listed, including the client's needs, acceptable technical performance, serviceability and safety criteria, continuity of function during repair, desirable service life, costs, and known experience of performance. A useful flowchart of concrete repair design is provided. The authors ultimately underline the need for an integrated and multidisciplinary approach, which includes structural design, durability and service life design, and consideration of sustainability issues. They stress the key role of the design phase of the repair project (including condition evaluation, detailed design, and development of specifications) on the future performance of the structure.

Wiggin, Vanessa Roth, and Seth Wiggin. 2007. “Set in Concrete? Conservation of Howard Taylor’s ‘The Black Stump.’” In *Contemporary Collections: Preprints from the AICCM National Conference 17th–19th October 2007, Brisbane*, edited by Amanda Pagliarino and Gillian Osmond, 25–30. Canberra: Australian Institute for the Conservation of Cultural Material.

See annotation on p. 109.

Wright, Alan, and Peter Kendall. 2008. “The Listening Mirrors: A Conservation Approach to Concrete Repair Techniques.” *Journal of Architectural Conservation* 14 (1): 33–54. https://doi.org/10.1080/13556207.2008.10785015.

This article examines conservation and stabilization efforts on three surviving listening mirrors constructed during the interwar period in Kent, England. The conservation study was one of the largest projects funded by the Aggregates Levy Sustainability Fund and was guided by English Heritage. The aim was to analyze conditions and investigate conservation options for the remotely located mirrors to ensure long-term stability. The team assessed three approaches: do nothing; stabilize by completing the most urgent repairs; and a complete restoration. They chose stabilization. In addition, the site was used to test the application of the most current methods of concrete repair and treatments. The methods tested included patch repairs with concrete developed to be as close as possible to the original and poured with matching form finish; four invisible corrosion inhibitor coatings from different manufacturers applied on the concrete surface; and sacrificial anode cathodic protection. The patch repairs were well matched, and different finishing techniques were tested to approach the weathered condition of the original concrete. The trials established that corrosion inhibitors were ineffective, but further investigation was recommended. The cathodic protection trial was effective, but installation was difficult and expensive. The study concludes that thought and care are required in the detailing of all repairs for historic concrete, and that maintenance requirements should be considered.

CHAPTER 5

# REPAIR AND TREATMENTS

## Key References

American Concrete Institute. 2014. *Guide to Concrete Repair: Reported by ACI Committee 546*. ACI 546R-14. Farmington Hills, MI: American Concrete Institute.

This comprehensive guide to concrete repair was produced by the American Concrete Institute. Chapter 1 outlines the steps of a repair methodology, including notes on condition evaluation, selecting repair methods and materials, and maintenance after completion of the repairs. This chapter also discusses design considerations such as material compatibility, feasibility, necessary considerations during the repair process, and the subsequent use of the building. Chapter 2 addresses concrete removal and the importance of surface preparation, and summarizes repair methods available and the features of each method as well as special considerations or limitations. The section on repair techniques includes discussion of the steps required for the repair of reinforcements, anchorage methods and materials, various techniques for placing materials, and bonding methods. Chapter 3, on repair materials, is divided into cementitious materials and polymer materials. Additional sections in this chapter cover bonding materials and coatings on reinforcement. The section on material selection looks at the importance of selecting a material compatible with the original in terms of coefficient of thermal expansion, permeability, color, and texture. Chapter 4 deals with protective systems for concrete, with a focus on corrosion prevention. Surface treatments are dealt with in some detail; the main types, requirements, and characteristics are identified, along with the appropriate standards for testing these treatment systems. This section also discusses joint sealants, cathodic protection, chloride extraction, and re-alkalization. The final chapter discusses strengthening techniques for a variety of structural components as an alternative to replacement. An earlier version is included in Mark E. Hughes and Carl R. Bischof, eds., *Concrete Repair Manual* (2013, see annotation on p. 100).

Bouichou, Myriam, and Élisabeth Marie-Victoire. 2021. *Cleaning Historic Concrete: A Guide to Techniques and Decision-Making*. Guidelines. Los Angeles: Getty Conservation Institute. http://hdl.handle.net/10020/gci_pubs_cleaning_historic_concrete.

This manual presents the results of two research projects that aimed to guide the selection of cleaning techniques for historic concrete. The first one (1996–2000) focused on cleaning mineral soiling on facades and outdoor sculptures, aiming to compare the most commonly used techniques for cleaning outdoor concrete with the gentler methods typically used in stone conservation. The second (2006–9) focused on interiors and on removing outdoor biological growth. These projects were developed by Le Cercle des Partenaires du Patrimoine. Section 1 of this technical manual describes the types of soiling encountered on concrete monuments. Section 2 describes the different techniques available for cleaning concrete. Section 3 reports on results from cleaning tests on the Maison du Brésil, the church of Saint-Esprit, and the church of Sainte-Odile, all located in Paris, and the Centre Jeanne Hachette in Ivry-sur-Seine. Sections 4 and 5 include decision trees and summary sheets describing the testing techniques, aiming to guide conservators and contractors in selecting the best cleaning procedures depending on the situation. This guide was originally published in French as Myriam Bouichou and Élisabeth Marie-Victoire, *Le nettoyage des bétons anciens: Guide des techniques et aide à la décision*, Les cahiers techniques du Cercle des Partenaires du Patrimoine 4 (Champs-Sur-Marne, France: Cercle des Partenaires du Patrimoine, 2009).

Broomfield, John P. 2007. *Corrosion of Steel in Concrete: Understanding, Investigation and Repair*. 2nd ed. London: Taylor and Francis.

See annotation on p. 27.

Croft, Catherine, Susan Macdonald, and Gail Ostergren, eds. 2018. *Concrete: Case Studies in Conservation Practice*. Los Angeles: Getty Conservation Institute.

See annotation on p. 69.

Grantham, Michael, ed. 2011. *Concrete Repair: A Practical Guide*. London: Routledge / Taylor and Francis.

This is a critical book for those working in concrete repair and wanting to learn more about durability. Chapter 1 offers a comprehensive overview of concrete deterioration and the different evaluation and testing techniques that can be used in diagnosing the causes of deterioration. Chapter 2 describes petrographic analysis of concrete and how it can be used to assess deterioration and repair issues. Chapter 3 focuses on structural repairs—requirements, challenges, and the repair process. Chapters 4 to 6 are dedicated to cathodic protection, with impressed current cathodic protection and sacrificial anode cathodic protection described in detail, including advantages and limitations. Chapter 6 covers the deterioration and component failures that can affect a cathodic protection system, which is essential information in setting up monitoring and maintenance protocols for these systems; it also reports on the durability of fifty-two systems installed in the Netherlands. Chapter 7 focuses on monitoring reinforcement corrosion, mainly through the embedding of sensors in the concrete. Chapter 8 covers electrochemical chloride extraction and explains the factors influencing the success of application, including the conditions of the concrete. Chapter 9 presents a basic explanation of electrochemical realkalization. Chapter 10 covers the two types of corrosion inhibitors: those that are mixed into fresh concrete for either new construction or repair, and those that are applied on the surface and migrate into the concrete, which usually requires the application of a coating. The author warns of the challenges in achieving a good application of the latter. Chapter 11 provides an overview of European Standards for concrete repair, mainly EN 1504. Chapter 12 discusses concrete repair from a contractor's perspective, including information on how to quantify, tender, and bid the work. Chapter 13 focuses on sprayed concrete (shotcrete) in repairs, which is less common in historic buildings unless that technique was used in the original construction. Chapter 14 summarizes the outcome of CONREPNET, a European research project that investigated durability of concrete repairs with the goal of developing a performance-based rehabilitation approach for reinforced concrete. This chapter reports on findings from 230 case studies of concrete repairs carried out in Europe, identifying original deterioration, repair techniques, performance after at least five years since installation, and repair failures. Chapter 15 explains service life models for chloride-induced corrosion and discusses probabilistic performance-based predictive models. Chapter 16 covers fiber-reinforced polymers (glass, carbon fiber, and aramid) in external structural reinforcement systems. And, finally, chapter 17 introduces coatings, which could be materials that impregnate the concrete either by lining pores or blocking them, or systems that form a continuous layer over the concrete surface.

Odgers, David, ed. 2012. *Practical Building Conservation: Concrete*. Farnham, UK: English Heritage / Ashgate.

See annotation on p. 70.

## General References

Akhurst, Paul, Susan Macdonald, and Trevor Waters. 2005. "Sydney Opera House: Analysis and Cleaning of the Concrete." *Journal of Architectural Conservation* 11 (3): 45–64. https://doi.org/10.1080/13556207.2005.10784952.

This article examines cleaning and conservation work undertaken on the folded concrete beams of the Sydney Opera House. The beams are of exceptional significance to the building, as they are important structural and design elements. This work is discussed in the context of two policy documents: "Sydney Opera House: A Plan for the Conservation of the Sydney Opera House and Its Site" (3rd ed., 2003) and "Sydney Opera House Utzon Design Principles" (2002). This article describes the investigative and analytical work undertaken to develop a sympathetic conservation approach for these elements. A multidimensional understanding of the visible defects and deterioration was developed through on-site investigation and analysis, archival research, and discussions with people closely connected to the building and its construction. This approach allowed the team to identify several inherent defects dating to the time of construction, such as the presence of efflorescence and staining. Following the initial research, the team trialed various cleaning techniques and adopted a low-pressure cleaning system that removes disfiguring and unwanted surface deposits, and at the same time results in the deposition of calcium carbonate, the combination of which has been found to even out the surface staining.

Albani, Francesca. 2016. "The Durability of Restoration of Exposed Concrete: Case Histories Compared." In *First International Workshop on Durability and Sustainability of Concrete Structures: Bologna, Italy, 1–3 October 2015*, edited by Mario Alberto Chiorino, Luigi Coppola, Claudio Mazzotti, Roberto Realfonzo, and Paolo Riva, 3.1–3.10. ACI Special Publication 305. Farmington Hills, MI: American Concrete Institute. https://doi.org/10.14359/51688563.

See annotation on p. 71.

Australian Concrete Repair Association (ACRA), Commonwealth Scientific and Industrial Research Organisation (CSIRO), and Standards Australia. 2006. *Guide to Concrete Repair and Protection*. 2nd ed. SAA HB 84-2006. Sydney: ACRA / CSIRO / Standards Australia.

This guide to concrete repair and protection is directed at a diverse range of people concerned with the maintenance, repair, and protection of concrete structures. It is intended as an overview of industry practices and methods, not as a standard. Seven chapters cover the following topics: concrete properties, causes of concrete deterioration, formation and types of cracks, inspection techniques, protective and remedial systems, repair practices, and case studies. The three appendices cover repair strategies for carbonation-induced steel corrosion, chloride-induced steel corrosion, and cracks. All topics are briefly introduced and described. Key information is provided using clear and simple illustrations in the form of tables, charts, and diagrams. Each of the six case studies in the final chapter examines a different type of concrete structure and details background information, investigations undertaken, repair specifications, and repairs completed.

Ayón, Angel. 2009. "The Guggenheim at Fifty: Notes on Recent Preservation Work." *DOCOMOMO Journal*, no. 41, 73–79.

See annotation on p. 44.

Bertolini, Luca, Maddalena Carsana, and Elena Redaelli. 2008. "Conservation of Historical Reinforced Concrete Structures Damaged by Carbonation Induced Corrosion by Means of Electrochemical Realkalisation." *Journal of Cultural Heritage* 9 (4): 376–85. https://doi.org/10.1016/j.culher.2008.01.006.

This article addresses the use of realkalization on eight reinforced concrete columns supporting the cupola of the bell tower at the church of Sant'Antonio Abate in Valmadrera, Italy (1926–30). A thorough technical description of realkalization is provided, followed by an investigation into the conditions that affect corrosion. Repair limitations are highlighted: performing full replacement of carbonated concrete on these columns was deemed impractical due to the extensive area affected, and removal of contaminated concrete would have undermined the columns' structural stability. After the condition assessment, a realkalization trial was installed and run to establish design parameters for all eight columns. Upon completion of the trial, testing of alkalinity at the steel and various depths of the concrete was performed. It was determined that the alkalinity reached deep enough to protect the steel. The results were successful in providing an extension of service life. This project illustrates best practices and acknowledges challenges in the field of conservation and concrete repair. Trials of electrochemical treatments should always be performed, and they are of particular importance on culturally significant buildings.

Bessling, Markus, Melanie Groh, Viola Koch, Michael Auras, Jeanette Orlowsky, and Bernhard Middendorf. 2022. "Repair and Protection of Existing Steel-Reinforced Concrete Structures with High-Strength, Textile-Reinforced Mortars." *Buildings* 12 (10): art. 1615. https://doi.org/10.3390/buildings12101615.

This paper describes a research study aimed at trialing a high-performance textile-reinforced mortar repair system in a case study: the transmission tower of the Berus broadcasting hall in Saarland, Germany. Textile-reinforced mortar combines the properties of high- and ultra-high-performance concrete and corrosion-free textile reinforcement made of carbon, alkali-resistant glass, or basalt fibers. The textiles, absorbing the tensile actions, are embedded in fine-grained concrete, which absorbs the compressive actions. This system, which can be applied for sealing cracks, local repair, and structural strengthening, presents the advantages of high durability, the potential for finely distributed crack development, and reduced thickness. In order to investigate the load-bearing behavior of the proposed system, high-performance twenty-millimeter-thick mortar slabs were produced and mechanically characterized, then the system was applied to seventy-millimeter-thick old concrete slabs. Both carbon and basalt fiber textiles were analyzed. In terms of load-bearing capacity, the carbon-fiber textiles were revealed to be superior to basalt fiber textiles, but no significant differences were observed for crack distribution, transverse tensile strength, or adhesion. Future research steps will concern workability on-site, durability, and color adaptation over time.

Bissonette, Benoît, Luc Courard, and Pierre Paquet. 2006. "Concrete Removal Techniques: Influence on Residual Cracking and Bond Strength." *Concrete International* 28 (12): 49–55.

This article documents a research project undertaken to assess the impact of a series of surface preparation techniques for patch repairs. Nine large concrete block specimens were produced with a standardized concrete mix on which the following surface preparation techniques were trialed: sandblasting, scarifying, high-pressure water jetting (hydrodemolition), and chipping using handheld breakers at three different weights followed by sandblasting. The surface textures and roughness produced by each method of surface preparation, the resulting surface and subsurface cracking, and the effect of these on the bond strength of a concrete patch repair were all documented. Concrete removal using handheld breakers was clearly shown to be the most deleterious technique, with the heavier breakers causing higher levels of surface cracking. Sandblasting and scarifying resulted in a low level of cracking, not enough to be considered harmful. The hydrodemolition technique used in the trials caused slightly higher levels of cracking than the previous three techniques, but far less than the breakers. Concrete patch repairs were applied to the prepared surfaces. Overall, the bond strength tests appeared to be directly related to the level of cracking that was recorded, with lower levels of surface cracking related to higher bond strengths. The conclusion is that sandblasting, scarifying, and hydrodemolition (at the levels of pressure and flow rate used in this research) are preferable to handheld breakers.

Blain, Catherine. 2016. "Living a Manifesto: The Second Life of EDF's Housing Towers in Ivry-sur-Seine (Atelier de Montrouge, 1963–67)." In *Adaptive Reuse: The Modern Movement Towards the Future, 14th International DOCOMOMO Conference Proceedings, 6–9 September 2016, Calouste Gulbenkian Foundation, Lisbon, Portugal*, edited by Ana Tostões and Zara Ferreira, 817–23. Lisbon: DOCOMOMO International.

See annotation on p. 72.

Bouichou, Myriam, Jean Ducasse-Lapeyrusse, Élisabeth Marie-Victoire, and Mirah Rakarabo. 2022. "Performance Evaluation of Patch Repairs on Historic Concrete Structures (PEPS): Preliminary Results from a Selection of French Case Studies." In *Concrete Solutions 2022: 8th International Conference on Concrete Repair, Durability & Technology*, edited by M. G. Grantham, M. Basheer, and R. Mangabhai, art. 04005. MATEC Web of Conferences 361. Les Ulis, France: EDF Sciences. https://doi.org/10.1051/matecconf/202236104005.

This paper presents preliminary results of the performance evaluation of patch repairs on three historic French concrete case studies. This work is part of the international research project Performance Evaluation of Patch Repairs on Historic Concrete Structures (PEPS). The three analyzed case studies are the Notre-Dame de la Consolation church in Le Raincy by Auguste Perret (1920–24), Maison Radieuse in Rezé by Le Corbusier (1955), and the Jaoul houses in Neuilly-sur-Seine by Le Corbusier (1953). The selected sites were repaired several decades ago, and they show different construction dates, concrete compositions, exposure conditions, repair materials, and application techniques. Such variability of key parameters makes the evaluation complex, but also crucial to meet the objectives of the project, which is to produce practical guidance for conserving historic concrete. At Notre-Dame de la Consolation, the overall durability of the patch repairs was found to be quite good, but the aesthetic matching was not fully achieved. At the Jaoul houses, a good aesthetic compatibility was evidenced, but with low mechanical performance for some patches. At the Rezé housing unit, aesthetic compatibility was not achieved, and corrosion was detected in the adjacent areas and at the interface with the original concrete, so the performance of this repair campaign was classified as poor.

Brocklebank, Ian. 2005. "Concrete, Carbonation, and Corrosion." *Journal of the Building Limes Forum* 12:35–45. https://www.buildinglimesforum.org.uk/wp-content/uploads/2023/02/2005-BLF-Journal-Vol-12.pdf#page=36.

This is an introduction to potential problems of deterioration in reinforced concrete, and some available repair solutions. The author addresses the issue that the field of reinforced concrete repair research is still relatively young. The draft European Standard DD ENV 1504–9, Products and Systems for the Protection and Repair of Concrete Structures. Definitions, Requirements, Quality Control and Evaluation of Conformity. General Principles for the use of Products and Systems (adopted in 2009) is discussed, highlighting the areas relevant to the conservation of historic buildings. It is noted that conservation philosophy was not taken into account in the preparation of the standard. Several reinforced concrete repair methods are discussed, including the application of anti-carbonation coatings, patch repair, electrochemical methods, impressed current cathodic protection, and realkalization, and each is assessed for its appropriateness in a conservation context. The author notes that in some cases, work undertaken in a conservation-appropriate manner may invalidate a manufacturer's standard guarantee.

Broomfield, John P. 2013. "Concrete Preservation Plan for Reinforced Concrete University Campus Buildings." In *Forensic Engineering: Informing the Future with Lessons from the Past: Proceedings of the Fifth International Conference on Forensic Engineering*, edited by John Carpenter, 401–13. London: Institution of Civil Engineers Publishing.

See annotation on p. 47.

Building Research Establishment. 2000. *Corrosion of Steel in Concrete: Protection and Remediation*. BRE Digest 444, part 3. Garston, UK: BRE.

This document is the third in a three-part series on corrosion of steel reinforcement in concrete, and covers the repair and preventive treatment options for reinforcement corrosion. It explains the method to develop a repair and remediation strategy based on a thorough diagnosis of the factors contributing to reinforcement corrosion, then proceeds to describe repair and protection methods based on principles 7 to 11 presented in EN-1504-9, the ones applicable to reinforcement corrosion. This includes restoring passivity (principle 7) with concrete patch repair, electrochemical realkalization, and electrochemical chloride extraction; increasing resistivity (principle 8), which involves methods to keep the concrete dry, such as application of a coating or hydrophobic impregnation; cathodic control (principle 9), which is dismissed as extremely difficult; cathodic protection (principle 10); and controlling anodic areas (principle 11), which includes corrosion inhibitors cast in the concrete or as coating on the reinforcement. Part 1 (see annotation on p. 31) focuses on describing the deterioration mechanism of corrosion in reinforced concrete and the factors that contribute to it, and part 2 (see annotation on p. 48) describes assessment techniques for and diagnosis of reinforcement corrosion.

Also included in Mark E. Hughes and Carl R. Bischof, eds., *Concrete Repair Manual* (2013, see annotation on p. 100).

Burovenko, V., and S. Shevchenko. 2003. "Protection, Repair and Strengthening of Concrete Constructions of Lighthouses." In *Concrete Solutions: 1st International Conference on Concrete Repair, St.-Malo, France, 15–17 July 2003*, edited by Michael Grantham, 847–53. London: GR Technologie Ltd.

This paper focuses on new scientific and technical developments in the field of concrete repair that provide alternative approaches to the protection, repair, and strengthening of lighthouses. Numerous reinforced concrete lighthouses were constructed over the past century, and the unique challenges and problems posed by their repair and rehabilitation are gaining urgency. Recent approaches by the authors take a holistic view of multiple factors: materials and construction elements, assessment and analysis of damage, preventive actions, repair solutions, selection of materials and equipment, skilled repair operations, and monitoring of structures post-repair. The paper describes causes and typical damages, and the repair choices that can provide the best durability from seawater impact. The paper also discusses technical challenges in mobilization and work platforms when the lighthouses are in the open sea. The key to a successful repair is a skilled team with in-depth knowledge of deterioration and durable repair options, and the experience necessary to choose the best solution while operating in extreme conditions, including potentially by helicopter.

Busse, Felix, Christa Heidrich, Markus Kleine, Christoph Sander, and Murat Ünal. 2015. "BEGLARES II Protection and Restoration of Monumental Concrete-Glazing with Cathodic Protection Systems." In *Le vitrail comment prendre soin d'un patrimoine fragile? 9e Forum sur la conservation et la technologie du vitrail. Paris, 8–10 juillet 2015 = Stained-Glass: How to Take Care of a Fragile Heritage? 9th Forum for the Conservation and Technology of Historic Stained-Glass, Paris, 8–10 July 2015*, edited by Claudine Loisel and Isabelle Pallot-Frossard, 83–90. Paris: International Council on Monuments and Sites, section française.

See annotation on p. 72.

Cailleux, Emmanuel, and Élisabeth Marie-Victoire. 2006. "Influence of the Concrete Composition on the Efficiency and the Durability of Realkalisation Treatment." In *Concrete Solutions: Proceedings of the Second International Conference on Concrete Repair, St. Malo, France, 27–29 June 2006*, edited by Michael Grantham, Raoul Jauberthie, and Christophe Lanos, 271–79. Watford, UK: BRE Press.

Realkalization has been identified as a useful treatment approach for historic concrete buildings due to its potential to reduce the amount of repair and replacement of the original material. But there is little information on the efficacy of these treatments in the long term. This paper discusses realkalization treatment trials in two case studies aimed to assess effectiveness and durability: Le Corbusier's Maison du Brésil, Paris (1959) and Cité Radieuse, Marseille (1951). A two-year monitoring period was established and employed various techniques: X-ray fluorescence was used to measure alkali ion migration; changes to pH were monitored using color indicators; and corrosion levels were evaluated using corrosion rate measurements and potential mapping. The study helped to identify effective means of monitoring the durability of realkalization treatments. The paper concludes that the efficacy of the treatment is limited by the composition of the concrete, and that realkalization should be avoided in structures where aggregates are susceptible to alkali-aggregate reaction.

Cailleux, Emmanuel, Élisabeth Marie-Victoire, Murielle Bach, Francoise Feugeas, and Alain Cornet. 2006. "Treatment of Precorroded Steel Reinforcement by Surface-Applied Corrosion Inhibitors: Solution Tests and Application to Concrete Samples." In *Concrete Solutions: Proceedings of the Second International Conference on Concrete Repair, St. Malo, France, 27–29 June 2006*, edited by Michael Grantham, Raoul Jauberthie, and Christophe Lanos, 619–28. Watford, UK: BRE Press.

This paper documents two investigations undertaken to evaluate the success of corrosion inhibitors. At the time of writing, laboratory trials had shown successful results, but in situ tests had been inconclusive. The study focuses on corrosion of reinforcements in historic buildings as a result of carbonation. Three commercially available corrosion inhibitors were trialed on panels of reinforced concrete removed from Le Corbusier's Maison du Brésil, Paris (1959), during restoration works. Carbonation depth was similar on all four panels and was past the depth of the reinforcement, which was found to have a corrosion layer. One panel was used as a control, while the other three were each treated with a different corrosion inhibitor: a mineral inhibitor, a mineral and organic inhibitor, and an organic inhibitor. The first was identified as probably anodic, the other two as probably both anodic and cathodic. Each treatment was applied by the manufacturer to remove application errors as a factor in the investigation. The mineral inhibitor did not penetrate the sample; the mineral and organic inhibitor penetrated, but not to the depth of the steel reinforcement; and the organic inhibitor successfully penetrated to the depth of the steel. The panels were reassessed two years later. The mineral inhibitor had not penetrated further and was removed from the trials at that point. The mineral-organic inhibitor had an increased concentration at depth, but no conclusion could be drawn as to its effect on corrosion rates. The concentration of the organic inhibitor had decreased at depth after two years, and the panel showed an increase in the rate of corrosion. Additional laboratory trials were undertaken to assess the validity of this investigation. Laboratory-produced non-corroded and pre-corroded steel samples were tested with the same inhibitors. The results appear to show that the corrosion inhibitors can work on non-corroded steel, but are not effective on pre-corroded steel.

Came, Andrew. 2007. "Repair Guidance Note 7: Concrete Injection." *Concrete* 41 (10): 56–58.

This is part of the series Repair Guidance Notes produced to supplement BS EN 1504 Products and Systems for the Protection and Repair of Concrete Structures. Definitions, Requirements, Quality Control and Evaluation of Conformity. It intends to help the reader navigate BS EN 1504, part 5, which addresses the issue of concrete crack injection. It briefly discusses two principles for injection that are defined in this part of the standard: principle 1, protection against ingress and waterproofing, and principle 4, structural strengthening. This guidance note comments on the scope of the standard, highlighting what it does and does not cover. The note also provides brief guidance to several other sections of BS EN 1504-5, including terms and definitions, performance characteristics, and annexes. The author notes that the standard is not a specification, nor does it offer guidance or restrictions on the methods and techniques for carrying out site applications.

Chess, Paul, and John P. Broomfield, eds. 2014. *Cathodic Protection of Steel in Concrete and Masonry*. 2nd ed. Concrete Technology. Boca Raton, FL: CRC Press.

This book introduces the state of the art in cathodic protection of steel in concrete and the allied, but separate, field of cathodic protection of metals in masonry structures. It provides a thorough introduction to the topic, and is directed toward the practicing professional. The history of cathodic protection and concrete is interwoven with technical material, providing evidence that this is a proven technology with a more than forty-year track record. Chapter 1 introduces the topic of cathodic protection, statistics on corrosion-related deterioration, and an in-depth introduction to corrosion and corrosion of steel in concrete. Chapter 2 focuses on corrosion of anchors, steel elements, and steel frames in historic masonry structures. Chapter 3 addresses site appraisal, life-cycle analysis, and the feasibility of using cathodic protection on concrete and/or masonry structures. Types of construction, anode types, and design requirements are summarized. Chapter 4 discusses the types of cathodic protection systems available and, most importantly, design and protection criteria. Standards are discussed, providing the reader with industry-established benchmarks indicative of cathodic protection. Chapter 5 discusses the history and principles of cathodic protection for reinforced concrete structures. Development and changes in system design and anode type reference current standards for cathodic protection in practice. Chapter 6 deals with immersed cathodic protection design (earth or water) where there are fewer cathodic protection applications. Chapter 7 discusses the various factors a designer should consider for a successful cathodic protection design for atmospherically exposed concrete structures; this includes system philosophy. The foundations of all major system design elements are discussed in detail. Chapter 8 discusses design parameters for masonry structures. Chapter 9 discusses cathodic prevention in new buildings through installation of cathodic protection systems. Chapter 10 discusses power supplies utilized in impressed current cathodic protection systems. Although some appear to be outdated, more recent control systems are touched upon. Chapter 11 provides information on monitoring systems, criteria, and limits. Chapter 12 provides case studies on impressed current cathodic protection, electro-osmosis, and galvanic cathodic protection systems. Chapter 13 addresses the economic aspects of cathodic protection, cost savings, and life extension. In summary, cathodic protection protects the client's investment, is a sustainable repair approach, and minimizes further deterioration. Numerous case studies support its use to mitigate corrosion in concrete and masonry.

Chhabra, Y., R. Jamaji, and B. K. Lim. 2003. "Case Study: Structural Investigation and Retrofitting of Heritage Shop-Houses at Hotel Rendezvous, Singapore with the Tyfo® Fibrwrap® Composite System." In *Concrete Solutions: 1st International Conference on Concrete Repair, St.-Malo, France, 15–17 July 2003*, edited by Michael Grantham, 721–30. London: GR Technologie Ltd.

This case study details the retrofitting and integration of a row of pre–World War II Singaporean shop houses into a new hotel development. The reinforced concrete beam and column elements were suffering from corrosion of the reinforcing steel, with a depth of carbonation exceeding concrete cover. The buildings lacked original construction drawings. A structural investigation and nondestructive evaluation were commissioned, which included a cover survey and ultrasonic pulse velocity for concrete strength and condition, as well as petrographic analysis, carbonation depth, half-cell potential, and tensile-strength testing. Numerous deficiencies in the concrete were found, and the structure was determined inadequate for its new loading requirements. Following the investigations, as built records were generated, patch repairs were performed at spalls and honeycombed concrete, cracks greater than 0.3 millimeters were filled, and anti-carbonation coating was applied to the surface. Composite strengthening was assessed to upgrade the structural system, and was carried out on the deficient concrete members. The authors state that the composite chosen met the demands of the construction industry for a lightweight, easily applicable, structurally powerful, and reasonably priced retrofit material. Column axial load and beam capacity were enhanced. Installation proved to be noninvasive and much easier than steel plate bonding methods. In conclusion, the successful strengthening project can serve as a model for structurally deficient historic concrete structures.

Collette, Quentin. 2017. "Investigation of the Reinforced-Concrete Construction of the Dotremont House in Brussels." *APT Bulletin: Journal of Preservation Technology* 48 (1): 40–48. https://www.jstor.org/stable/26291034.

See annotation on p. 49.

Coppola, Luigi. 2019. "Repair and Conservation of Reinforced Concrete Tent-Church by Pino Pizzigoni at Longuelo – Bergamo (Italy)." *International Journal of Architectural Heritage* 13 (5): 630–38. https://doi.org/10.1080/15583058.2018.1453887.

This paper presents restoration works carried out at the concrete tent-church in Bergamo, Italy, designed by Giuseppe "Pino" Pizzigoni and built in 1965. The building consists of four portions made statically independent by structural joints and characterized by vertical and inclined pillars with circular sections. Pillars are connected by thin vaults with a double curvature and thickness ranging between four and six centimeters. The investigation revealed that the church was affected by exposure to rainfall and snowfall, causing severe spalling of concrete cover and reinforcement corrosion, as well as defects from the construction process and failed repairs. The most problematic past intervention was the application of a cementitious surface layer, which had detached and cracked and was also hiding severe deterioration conditions of the structural elements. In the most recent conservation work, the highly deteriorated sections of the pillars were repaired with a self-compacting shrinkage-compensating mortar poured in wooden formworks that faithfully reproduced the original texture. The deteriorated parts of the thin vaults were repaired with hand-applied mortars. Repairs were followed by application of a thin layer of mortar and application of an acrylic coating on the entire building. Also, the entire drainage system was rehabilitated. Detailed images help to illustrate the repair procedures.

Courard, Luc, Zengfeng Zhao, and Frédéric Michel. 2021. "Influence of Hydrophobic Product Nature and Concentration on Carbonation Resistance of Cultural Heritage Concrete Buildings." *Cement and Concrete Composites* 115:art. 103860.

This paper investigates the effects of hydrophobic treatments on carbonation resistance and chloride diffusion. Concrete samples were made with the type of cement, components, and water-to-cement ratios (0.5, 0.6, and 0.7) found in historic concrete buildings. These samples were treated with six different market products based on silanes and siloxanes at different concentrations and submitted to accelerated aging. These samples were then analyzed for penetration depth, capillary water absorption, water vapor permeability, oxygen permeability, water contact angle, and carbonation depth. Results showed that in samples with lower water-to-cement ratios (0.5 and 0.6), carbonation depth is lower when the product concentration and penetration depth are higher, while for samples with a higher water-to-cement ratio (0.7), common in historic concrete structures, the high concentration treatments caused a slight increase in carbonation, and lower concentration products had little to no effect on carbonation. Further analysis to understand the treatments' effect on chloride ingress confirmed that they can slow down chloride diffusion, and that their effect increases with product concentration. The testing also confirmed that hydrophobic treatments can significantly decrease water ingress. Therefore, for historic concrete surfaces, high-quality products with high active concentration are recommended.

Currie, Helena M., and Matthew B. Bronski. 2018. "Evaluation and Restoration of Architecturally Significant Mid-Century Modernist Concrete Facades in the United States." In *10th International Masonry Conference, Milan, Italy, July 9–11, 2018*, edited by Gabriele Milani, Alberto Taliercio, and Stephen Garrity, 883–906. Stoke-on-Trent, UK: International Masonry Society.

The authors of this paper draw from their extensive experience and research in repairing concrete buildings to address the complex issue of carrying out patch repairs on architectural concrete facades, which deserve a careful approach for being simultaneously a fundamental aesthetic feature and part of the load-bearing structure. The authors discuss, in particular, the inadequate long-term color match of repairs based on methods that use pigments and/or rely solely on matching cement paste color. They report on the findings of in situ and laboratory research studies aiming to quantify the contribution of sand and coarse aggregates to the variation of the perceived color of concrete surfaces over time. The results reveal that even if an initial match is achieved by using pigments, the color of the repaired areas will change over time due to weathering—erosion of the superficial cement paste gradually exposes more sand and coarse aggregates, changing the perceived concrete color. These results are used to provide practical recommendations for designing concrete repair materials to provide a long-term aesthetic match. The suggested approach is to use constituent ingredients in the repair material—cement, sand, and coarse aggregate—that are as close as possible to the existing concrete.

Czarniecki, Maciej, and Daniel Czerek. 2015. "Renovation of the Centennial Hall." *Journal of Civil Engineering and Architecture* 9:573–82.

This paper presents comprehensive information about conservation works at Centennial Hall in Wrocław, Poland, designed by the architect Max Berg as a multipurpose recreational building and built in 1911–13. Its shape resembles a quatrefoil, with a large central space covered by a twenty-three-meter-high ribbed dome with steel-and-glass windows and a lantern. In 2006, the complex was included in the UNESCO World Heritage List as a pioneering achievement in engineering and architecture of the twentieth century. Between 2009 and 2011, this monumental building underwent its largest intervention since its completion, aimed at preserving its integrity and authenticity and to make the complex compliant with current standards for public sports and entertainment facilities. The authors, after a detailed description of the preliminary studies and investigations into the conditions of the building components, discuss the solutions adopted for the conservation of the plastered facades (highly heterogeneous, due to the use of different types of concrete), including cleaning operations

with low-pressure water jet, crack injections, patch repairs, and application of a protective impregnating product. The authors also describe the structural consolidation of the building, which consisted of girding the main ring of the dome with "super-cables." Finally, the paper outlines the rehabilitation of the interior spaces.

de Jonge, Wessel. 1997. "Concrete Repair and Material Authenticity: Electrochemical Preservation Techniques." *APT Bulletin: Journal of Preservation Technology* 28 (4): 51–57. https://doi.org/10.2307/1504594.

See annotation on p. 75.

de Jonge, Wessel, and Arjan Doolaar, eds. 1998. *The Fair Face of Concrete: Conservation and Repair of Exposed Concrete*. Preservation Technology Dossier 2. Eindhoven, the Netherlands: DOCOMOMO International / Eindhoven University of Technology.

See annotation on p. 15.

Drewett, John, and Nadine Bott. 2012. "The Refurbishment of Bideford Longbridge." In *Concrete Solutions: Proceedings of Concrete Solutions, 4th International Conference on Concrete Repair, Dresden, Germany, 26–28 September 2011*, edited by Michael Grantham, Viktor Mechtcherine, and Ulrich Schneck, 15–18. Boca Raton, FL: CRC Press.

This brief paper details work at the Grade I–listed Bideford Long Bridge in Devon, England. The main structure is a twenty-four-span masonry arch bridge. In 1928, additional cantilevered reinforced concrete spans were added to either side of the bridge. In 2001, it was determined that the cantilevered sections were too weak to support the previous weight allowance on the bridge, and that corrosion induced by high chloride levels and insufficient concrete cover was occurring. In 2007, the decision was made to implement an impressed current cathodic protection system using a combination of mixed-metal-oxide-coated titanium mesh and discrete mixed-metal-oxide-coated titanium tubular anodes. Repairs were undertaken to remove deteriorated concrete cover. Deteriorated areas were cut back and the reinforcement stripped by hydrodemolition. Visible and non-visible areas were treated differently. Visible areas were repaired using shuttering and a proprietary repair mortar, and non-visible areas were repaired using sprayed concrete (shotcrete). The use of the impressed current cathodic protection system was shown to be particularly beneficial for historic buildings. Since there is no need to replace carbonated or high-chloride concrete, it limits the amount of repairs necessary. System installation was completed in 2010. In its design and installation, it is one of the most complex impressed current cathodic protection systems undertaken in the United Kingdom to date.

Ducasse-Lapeyrusse, Jean, Élisabeth Marie-Victoire, Myriam Bouichou, Ana Paula Arato Gonçalves, Simeon Wilkie, Susan Macdonald, Nicki Lauder et al. 2022. "Performance Evaluation of Patch Repairs on Historic Concrete Structures (PEPS): A Bibliographic Review of Patch Repair Durability." In *Concrete Solutions 2022: 8th International Conference on Concrete Repair, Durability & Technology*, edited by M. G. Grantham, M. Basheer, and R. Mangabhai, art. 04001. MATEC Web of Conferences 361. Les Ulis, France: EDP Sciences. https://doi.org/10.1051/matecconf/202236104001.

The literature review presented in this paper was developed as part of the international research project Performance Evaluation of Patch Repairs on Historic Concrete Structures (PEPS) with the purpose of highlighting the key factors contributing to the performance of patch repairs from a conservation perspective, with particular attention to compatibility issues between repair system and original material. Durability of concrete patch repairs is affected by several different factors, including diagnosis of underlying causes of deterioration, design of the repair material, surface preparation, workmanship, loading, and exposure conditions, which should be individually understood as well as considered holistically, since the various parameters may affect each other differently. While durability of patch repair in contemporary concrete structures is widely addressed in the scientific literature, little attention is dedicated to this topic with respect to historic concrete structures, given the added requirements to preserve the site's cultural significance beyond just durability. The visual impact of a patch repair is not of primary importance for most contemporary concrete, while it is essential to historic concrete heritage. The addition of such conservation criteria as minimizing loss

of original material, and reversibility (or retreatability) in interventions, make the challenge of patch repair even more complex.

Farrell, David, and Kevin Davies. 2005. "Repair and Conservation of Reinforced Concrete." In *Historic Churches: The Conservation and Repair of Ecclesiastical Buildings*, 17–19. Tisbury, UK: Cathedral Communications Limited. https://www.buildingconservation.com/articles/concrete-repair/concrete-repair.htm.

This article overviews methods available for the repair of concrete churches. It opens with a brief explanation of reinforced concrete's physical properties and uses, followed by a section discussing deterioration mechanisms. The key points of an investigation and condition survey are discussed, as are best-practice procedures for historic buildings. The article recommends completing an integrated condition assessment prior to a repair and provides a brief list of related test methods and laboratory analyses. Both traditional repair methods and electrochemical repair methods are discussed, and examples of treatments and repairs are provided.

Farrell, David, and Chris Wood. 2015. "Concrete Repairs: Traditional Methods and Like-for-Like Materials." In *The Building Conservation Directory, 2015*, 53–58. Wiltshire, UK: Cathedral Communications. https://www.buildingconservation.com/articles/repair-historic-concrete/repair-historic-concrete.htm.

In this article, the authors describe in detail a methodology to develop patch repairs that are as close as possible to the original concrete, in both aesthetic and composition. This method of "like-for-like" repair is preferable to using industrialized mortars not specifically developed for the structure to be repaired. It has been adopted in the National Theatre in London, and the process is described here in detail. The authors enumerate the development of the repair material for this case study, starting with historical research on the original construction, followed by analysis of collected samples. They were able to source the same type of aggregate and cement as used in the original construction and the mix proportions were adjusted through a series of trials. The authors advocate for matching color by using sand and cement; pigments are only recommended in certain circumstances. The article describes each step of the repair installation: breaking out the concrete, installing formwork, placing the concrete, and finishing the surface.

Frens, Dale H. 2002. "Restoration of the Concrete Roof of the Mercer Museum in Doylestown, Pennsylvania." *APT Bulletin: Journal of Preservation Technology* 33 (1): 13–19. https://doi.org/10.2307/1504784.

This article describes the project-management approach to the repair of the Mercer Museum in Doylestown, Pennsylvania. The building was designed and constructed between 1913 and 1916 by Henry Chapman Mercer to house his collection of cultural materials. Concrete was used in every possible way: the structural system and building envelope, including the roof, are made of cast-in-place reinforced concrete, and interior floors, walls, ceiling surfaces, and windows are also of concrete. A survey undertaken in 1991 found most of the exterior concrete to be in good condition, except for the roof, which was suffering many forms of deterioration and is the focus of this article. A year later, the author undertook a more detailed survey of the roof, which included collection and analysis of concrete samples. The detailing of the concrete, rather than its composition, was identified as the key issue. With maximum retention of original material as the preservation philosophy, a large test panel was created to trial proposed treatments. The trial panel was revisited two years later, and the success of the repairs was assessed. Following a condition survey, detailed drawings were produced identifying the defects and the repairs that should be undertaken. A contractor was selected following a competitive bidding process. The contract was unusual in that there was an agreed guaranteed maximum price, which protected the owner in this respect, but there was no agreement on the exact amount of work that would be completed. This form of contract requires a high level of trust between owner, architect, and contractor.

Garmendia Arrieta, Leire, Ignacio Marcos Rodríguez, Natalia Lasarte Arlanzón, and Estibaliz Briz Blanco. 2018. "Damage Assessment and Conservation Strategy for the Largest Covered Market in Europe: The Ribera

Market (Bilbao)." *International Journal of Architectural Heritage* 12 (6): 997–1018. https://doi.org/10.1080/15583058.2018.1431728.

See annotation on p. 53.

Gaudette, Paul E., and Harry J. Hunderman. 1997. "Repair of Mies van der Rohe's Promontory: A Multiphased Approach to Facade Restoration." *APT Bulletin: Journal of Preservation Technology* 28 (2–3): 45–50. https://doi.org/10.2307/1504593.

This article documents the restoration project undertaken at the Promontory Apartments in Chicago, designed by Mies van der Rohe and constructed in 1949. The building has an exposed reinforced concrete frame with brick infills. The article provides a brief history and description of the building, and details the investigation, laboratory analysis, strategy, and repair program undertaken. Four representative bays were selected for detailed survey, and selected areas within these were opened up to investigate the processes of deterioration. Previous repairs that had poor aesthetic match were also investigated. The main form of deterioration of the concrete was corrosion of the steel reinforcement due to inadequate coverage in isolated areas. The repair material was designed to visually match the original concrete, with similar physical characteristics. Repair trials were undertaken on the building to fine-tune the process to achieve the required finish and performance. The original deteriorated concrete was chipped back to behind the reinforcements and all deteriorated material removed to provide repairs with a good mechanical anchoring to the original steel. All patch repairs were undertaken using form-and-pour technique. Various surface finishing techniques were trialed and are discussed. In the end, a combination of light water-blasting and hand finishing was selected. Sealants are also discussed, and a silane-based, non-film-forming treatment was selected for the building. An alternate version of this article can be found in Wessel de Jonge and Arjan Doolaar, eds., *The Fair Face of Concrete: Conservation and Repair of Exposed Concrete* (see annotation on p. 15).

Gralińska-Grubecka, Aleksandra, and J. Witold Łukaszewicz. 2012. "A Comparative Study of Anti-Corrosion Products for the Protection of Reinforcement in Monuments." In *Concrete Solutions: Proceedings of Concrete Solutions, 4th International Conference on Concrete Repair, Dresden, Germany, 26–28 September 2011*, edited by Michael Grantham, Viktor Mechtcherine, and Ulrich Schneck, 237–42. Boca Raton, FL: CRC Press.

This paper documents a laboratory-based product investigation designed to identify the best commercially available anticorrosion coating for steel reinforcement for use in conserving reinforced concrete monuments and artworks. The introduction highlights the previous lack of testing of these products for conservation work and notes the different requirements for concrete repair versus concrete conservation. Eleven commercially available and widely used products with a range of compositions—including cement-based, epoxy-based, and polymer-based—were trialed in this study. Following European Standards, three groups of tests were undertaken: corrosion, adhesion, and water absorption. In addition, observations were made for each product on ease of application, workability, and finished appearance. For the corrosion tests, each product was trialed on corroded and cleaned steel bars and underwent cycles of condensation, sulfur dioxide activity, and storage in a neutral salt mist. For the adhesion tests, two layers of each product were applied to rigid steel plates and the minimum stress required to detach or rupture the coating was recorded. Both absorption and sorption tests were undertaken on samples of the products applied to glass plates, with observations and measurements recorded over several days. Based on the trials, two products were identified as suitable for use in the preservation of reinforced concrete monuments: Funcosil Epoxi-Rostschutz, a two-component material based on epoxy resin with an anticorrosion pigment, and Monotop-610, a one-component Portland cement modified mortar that includes a corrosion inhibitor. Both showed good corrosion protection and easy and uniform application, though Monotop-610 had a lower adhesion to steel. A third product was identified as successful on reinforcement that had all corrosion removed, but was less successful where corrosion products were present.

Graves, Kiernan, and Katey Corda. 2016. "Conserving a Boundary: The Conservation and Management of a Berlin Wall Mural." *Studies in Conservation* 61 (2, suppl. 2): 61–66. https://doi.org/10.1080/00393630.2016.1190996.

See annotation on p. 78.

Grignolo, Roberta. 2015. "The Couvent de La Tourette from 1960 to the Present Day: Future Discernibility of Past Interventions." *DOCOMOMO Journal*, no. 53, 64–73. https://doi.org/10.52200/53.A.1IG88ORF.

See annotation on p. 79.

Guades, Ernesto J., and Henrik Stang. 2019. "Structural Performance of Concrete Elements Retrofitted by a Geopolymer Strengthening System: Input in the Rehabilitation of Historical Buildings." In *Structural Studies, Repairs and Maintenance of Heritage Architecture XVI*, edited by P. De Wilde, 369–80. WIT Transactions on the Built Environment 191. Southampton, UK: WIT Press. https://doi.org/10.2495/STR190321.

This paper consists of a literature review regarding experimental studies and field applications of geopolymer for repair and strengthening in concrete structures. Geopolymer is gaining popularity in the civil infrastructure industry due to its lower creep and shrinkage, greater durability in severe environments, fire resistance, and (perceived) environmental sustainability. But it is relatively new in the rehabilitation sector, and just a few research studies have addressed its performance as a repair and strengthening system. Existing literature on this topic revealed that the load-bearing capacity of non-damaged and fully damaged reinforced concrete beams, strengthened with plain geopolymer, could be increased respectively by 12 percent and 100 percent. Moreover, the authors compared the results of several research studies related to the use of short-fiber-reinforced geopolymer and continuous-fiber-reinforced geopolymer for strengthening reinforced concrete beams and columns. The paper includes useful tables that summarize the gathered experimental results. The review of field applications showed that geopolymer has been used as a strengthening system for large concrete pipes and culverts, a water dam, and a few modern heritage buildings. The experimental studies and field applications analyzed lead the authors to conclude that geopolymer is also a promising technique for the rehabilitation of historical buildings.

Hamada, Keizo. 2015. "Efforts to Improve the Earthquake Resistance of the Kagawa Prefectural Government Office East Building." *DOCOMOMO Journal*, no. 52, 72–79. https://doi.org/10.52200/52.A.BDI24625.

See annotation on p. 79.

Harrer, Ann, and Jeffrey Caldwell. 2017. "Repairs to Concrete at the Pilgrimage Theatre in Los Angeles, California." *APT Bulletin: Journal of Preservation Technology* 48 (1): 49–57. https://www.jstor.org/stable/26291035.

In this article, the authors describe the concrete repair process undertaken on an eighty-year-old open-air amphitheater in Los Angeles. The first part describes the history of the Pilgrimage Play Theatre, now the Ford Theatre, built in 1931 and designed by William Lee Woollett as a cast-in-place reinforced concrete structure with board-formed exposed concrete surfaces. A comprehensive rehabilitation project began in 2013, which included repairs to the reinforced concrete and reinstated the original exposed concrete aesthetic by removing coatings applied through the years. The second part of the article describes in detail the development of the repair strategy, design of repairs, coating removal method, trials, and implementation. Areas that required repair had been affected by delamination and spalling caused by reinforcement corrosion due to localized low concrete cover. The implementation section describes the steps taken in each repair: concrete removal, cleaning of reinforcement, substrate preparation, formwork installation, concrete placement, and surface finishing.

Harrer, Ann, Paul Gaudette, and Deborah Slaton. 2020. "Approach to Preservation of Historic Concrete." *Concrete Repair Bulletin* 33 (2): 12–17. https://cdn.ymaws.com/icri.site-ym.com/resource/resmgr/crb/2020marapr/ICRI-CRB-Mar-Apr2020-web.pdf#page=14.

See annotation on p. 79.

Haydon, Paul B. 1994. "Recasting at the Edge." *Building Renovation: BR* (Summer): 24–29.

This article reports on repair works undertaken at East Midtown Plaza in New York, designed and built between 1969 and 1974. As early as 1985, an extensive repair program was undertaken to treat areas of spalling on the reinforced concrete structure. Despite this work, a 1991 survey showed the spalling to have reached a critical level, and in fact, more than 50 percent of the areas identified as spalling in the 1991 survey were patches from the 1985 repair works. The survey found that, in many places, the reinforcing bars were just below or almost flush with the concrete surface. Carbonation was identified as the key factor, although not the sole cause, in the concrete deterioration. Further patching was considered a temporary option; therefore, the architects proposed re-casting the protruding areas of the concrete structure where the spalling was occurring and adding an additional inch of concrete to the outer edges. Before the wholesale repair, a trial determined that the proposed scheme was feasible, with a slight modification. To prepare the surfaces, the defective concrete was removed to an inch behind the reinforcement to allow the corrosion to be cleaned away and improve the bond between the new and existing concrete. In addition, to prevent the creation of cold joints, formwork was created that enabled the concrete to be run along a full slab or balcony. A water repellent was applied to the new concrete twenty-eight days after the forms were removed.

Hughes, Mark E., and Carl R. Bischof, eds. 2013. *Concrete Repair Manual*. 2 vols. 4th ed. Farmington Hills, MI: American Concrete Institute; Rosemont, IL: International Concrete Repair Institute.

This two-volume set is a comprehensive resource on concrete repair. It compiles documents from the American Concrete Institute (ACI); BRE (formerly the Building Research Establishment); Concrete Society (CS); International Concrete Repair Institute (ICRI); NACE International (formerly National Association of Corrosion Engineers); SSPC: Society for Protective Coatings; and the US Army Corps of Engineers. It is worth noting that these documents are also available individually from their respective institutions, and that some, especially from ACI, are periodically revised. The manual is comprised of seven sections: general, condition evaluation, concrete restoration, contractual, strengthening, protection, and special cases. The most relevant documents for concrete conservation are included in this bibliography individually in their most recent versions: ICRI's *Concrete Repair Terminology* (see annotation on p. 101); ACI 201.1R-08: *Guide for Conducting a Visual Inspection of Concrete in Service* (see annotation on p. 29); ACI 228.2R-13: *Report on Nondestructive Test Methods for Evaluation of Concrete in Structures* (see annotation on p. 44); ACI 364.1R-19: *Guide for Assessment of Concrete Structures before Rehabilitation* (see annotation on p. 42); ACI 546R-14: *Guide to Concrete Repair: Reported by ACI Committee 546* (see annotation on p. 87); CS Technical Report 54: *Diagnosis of Deterioration in Concrete Structures: Identification of Defects, Evaluation and Development of Remedial Action* (see annotation on p. 33); CS Technical Report 22: *Non-Structural Cracks in Concrete* (see annotation on p. 33); CS Technical Report 32: *Analysis of Hardened Concrete: A Guide to Tests, Procedures and Interpretation of Results* (see annotation on p. 49); BRE Digest 405: *Carbonation of Concrete and Its Effects on Durability* (see annotation on p. 31); and BRE Digest 444: *Corrosion of Steel in Concrete*, parts 1–3 (see annotations on pp. 31, 48, and 91).

Ignoul, Sven, and Dionys Van Gemert. 2016. "Durable Restoration of Reinforced Concrete Grillage Roof Shell of Ensor Gallery in Ostend (B)." *Restoration of Buildings and Monuments* 22 (2–3): 65–73. https://doi.org/10.1515/rbm-2016-0002.

This article describes the conservation strategy developed for the vaulted roof of the Ensor gallery in Ostend, Belgium, built in 1945 to replace the glass roof originally built in 1892. The vaulted roof consists of reinforced concrete beams and arches with embedded reinforced concrete panels with integrated prismatic glass tiles. Due to sea air exposure, extensive reinforcement corrosion had seriously damaged this roof. The paper summarizes data from the assessment conducted and presents the conservation strategy, which aimed to limit as much as possible the loss of original material. The strategy was based on a combination of techniques: galvanic cathodic protection, chloride-inhibiting impregnation followed by a re-alkalizing treatment, and concrete repair. The most damaged beams were repaired with a poured self-compacting shrinkage-compensating repair mortar, selected for its capacity to maintain the small dimensions of all structural elements (arches, purlins, cornices). For the same reason, concrete cover was limited to a few millimeters, but this was compensated for by the application of extra corrosion protection and chloride inhibitors. The less damaged beams were repaired with a fiber-reinforced shrinkage-compensating repair mortar applied by trowel. Original glass tiles were reused as much as possible, and missing tiles were reproduced.

International Concrete Repair Institute. 2022. *Concrete Repair Terminology*. St. Paul, MN: International Concrete Repair Institute. https://www.icri.org/wp-content/uploads/2024/01/icri-crterminology-2022.pdf.

This document was developed by the International Concrete Repair Institute and is periodically revised. It is a useful tool for owners, design professionals, and contractors involved in the repair of concrete buildings and structures. It includes cross-referenced definitions of terms commonly used when designing or implementing a concrete repair project related to different subject categories, for instance materials and components, typologies of concrete, chemical substances, physical properties, finishing techniques, deterioration mechanisms and defects, diagnostic techniques, repair techniques, repair materials, technical equipment, and technical documents, to mention just a few. An earlier version is included in Mark E. Hughes and Carl R. Bischof, eds., *Concrete Repair Manual* (2013, see annotation on p. 100).

Jerome, Pamela. 2013. "Conserving Frank Lloyd Wright's Solomon R. Guggenheim Museum." *Historic Environment* 25 (1): 62–70. https://australia.icomos.org/wp-content/uploads/Conserving-Frank-Lloyd-Wrights-Solomon-R.-Guggenheim-Museum-vol-25-no-1.pdf.

See annotation on p. 81.

Jerome, Pamela, Norman Weiss, and Hazel Ephron. 2006. "Fallingwater Part 2: Materials-Conservation Efforts at Frank Lloyd Wright's Masterpiece." *APT Bulletin: Journal of Preservation Technology* 37 (2/3): 3–11. https://www.jstor.org/stable/40004684.

This is the second part of a two-part article (see annotation on p. 67 for the first) addressing conservation works undertaken at Frank Lloyd Wright's Fallingwater in Mill Run, Pennsylvania (1939), at the start of the twenty-first century. It describes the implementation and results of the conservation works led by Wank Adams Slavin Associates, including details regarding work on the roofs, terraces, skylights, concrete, stucco, stone, windows, doors, paints and coatings, and interiors. The reconstruction of a set of stairs suspended over the stream that were suffering from corroding reinforcement and spalling are described in detail. In this case, patch repairs were determined to be insufficient given the level of damage. The stairs had already been rebuilt in the 1950s, following storm damage, so the decision was made to reconstruct them using stainless steel for the reinforcement. The formwork used for re-casting the concrete on the steps was undersized to allow for reinstatement of a stucco finish as on the original. The entire restoration project took five years to complete and cost $11.5 million.

Jester, Thomas C. 2014. "Part II: Concrete." In *Twentieth-Century Building Materials: History and Conservation*, 45–86. Los Angeles: Getty Conservation Institute.

See annotation on p. 9.

Johnson, Arne P., John S. Lawler, and Michael S. Murphy. 2019. "Lessons in Galvanic Cathodic Protection Technology from Soldier Field and the Franklin Avenue Bridge." *APT Bulletin: Journal of Preservation Technology* 50 (2–3): 27–36.

This paper focuses on two case studies: Soldier Field stadium in Chicago (1922–26) and the Franklin Avenue Bridge in Minneapolis (1919–23). It describes structural features, cathodic protection systems installed, and performance evaluations. In the second part, the authors summarize lessons learned from the two examples and suggest five design factors that should be taken into account to achieve long-term protection using cathodic protection: assessing technical and economic merits of cathodic protection on a case-by-case basis, developing an in-depth understanding of deterioration mechanisms motivating the use of cathodic protection, costs-and-benefits evaluation, service-life predictions, and life-cycle cost analyses; impacts on the historic resource, considering whether the impact of the cathodic protection installation is minimal or otherwise, and if the system selected has proven to be effective; sufficient source of protection current in a galvanic cathodic protection system, underlining that the anode material and geometry should be selected to provide a sufficient source of protection current; complete path of protection current in a galvanic cathodic protection system, highlighting that the current path must not include high-resistivity materials that will impede the current flow; and performance specifications and field verification, stressing the importance of adopting ongoing monitoring to verify the intended performance over time.

Joshi, Kiran, ed. 2005. *Corbusier's Concrete: Challenges of Conserving Modern Heritage*. Chandigarh, India: Chandigarh Perspectives.

See annotation on p. 81.

Karydis, Georgios. 2006. "Advanced Strengthening Systems for Conserving 20th Century Concrete Heritage: The Ethical Justification of Utilizing Fibre Reinforced Polymer (FRP) Composites." In *Proceedings of the 2nd FIB Congress: June 5–8, 2006, Naples, Italy*. Naples: FIB Italia.

This paper provides an ethical justification for the use of fiber-reinforced polymer composites, both generally and on architectural and historically significant concrete structures. The benefits of using modern materials must be carefully examined before any intervention, and long-term durability must be assessed. The author notes that the use of fiber-reinforced polymers in heritage structures introduces technical complexities and ethical obstacles. However, when taking on a structural rehabilitation, the addition of more concrete or steel plates to enhance capacity can lead to great variations in the structure. Fiber-reinforced polymers are the main alternative. They are minimally invasive, can be concealed, and are less destructive than shotcrete or steel plates. The paper addresses issues with techniques and materiality, discusses use in relation to the Venice and Burra charters, British Standards, and guidelines used by English Heritage and Historic Scotland. Material incompatibility is acknowledged, but the paper highlights advantages compared to traditional strengthening approaches. Reversibility, tangibility, authenticity, and sustainability are addressed. The conclusion is that fiber-reinforced polymers can be morally justified for use in strengthening twentieth-century concrete heritage structures.

Lauder, Nicola, and David Farrell. 2022. "Performance Evaluation of Patch Repairs on Historic Concrete Structures (PEPS): The Evolution of Conservation Repairs on the Historic England Phase II Test Sites and PEPS Phase II Results." In *Concrete Solutions 2022: 8th International Conference on Concrete Repair, Durability & Technology*, edited by M. G. Grantham, M. Basheer, and R. Mangabhai, art. 04003. MATEC Web of Conferences 361. Les Ulis, France: EDP Sciences. https://doi.org/10.1051/matecconf/202236104003.

The research work presented in this paper is part of the international research project Performance Evaluation of Patch Repairs on Historic Concrete Structures (PEPS). This paper is focused on phase II, "Preliminary Assessment," carried out by Historic England on ten English sites, which included buildings and structures where like-for-like repair works had been carried out over the last twenty years with input from Historic England. These sites are all designated structures, either listed or scheduled as monuments, and show quite varied situations in terms of age, environmental conditions, and locations, including urban, rural, and maritime areas. Phase II was aimed at examining the technical performance of past repairs using nondestructive testing techniques and high-quality photographic images. The tentative conclusions after Phase II include, among others, the following considerations: repairs can be successfully achieved using like-for-like concrete, but the removal of original material needs to be relatively deep and undercut or dovetailed to improve the mechanical bond of the patch; and the presence of corroding steel in reinforced concrete is the major challenge to overcome in achieving a long-lasting patch repair.

Lucquiaud, V., L. Courard, O. Gérard, F. Michel, M. Handy, S. Aggoun, and A. Cousture. 2014. "Evaluation of the Durability of Hydrophobic Treatments on Concrete Architectural Heritage." *Restoration of Buildings*

*and Monuments: An International Journal = Bauinstandsetzen und Baudenkmalpflege: eine internationale Zeitschrift* 20 (6): 395–404.

This article describes the results of laboratory-based research aimed at evaluating the durability of hydrophobic treatments, including both water- and solvent-based products. These treatments were applied on the surface of concrete samples designed to mimic low-quality old concrete by using a water-to-cement ratio of 0.7. Two products available on the European market at the time of the research were tested: a water-based alkyl alkoxy silane and a siloxane mix in an alcoholic solvent. Treatment performance was evaluated based on permeability to water vapor, capillary absorption, chloride ion permeability, and contact angle. Separate sets of samples were submitted to different types of artificial aging: UV exposure, freeze-thaw cycles, thermal shocks, relative humidity cycling, and carbonation. The research concluded that treatment performance was mostly affected by thermal shocks and UV exposure, with the solvent-based product demonstrating better performance.

Macdonald, Susan, ed. 2003. *Concrete: Building Pathology*. Oxford: Blackwell Science.

See annotation on p. 43.

Macdonald, Susan, and New South Wales Heritage Office. 2003. *The Investigation and Repair of Historic Concrete*. Parramatta, Australia: NSW Heritage Office. https://www.environment.nsw.gov.au/-/media/OEH/Corporate-Site/Documents/Heritage/investigation-repair-historic-concrete-0303.pdf.

See annotation on p. 57.

Mändel, Maris, and Karl Õiger. 2016. "Conservation of Tallinn Seaplane Hangars." *Proceedings of the ICE – Engineering History and Heritage* 169 (1): 3–10. https://doi.org/10.1680/jenhh.15.00011.

See annotation on p. 82.

Marie-Victoire, Élisabeth, Myriam Bouichou, Véronique Bouteiller, and Yun Yun Tong. 2014. "Realkalisation of a Late 19th Century Bridge." In *Concrete Solutions: Proceedings of Concrete Solutions, 5th International Conference on Concrete Repair, Belfast, Northern Ireland, 1–3 September 2014*, edited by Michael Grantham, P. A. Muhammed Basheer, Bryan Magee, and Mario Soutsos, 645–54. Boca Raton, FL: CRC Press.

This paper reviews a three-year restoration project on the historic Camille De Hogues Bridge in Châtellerault, France, where realkalization was applied. This was part of a program designed by the French ministries of culture and sustainable development to determine best repair methodologies for historic carbonated concrete. The three-arch bridge, which crosses the Vienne river, was built by the François Hennebique Company in 1899–1900. This active bridge was suffering from heavy corrosion, cracking, spalling, and leakage. Low-quality concrete was originally used, most likely due to limited knowledge of concrete construction. Concrete cover was thin and construction defects were observed, but carbonation was generally low. Prior to treatment, two zones were assessed. These zones had pH values as low as 9, up to seven centimeters deep. Corrosion current and resistivity values indicated negligible corrosion risk despite the carbonated condition. Realkalization was performed for fifteen days. To track progress, phenolphthalein and thymolphthalein tests were performed on drilled powder samples, and potential, resistivity, and polarization resistance were mapped. This evaluation was performed after treatment, two months after treatment, and one year after treatment. It was concluded that realkalization on this project was not successful. While there was an increase in pH at the reinforcing steel and a short-term decrease in corrosion activity, the challenges of old concretes with construction anomalies may prevent a successful outcome from the use of this technology.

Marie-Victoire, Élisabeth, and Annick Texier. 2003. "Realkalisation and Corrosion Inhibitors, a Conservation Method for Ancient Buildings?." In *Sixth CANMET/ACI International Conference on Durability of Concrete: Supplementary Papers*, edited by Nabil Bouzoubaâ, 615–29. Farmington Hills, MI: American Concrete Institute.

This study addresses the use of three migrating corrosion inhibitors and two methods of electrochemical realkalization for the conservation of twentieth-century built heritage. The testing was performed on hollow panels removed from a landmark church. The aim of the program was to establish penetration profiles of the inhibitors to determine if there was migration to the steel and if the realkalization increased alkalinity of the concrete. The concrete was characterized, and corrosion condition was established prior to undertaking the testing program. After application of the inhibitors, it was concluded through scanning electron microscopy, optical microscopy, electrodes, and ionic chromatography that there were no side effects on the cement paste, but penetration depths were uneven and insufficient. The results raise two questions: Is the migrating power too low to penetrate the concrete? And does there need to be an improvement in how the concentration of the inhibitor at the steel is measured? The realkalization testing included both impressed current realkalization and a galvanic-based realkalization method. The galvanic method did not provide enough energy to increase pH, while the impressed current system was successful. This was the first step in a long-term study.

Matsui, Isama, Atsushi Onda, Sachiyo Shinozaki, Eitou Kyo, Kaori Nagai, and Noboru Yuasa. 2006. "Method of Removing Graffiti from the Surface of Concrete." In *Environmental Ecology and Technology of Concrete: Proceedings of the International Symposium on Environmental Ecology and Technology of Concrete, EETC-2005: 6–8th June 2005, Urumqi, XinJiang, China*, edited by Nai-Qian Feng and Gai-Fai Peng, 363–70. Zurich: Trans Tech Publications. https://doi.org/10.4028/www.scientific.net/KEM.302-303.363.

This paper describes the results of a comparative study of two different techniques for removing graffiti from concrete surfaces: laser irradiation and high-pressure water jet using water with sodium bicarbonate. The investigation was developed on concrete specimens covered with oil spray paint and emulsion spray paint in different colors. Research results show that oil paint is easier to remove than emulsion paint, and that yellow and orange are harder to remove than other colors. The variation of the sublimation temperature for the various colors is due to the type of pigment in the paint, but in all cases, extremely high temperatures are necessary. From the overall comparison of methodologies, laser irradiation appears to be more effective for graffiti removal than water jet, but laser irradiation causes the concrete surface to rapidly reach high temperatures and popout may occur.

Mays, Geoff, ed. 1992. *Durability of Concrete Structures: Investigation, Repair, Protection*. London: E & FN Spon.

See annotation on p. 60.

McGovern, Martin S. 2000. "A Clear View of Sealers." *Concrete Construction* (January): 53–58.

This article discusses the use of film-forming and penetrative sealers on concrete, breaking down the two groups and briefly describing each of the most common types. The film-forming group includes acrylics, epoxies, silicones, and stearates, and the penetrants group includes silanes, siloxanes, silicates, and siliconates. Silanes and siloxanes are identified as the most efficient penetrants, but a resurgence in the use of silicates and siliconates is noted. This is due to their little-to-no volatile organic compound content, which at the time of writing had recently been limited by the Environmental Protection Agency. The article highlights some of the marketing techniques used by manufacturers that can make it difficult to distinguish between the different types. It is also noted that laboratory tests are often not adequate to determine how a product will perform in the field. A method for undertaking on-site testing is given.

Meier, Steven J., and Folker H. Wittmann. 2011. "Recommendations for Water Repellent Surface Impregnation of Concrete." *Restoration of Buildings and Monuments* 17 (6): 347–56. https://doi.org/10.1515/rbm-2011-6476.

This article focuses on water-repellent surface treatments for concrete and provides performance details and recommendations. It introduces the three main protective surface finish technologies for concrete: water repellents, sealants, and coatings. The authors focus on water-repellent technologies, as they are the only protective surface finish that does not prevent the movement of moisture vapor into and out of the concrete. It describes how water repellents work and highlights some of the potential performance issues with this technology. The parameters required for water repellent applications differ depending on the goals of each project. The results of trials identifying penetration depth, concentration of solution, and application method are presented and shown in a series of graphs. The article discusses the appropriate selection of concentration level and method of application of a water repellent, as well as appropriate site testing prior to full-scale application. The effectiveness of a water repellent can be tested by applying a chloride solution; monitoring of the chloride levels before and after application of the solution provides information on the repellent's penetration depth and effectiveness.

Meurs, Paul, and Maria Theresia van Thoor, eds. 2010. *Sanatorium Zonnestraal: History and Restoration of a Modern Monument*. Rotterdam: NAi.

See annotation on p. 83.

Miranda, Judite, Jónatas Valença, Hugo Costa, and Eduardo Júlio. 2022. "Methodology for the Restoration of Heritage Built in Exposed Concrete: The Case Study of 'Piscina das Marés,' Portugal." *Construction and Building Materials* 328:art. 127040. https://doi.org/10.1016/j.conbuildmat.2022.127040.

This paper proposes a repair approach for concrete heritage that includes the chromatic characterization of exposed concrete surfaces by image processing to design customized restoration mortars. This approach pays particular attention to matching color and finish, in addition to mechanical compatibility and durability. The methodology is applied to the case study of the Piscina das Marés by Álvaro Siza in Leça da Palmeira, Portugal. The methodology proposed comprises a sequence of steps, each one including several tasks, described in a flowchart: surface assessment; design of restoration mortars; on-site selection of restoration mortar; restoration intervention; compliance checking; final reintegration; and monitoring and maintenance. The image processing technique is used to fine-tune the color of the restoration mortar by adding pigments to the reference repair mortar, after verification of mechanical compatibility and durability. Even though the use of pigments is questioned in both research and practice due to issues of color variation over time and the pigments' compatibility with concrete, this is a solution that could be considered for further investigation when matching color by using constituent materials similar to the original concrete is not feasible. As this paper's authors underline, before a mixture colored with pigments is used, it is necessary to test the loss of color under the effect of solar radiation, the chemical stability of the pigment, and the effects that the pigments may have on the properties of the concrete. Still, long-term in situ performance is difficult to guarantee.

Neto, Elsa, Sandra Magina, Aires Camões, Arlindo Begonha, Dmitry V. Evtuguin, and Paulo Cachim. 2016. "Characterization of Concrete Surface in Relation to Graffiti Protection Coatings." *Construction and Building Materials* 102 (pt. 1): 435–44. https://doi.org/10.1016/j.conbuildmat.2015.11.012.

This article provides new knowledge on interactions between anti-graffiti products and exposed concrete surfaces, and the effect of graffiti removal on the durability of concrete surfaces. Paints are absorbed through the concrete pores, making the removal process difficult. According to the authors, anti-graffiti products are often selected without due attention to the properties of the concrete, leading to insufficient protection or even deterioration. The authors analyze changes in concrete surface properties and efficiency for two anti-graffiti treatments, one permanent and one sacrificial, evaluating the following cases: concrete without protection, before and after application of graffiti paint; concrete with protection, before and after application of graffiti paint; and concrete after graffiti paint removal. Contact angles and wetting envelope graphs are examined. The results reveal changes to the concrete surface produced by graffiti, graffiti protection treatments, and graffiti removal, and show the advantage of a permanent protection coating over a sacrificial one.

Pardo Redondo, Gabriel, Barbara Lubelli, and Silvia Naldini. 2019. "State of the Art Report on New Technologies to Monitor, Conserve and Restore the Materiality of Modern Buildings in a Compatible, Durable and Sustainable Way." Report, CONSECH20, Working Package 2–Task (i), Version 03. https://consech20.eu/wp-content/uploads/2022/01/WP2_TUD-SoA_Report_New_Technologies_Restore.pdf.

This technical report was developed by the Technische Universiteit Delft working group within the European project CONSECH20 (CONSErvation of 20th century concrete Cultural Heritage in urban changing environments). Chapter 1 provides a concise but comprehensive state of the art on the most common damage processes affecting concrete structures. Chapter 2 focuses on techniques for structural assessment, and surveying and monitoring the state of conservation of concrete buildings. Chapter 3 focuses on materials and techniques for conservation of historic concrete, including repair techniques, surface treatments, electrochemical techniques, strengthening, and ductility increase.

Pepi, Raymond M., Laura N. Buchner, and Christopher Gembinski. 2014. "Conservation of Dalle de Verre at the New York Hall of Science." *APT Bulletin: Journal of Preservation Technology* 45 (4): 3–12.

This case study presents the investigation, diagnosis, and subsequent conservation work on the concrete dalle de verre panels at the New York Hall of Science (1964–65). It was authored by members of the team responsible for the conservation project. The article briefly discusses dalle de verre—a glass and concrete matrix developed in the 1930s—which was used in numerous buildings, such as churches, in the postwar period. The Hall of Science's dalle de verre is arranged in precast concrete panels with glass inset, originally coated with an epoxy. The article explains in detail the various investigations undertaken to understand the original materials and their deterioration, including laboratory and on-site testing. Testing of the proposed repair materials is also described. Typically, concrete dalle de verre panels are replaced with epoxy panels, but this project retained and conserved the large majority of the original panels. The methodology for achieving a conservation rather than large-scale replacement solution is outlined.

Piffaretti, Paola, and Giacinta Jean, ed. 2018. *Conservazione del calcestruzzo a vista: dal minimo intervento alla ricostruzione: analisi di casi studio = Conservation of Fair-Faced Concrete: From Minimum Intervention to Reconstruction: Examination of Case Studies*. Atlanti della conservazione. Florence: Nardini editore.

See annotation on p. 83.

Polder, Rob B., and Anthony W. M. van den Hondel. 2022. "Cathodic Protection of Reinforcement in Concrete: Overview and Experience over 30+ Years." In *International Conference on Concrete Repair, Rehabilitation and Retrofitting (ICCRRR 2022): Cape Town, South Africa, October 3–5, 2022*, edited by H. Beushausen, J. Ndawula, M. G. Alexander, F. Dehn, and P. Moyo, art. 01001. MATEC Web of Conferences 364. Les Ulis, France: EDP Sciences. https://doi.org/10.1051/matecconf/202236401001.

This paper comprehensively overviews long-term performance (up to thirty years) of cathodic protection systems applied on concrete structures in the Netherlands. Different case studies are presented. The authors analyze the service lives of different types of systems and components and give end-of-life considerations based on observed failures and replacements. Their observations show that activated titanium-based systems allow for very long service lives; the activated titanium itself kept working well beyond the observed period, while other components had relatively higher failure rates. Repairs required in the cases presented were predominantly due to failing anode-copper connections and, to a lesser extent, power sources and potential sensors.

Reed, Peter, Kate Schoonees, and Jeremy Salmond. 2008. *Historic Concrete Structures in New Zealand: Overview, Maintenance and Management*. Wellington, NZ: Science & Technical Pub., Dept. of Conservation. https://www.doc.govt.nz/globalassets/documents/science-and-technical/sap248entire.pdf.

See annotation on p. 84.

Robery, Peter. 2007. "Repair Guidance Note 3: Fixing Concrete." *Concrete* 41 (6): 9–10.

This is part of the series Repair Guidance Notes that supplement BS EN 1504 Products and Systems for the Protection and Repair of Concrete Structures. Definitions, Requirements, Quality Control and Evaluation of

Conformity. This note offers guidance on general principles of repair, identified as treating exposed steel, filling voids where concrete has been lost, stopping and preventing further deterioration, and strengthening of weakened structures. An introduction identifies principles for the treatment of corrosion resulting from carbonation or chloride attack. The note summarizes the factors that should be considered in a pre-repair assessment.

Robery, Peter. 2007. "Repair Guidance Note 4: Scope of EN 1504: Part 9." *Concrete* 41 (7): 9–10.

This is the fourth part in the series Repair Guidance Notes produced to supplement BS EN 1504 Products and Systems for the Protection and Repair of Concrete Structures. Definitions, Requirements, Quality Control and Evaluation of Conformity. This note aims to increase readers' understanding of part 9 of the standard, which contains guidance on repair approaches. It explains the different sections and identifies what is and is not addressed. This note includes two useful tables: table 1 outlines the assessment, specification, repair, and maintenance processes described in the standard, and table 2 identifies the primary concrete repair principles and methods.

Sahal, Mohamed, Yun Yun Tong, Beatriz Sanz Merino, Véronique Bouteiller, Élisabeth Marie-Victoire, and Suzanne Joiret. 2011. "Durability of Impressed Current Realkalization Treatment Applied on Reinforced Concrete Slabs after 5 Years." In *XII International Conference on Durability of Building Materials and Components, 12–15 April 2011, Porto, Portugal*, vol. 3, edited by Vasco Peixoto de Freitas, 1505–13. Porto, Portugal: FEUP Edições.

This study evaluates the durability of an impressed current realkalization treatment. Reinforced concrete slabs were cast and artificially carbonated, then realkalized using a current density of 1 Amp per square meter of steel following specification from CEN/TS 14038-1 (current version: EN 14038-1:2016 Electrochemical Realkalization and Chloride Extraction Treatments for Reinforced Concrete – Realkalization). The durability of the treatment was determined by several electrochemical measurements and analytical characterizations taken at different times after the realkalization treatment, up to five years following application. Immediately after the treatment, the efficiency of realkalization was demonstrated both by an increase in pH of the concrete matrix and by a lowering of corrosion current density values. The subject slabs were weathered for three and a half years in a natural environment. Five years after realkalization, an alkaline concrete zone still surrounded the reinforcing steel, but both the rest potentials and corrosion rate were almost back to their initial values. Results were confirmed through scanning electron microscopy observations, which revealed the presence of corrosion on the steel reinforcement.

Silman, Robert. 2000. "The Plan to Save Fallingwater." *Scientific American* 283 (3): 70–77. https://www.jstor.org/stable/26058864.

See annotation on p. 65.

Simpson, Lorne, Paul Gaudette, and Deborah Slaton. 2001. "Centre Street Bridge Lions: Rehabilitation and Replication of Historic Concrete Sculpture." *APT Bulletin: Journal of Preservation Technology* 32 (2–3): 13–20. https://doi.org/10.2307/1504734.

See annotation on p. 85.

Slaton, Deborah. 2000. "Cleaning Historic Concrete." *Concrete Repair Bulletin* (January/February): 14–15.

This paper summarizes methods available for cleaning historic concrete. Water, chemical, and abrasive systems are discussed. Different types within each category are identified, and the benefits and potential issues with each system are reviewed. The author recommends laboratory analysis of the surface deposits to be removed, as this will influence the selection of an appropriate cleaning method. Conducting trials with a range of potentially suitable cleaning techniques is an important part of the selection process. These should be assessed in terms of effectiveness, damage to the concrete surface, and changes in appearance of the concrete.

The author recommends keeping final field trial areas as reference for quality control in the implementation phase. The paper highlights the importance of having skilled site operators and the correct safety measures in place.

Terenzi, Gloria, Elena Fuso, and Stefano Sorace. 2024. "Structural Performance Study and Improvement of Artemio Franchi Stadium in Florence." *Engineering Structures* 298:art. 117068. https://doi.org/10.1016/j.engstruct.2023.117068.

See annotation on p. 66.

Thomas Trienens, Amanda, Glenn Boornazian, and Norman Weiss. 2008. "Concrete Repairs and Coatings for Frank Lloyd Wright's Solomon R. Guggenheim Museum." In *The Challenge of Change: Dealing with the Legacy of the Modern Movement: Proceedings of the 10th International DOCOMOMO Conference*, edited by Dirk van den Heuvel, 375–82. Amsterdam: IOS Press.

This paper documents an extensive testing program to identify the most appropriate crack fillers, patching materials, and coating materials for the conservation of Frank Lloyd Wright's Guggenheim Museum in New York. The paper first looks at the history of coating materials applied to the Guggenheim. The condition of the substrate is discussed, and defects that would impact selection of conservation materials are identified. It is noted that substrate repairs dating to the late 1990s had failed badly. Requirements for each repair material are discussed, and the testing program is described in detail. In 2006, following discussions with a group of manufacturers, six were invited to propose a crack filler, a patching material, and a coating material, all needed to accommodate thermal movement. The intent was to use a single manufacturer's system for material compatibility. Initial trials were undertaken on test panels created to match the composition of the original concrete. Laboratory tests subjected each of the repair materials, alone and in combination, to a range of aggressive environments. Two additional trials were undertaken to test for adhesion and color stability. The three best-performing product systems were selected for in situ tests, each undertaken in a different area of the building. One of the three systems was discounted due to poor performance, while the other two were subjected to additional in situ trials. After a nine-month review of the first set of in situ trials, Mapei International's repair system, using an acrylic crack filler and coating and a polymer-modified patching compound, was selected for implementation. The conservation work began in 2007 and was scheduled to finish in mid-2008.

Tilly, G. P., and J. Jacobs. 2007. *Concrete Repairs: Performance in Service and Current Practice*. Bracknell, UK: IHS BRE Press.

This report is one of the products of the EU-funded CONREPNET project, a network intended to "improve the durability of concrete repairs through performance-based rehabilitation" (p. vii). It documents the results of a series of questionnaires completed by respondents from all parts of the concrete repair industry, grouped as consultants, repairers, academics, and owners. The report is organized into chapters covering expectations of concrete repairs, performance of repairs in practice, current practices, and current research. Questionnaire respondents were asked to provide background on the structure, information on the original concrete deterioration that led to the repair, repair type, repair performance, and the reason for its subsequent failure. Most of the repairs reported were carried out between 1960 and 1990. The study acknowledges that the data requested requires a certain level of judgment on the part of the respondent, but it has produced important statistics, such as the fact that 50 percent of the repairs reported had failed. Forms of pre-repair investigation in current practice are discussed. It is noted that in most cases, visual inspections, at a minimum, are undertaken prior to repairs being carried out. Although approximately 90 percent of repair projects are subject to quality control, the lack of a standard procedure presents challenges. The section on current research reports data on 138 research projects related to concrete repair. Data collected included budget, number of participants, and general research topic. The final chapter discusses the current European Standards on concrete repair, particularly EN 1504 Products and Systems for the Protection and Repair of Concrete Structures- Definitions, Requirements, Quality Control and Evaluation of Conformity.

Tonelli, Monica, Rita Gelli, Rodorico Giorgi, Maria Isabella Pierigè, Francesca Ridi, and Piero Baglioni. 2021. "Cementitious Materials Containing Nano-Carriers and Silica for the Restoration of Damaged Concrete-Based Monuments." *Journal of Cultural Heritage* 49:59–69. https://doi.org/10.1016/j.culher.2021.03.002.

This paper describes the results of research to develop and test three different cement-based formulations to repair various types of nonstructural cracks and delaminations in concrete. To obtain good workability and a proper setting time, the different formulations were improved with additives. In addition, silica was included to enhance the adhesion to old concrete substrates, and halloysite nanotubes loaded with a corrosion inhibitor were incorporated to address the corrosion of reinforcement. A multi-technique approach was developed to characterize the formulations of the repair materials in terms of physical-chemical features, their adhesion to old concrete substrates, and the release of the corrosion inhibitor within the cement matrix. Given the promising results obtained, the formulations were applied at the war memorial at Torricella Peligna, Italy.

Tong, Yun Yun, Véronique Bouteiller, Élisabeth Marie-Victoire, and Suzanne Joiret. 2012. "Efficiency Investigations of Electrochemical Realkalisation Treatment Applied to Carbonated Reinforced Concrete – Part 1: Sacrificial Anode Process." *Cement and Concrete Research* 42 (1): 84–94. https://doi.org/10.1016/j.cemconres.2011.08.008.

This study aimed to test the efficiency and durability of sacrificial anode realkalization, in response to the limited literature on sacrificial anode realkalization compared to impressed current realkalization. Aged concrete specimens were realkalized using an aluminum alloy set in a cellulose alkaline buffer. The aluminum alloy provided current through galvanic reactions acting in a sacrificial manner. The time required to pass current with a galvanic system was three times greater than using an impressed current system. Testing indicated an increase in pH at the reinforcement immediately after treatment, which was confirmed one year after treatment. However, repassivation of the steel bars could not be verified. Deleterious effects on the concrete microstructure were not identified after treatment.

Urquhart, Dennis. 2014. *Historic Concrete in Scotland*, part 3, *Maintenance and Repair of Historic Concrete Structures*. Short Guide 5. Edinburgh: Historic Scotland. https://www.historicenvironment.scot/archives-and-research/publications/publication/?publicationId=c2a38944-eb81-44e8-bd5e-a59100fb611a.

This is the third volume in a three-part Short Guide produced by Historic Scotland. Part 1 (see annotation on p. 25) introduced the history and development of pre-1945 concrete, and part 2 (see annotation on p. 67) addressed concrete defects and decay, as well as site and materials investigation and assessment. This volume deals with the maintenance and repair of historic concrete structures and is intended as an introduction to the main concepts of conserving concrete heritage; it should be read in conjunction with the other two parts. The maintenance section discusses surface cleaning. It introduces the types of soiling that may need to be removed and discusses the main cleaning systems that are available, including pros and cons. This section also covers surface protection, which may be present as an original surface finish or introduced at a later stage. The second section looks at repair methods and materials, overviewing the factors to consider when undertaking repairs to historic concrete, as well as the treatments available. Four of the key topics highlighted are surface preparation, selection of repair materials, concrete patch repairs, and repair of cracks. Selection of appropriate methods and techniques is discussed. Each of the main causes of reinforcement corrosion is briefly described, and potential repair approaches and treatment methods available are presented. Due to their significance to the built heritage of Scotland, a short section on conservation of concrete maritime structures is included. A final table summarizes the key issues covered in this guide.

Wiggin, Vanessa Roth, and Seth Wiggin. 2007. "Set in Concrete? Conservation of Howard Taylor's 'The Black Stump.'" In *Contemporary Collections: Preprints from the AICCM National Conference 17th–19th October 2007, Brisbane*, edited by Amanda Pagliarino and Gillian Osmond, 25–30. Canberra: Australian Institute for the Conservation of Cultural Material.

This paper focuses on the conservation of Howard Taylor's *The Black Stump*. This sculpture is made of reinforced concrete, exposed aggregate, and glass tile, and was realized in 1975 for St. George's Terrace in Perth,

Australia, then relocated to the University of Western Australia. The authors describe the deterioration conditions, the conservation approach, and the implemented repair solutions. High chloride levels had induced the corrosion of the steel reinforcement, which in turn caused concrete cracking and tile loss. A detailed description of the cleaning and repair techniques is provided, together with a clear explanation of why these techniques were selected out of the many available options. Where necessary, previous repairs were removed.

Wiles, Andrew. 2009. "St John and St Mary Magdalene, Goldthorpe: The Conservation of an Early Concrete Building." *Transactions (Association for Studies in the Conservation of Historic Buildings)* p. 32:40–50. https://www.aschb.org.uk/wp-content/uploads/2022/01/Vol-32.pdf#page=41.

This is a case study of the conservation of Saint John and Saint Mary Magdalene, Goldthorpe, a historic concrete church in South Yorkshire, England. Completed in 1918, the concrete structure is unusual in an area where brick was the traditional building material. By the 1950s, the tower was showing major decay and a hard, impermeable layer of shotcrete was applied. In the 1990s, the church was listed as being at risk. Two years later, grant funding for conservation and repair work was received. This article discusses the methods of construction and concrete deterioration at this site, and provides a brief overview of the processes of deterioration of historic concrete. Poor-quality repairs in the 1950s allowed water to penetrate behind the gunite coating, allowing decay to continue beneath it. The conservation and repair works undertaken are described, as is the difficulty in locating a concrete repair contractor prepared to undertake work with a conservation emphasis.

Wilkie, Simeon, Ana Paula Arato Gonçalves, Paul Gaudette, and Ann Harrer. 2022. "Performance Evaluation of Patch Repairs on Historic Concrete Structures (PEPS): Preliminary Results from an American Case Study." In *Concrete Solutions 2022: 8th International Conference on Concrete Repair, Durability & Technology*, edited by M. G. Grantham, M. Basheer, and R. Mangabhai, art. 04004. MATEC Web of Conferences 361. Les Ulis, France: EDP Sciences. https://doi.org/10.1051/matecconf/202236104004.

This paper presents preliminary results of the international research project Performance Evaluation of Patch Repairs on Historic Concrete Structures (PEPS). The authors focus on the preliminary results from an in situ assessment of one of the case studies located in the United States. The building has aesthetically valuable exposed aggregate precast reinforced concrete elements on the facades, which suffer from recurring reinforcement corrosion. Consequently, these elements have been repaired multiple times. The paper discusses the differences in aesthetic and technical performance between repairs from three different intervention campaigns, each of which used different materials and techniques to reach the desired technical and aesthetic performance, with different degrees of success. Of the three repair campaigns evaluated, the research team only had diagnostics, design, and implementation records from the most recent one, but despite the lack of background information, in situ observations using a field microscope and inspection openings gave important evidence of the materials and techniques used in each campaign. For example, inspection openings of repairs from the two older campaigns showed, in one case, poor substrate preparation, and on the other, consolidation issues, both of which likely contributed to the deterioration observed on those repairs. The authors conclude that this case study demonstrates that despite available guidance on concrete repair, on-site implementation may not always follow it, resulting in repairs with poor performance. Moreover, they underline the need for owners and others responsible for hiring professionals to conduct this type of work to recognize the high level of experience needed.

Wilkie, Simeon, David Farrell, Nicola Lauder, and Ana Paula Arato Gonçalves. 2024. "Performance Evaluation of Patch Repairs on Historic Concrete Structures (PEPS): Preliminary Results from Two English Case Studies." In *Structural Analysis of Historical Constructions SAHC 2023*, edited by Yohei Endo and Toshikazu Hanazato, 899–912. Cham, Switzerland: Springer Nature Switzerland.

This paper presents preliminary results of the international research project Performance Evaluation of Patch Repairs on Historic Concrete Structures (PEPS). The authors focus on the results obtained on two English case studies: the first, built in 1935–37, had a history of carbonation-induced reinforcement corrosion; the second, built in 1928–30, had a history of chloride-induced reinforcement corrosion due to its location one mile from the sea. The authors investigated five patches at each of the two sites and, after a comparison of the results, they discuss the different repair approaches implemented. In the first case study, the attempt to reduce the loss of original fabric has resulted in repairs with a shorter lifespan and ongoing corrosion of the original reinforcement. The second case was more successful in terms of performance, but the approach toward the original fabric was different, since most of the corroded steel had been replaced with new steel; the same applied to contaminated and/or damaged concrete that was removed and replaced with repair material. The two cases underline how patch repairs are influenced by the skills of the craftspeople on-site, available materials, the original design, and environmental conditions, and highlight the potential dilemma vis-à-vis the philosophical approach to repair and the extent to which invasive interventions should be undertaken.

Wright, Alan, and Peter Kendall. 2008. "The Listening Mirrors: A Conservation Approach to Concrete Repair Techniques." *Journal of Architectural Conservation* 14 (1): 33–54. https://doi.org/10.1080/13556207.2008.10785015.

See annotation on p. 86.

Yazdi, Mohammad Ali, Elien Dejager, Mats Debraekeleer, Elke Gruyaert, Kim Van Tittelboom, and Nele De Belie. 2020. "Bond Strength between Concrete and Repair Mortar and Its Relation with Concrete Removal Techniques and Substrate Composition." *Construction and Building Materials* 230:art. 116900. https://doi.org/10.1016/j.conbuildmat.2019.116900.

The laboratory investigation presented in this article addresses how concrete removal techniques affect bond strength between concrete substrate and repair mortar. Different concrete compositions were taken into consideration: micro-concrete, gravel concrete, and crushed stone concrete. Three common concrete removal techniques are compared: hydrodemolition / water jetting, jackhammering, and grit blasting. The authors investigate the effect of aggregate size and uniformity of the substrate on bond strength and failure modes. Test results show a high correlation between the measured water transport and bond strength of samples. Microcracking and a weak interfacial transition zone seem to be the detrimental factors influencing bond strength of samples treated with jackhammering and hydrodemolition / water jetting, respectively. The results of this investigation can be useful when removal of existing concrete is needed due to deterioration and in preparation for repair.

Zykubek, Kris, Trevor Proudfoot, Katy Lithgow, and Douglas Carpenter. 2020. "Research on the Selection of Biocides for the 'Disinfection' of Statues and Masonry at the National Trust (UK)." *Journal of the Institute of Conservation* 43 (3): 225–41. https://doi.org/10.1080/19455224.2020.1810092.

This paper examines the result of a study dedicated to the in situ testing of sixteen biocides available on the British and European markets. Eleven properties of the National Trust located in England and Wales were selected as case studies, including both decorative and architectural elements made of various materials (limestone, sandstone, marble, slate and granite, cement-based composite, terra-cotta, and brick). On-site investigations included the preliminary evaluation of the local microclimate and visual analysis of the current condition of the objects. Previous conservation works were reviewed and taken into consideration. During the two years after application, the effectiveness of the products and the potential side effects were periodically evaluated. While the most important outcome of the project was to recommend which biocides to use and when their use would not be advisable, it is interesting to observe that the five most effective biocides showed the same level of effectiveness on cement-based composite, which may be useful information to professionals considering their use in concrete conservation projects.

# APPENDIX

## Concrete Conservation Research Projects

The research projects listed here were developed after the publication of the first edition of this bibliography. Organized by international collaborations, they produced multiple publications included in the present edition of this bibliography:

- REDMONEST (Development of a Monitoring Dynamic Network for Existing Structures of Cultural Patrimony) was an international research project supported by the Joint Programming Initiative on Cultural Heritage and Global Change (JPI CH). It was developed between 2014 and 2016 by Laboratoire de Recherche des Monuments Historiques (France), ELab Scientific srl – Consiglio Nazionale delle Ricerche (Italy), Istituto per la Conservatione e la Valorizzazione dei Beni Culturali – Consiglio Nazionale delle Ricerche (Italy), Centre Scientifique et Technique de la Construction (Belgium), and the Université de Liège (Belgium), and coordinated by Instituto de Ciencias de la Construcción Eduardo Torroja (Spain). This project aimed to develop a system to monitor corrosion in historic concrete in real time. For more information, visit heritageresearch-hub.eu/project/redmonest.
- InnovaConcrete was a large-scale international research project funded by the European Union's Horizon H2020 Research and Innovation Programme and developed between 2018 and 2021. The Universidad de Cádiz coordinated the project consortium, composed of twenty-nine partners from eleven different countries. This project aimed to develop new materials for the repair and treatment of historic concrete, raise awareness of concrete heritage in participating countries, and propose a conservation approach to concrete heritage.
- CONSECH20 (CONSErvation of 20th century concrete Cultural Heritage in urban changing environments) was an international research project supported by the Joint Programming Initiative on Cultural Heritage and Global Change (JPI CH). It was developed between 2019 and 2021 by the Institute of Theoretical and Applied Mechanics of the Czech Academy of Sciences (ITAM CAS), Delft University of Technology (TU Delft), the University of Cyprus (UCY), the University of Genoa (UNIGE), and the Institute of Sociology of the National Academy of Sciences of Belarus (ISNAS). This project aimed to develop innovative approaches for the conservation of twentieth-century heritage concrete buildings against ever-changing urban impacts, taking into account both technical and social aspects, and focusing on the four different European partner countries: Cyprus, Italy, the Netherlands, and the Czech Republic. For more information see https://consech20.eu/.
- Performance Evaluation of Patch Repairs on Historic Concrete Structures (PEPS) is an ongoing international research project started in 2018 by the Getty Conservation Institute (United States), Historic England (England), and Laboratoire de Recherche des Monuments Historiques (France). The project involves in situ and laboratory tests

performed on representative historic concrete structures in the three partner countries. The assessment methodology was developed by the three institutional partners on the PEPS project. For more information visit getty.edu/projects/concrete-conservation/performance-evaluation-of-patch-repairs.

# ACKNOWLEDGMENTS

In this second edition, we built on the work by Alice Custance-Baker and Gina Crevello in selecting and annotating sources, with Stefania Landi mostly working on chapters 2 to 5, and Ana Paula Arato Gonçalves working mostly on chapter 1, leading the research, and managing the process. The structure developed for the first edition—under the guidance of Kyle Normandin, former senior project specialist at the Getty Conservation Institute, and Susan Macdonald, head of the Getty Conservation Institute's Buildings and Sites department—was largely retained.

The second edition would not have been possible without the valued contributions of:

- Anna Duer, reference librarian at the Getty Conservation Institute's Information Center, who provided initial research for the first edition and many new additions for the second edition, making sure it was truly comprehensive, and provided support in managing the reference database for this project
- Elsa Haarstad, graduate intern 2022–23 in the Conserving Modern Architecture Initiative, who identified new references
- Kate Mendoza, associate editor at the Getty Conversation Institute, who guided the publication process for this volume
- Timothy Y. Ong, graduate intern 2023–24 in the Conserving Modern Architecture Initiative, who identified new references and helped manage the reference database
- Simeon Wilkie, former associate scientist at the Getty Conservation Institute's Science Department Built Heritage Research group, who contributed many references outside of the conservation field.

# ABOUT THE CONTRIBUTORS

## First Edition

**Gina Crevello** is an architectural conservator and corrosion specialist with an MSc in historic preservation and an advanced certificate in the conservation of historic buildings and sites from Columbia University's Graduate School of Architecture, Planning and Preservation. She trained in electrochemistry and corrosion diagnostics and is the founding principal of Echem Consultants, specializing in forensics and electrochemical repair of historic and existing buildings. Crevello is a professional associate of the American Institute of Conservation and a recognized professional (and past president) of the Association for Preservation Technology, and has been an active member in several technical committees for professional organizations over her career. She has co-chaired the NACE Concrete Service Life Conference for four years and has published and presented extensively on corrosion diagnostics and durability of historic structures.

**Alice Custance-Baker** is a former consultant to the Getty Conservation Institute. She worked in the preservation field in both the United States and Scotland as a materials conservation specialist with experience in research, materials analysis, surveying, and hands-on conservation work. She previously served on the board of directors of the Western Chapter of the Association for Preservation Technology. Custance-Baker received her BSc Hons and MSc by research in geology from the University of Edinburgh in collaboration with Historic Environment Scotland. She has undertaken a wide range of professional conservation training, including the International Centre for the Study of the Preservation and Restoration of Cultural Property (ICCROM) International Course on Stone Conservation.

**Susan Macdonald** is the head of the Buildings and Sites department at the Getty Conservation Institute. She has worked in the private and government sectors in Australia and the United Kingdom, and has written widely on twentieth-century heritage, including authoring and editing *Concrete: Building Pathology* (2002), and coauthoring the Getty Conservation Institute's *Conservation Principles for Concrete of Cultural Significance* (2020) with Ana Paula Arato Gonçalves and *Concrete: Case Studies in Conservation Practice* (2019) with Catherine Croft. She is a member of the Docomomo International Specialist Committee on Technology (Docomomo ISC/T), the International Council on Monuments and Sites International Scientific Committee on Twentieth-Century Heritage (ICOMOS ISC20c), and the Association for Preservation Technology's Technical Committee on Modern Heritage.

**Kyle Normandin** is a principal at Wiss, Janney, Elstner Associates Inc., with more than twenty years of experience in historic preservation. He is an adjunct associate professor at Columbia University's Graduate School of Architecture, Planning and Preservation, where he received his MS in historic preservation. He holds a bachelor of arts in architecture from the College of Environmental Design at the University of California at Berkeley. He was formerly a senior project specialist at the Getty Conservation Institute working under the Conserving Modern Architecture Initiative. He has contributed many technical papers on architectural conservation, and he serves as associate editor for the *Journal of Architectural Conservation*. Normandin is a member of the Association for Preservation Technology's College of Fellows and is a fellow member of the American Institute of Conservation. He serves on the Bureau of ICOMOS ISC20c and is a member of Docomomo ISC/T.

## Second Edition

**Ana Paula Arato Gonçalves** joined the Getty Conservation Institute in 2017. She is currently an associate project specialist focused on the conservation of modern concrete. She has a bachelor's degree in architecture from the School of Architecture and Urbanism at the Universidade de São Paulo and an MS in historic preservation from the University of Pennsylvania. In Brazil, she worked as an architect in private practice and for public institutions engaged in the conservation of modern buildings. She coauthored the Getty Conservation Institute's *Conservation Principles for Concrete of Cultural Significance* (2020) with Susan Macdonald.

**Stefania Landi** is a researcher in architectural conservation at the Politecnico di Milano (Department of Architecture, Built Environment, and Construction Engineering), where she develops research activities in the field of architectural heritage and cultural landscapes preservation. She has a master's degree in building engineering and architecture (2012) and a PhD in architectural conservation (2017) from the Università di Pisa. In 2015 and 2016, she was a visiting researcher at the Getty Conservation Institute, working alongside the Conserving Modern Architecture Initiative. She is co-secretary general of ICOMOS ISC20c, executive board member of ICOMOS Italy, and a member of SIRA (Società Italiana per il Restauro Architettonico) and CSSAr (Centro di Studi per la Storia dell'Architettura).

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