Literature Review

Conserving Concrete Heritage

An Annotated Bibliography

Edited by
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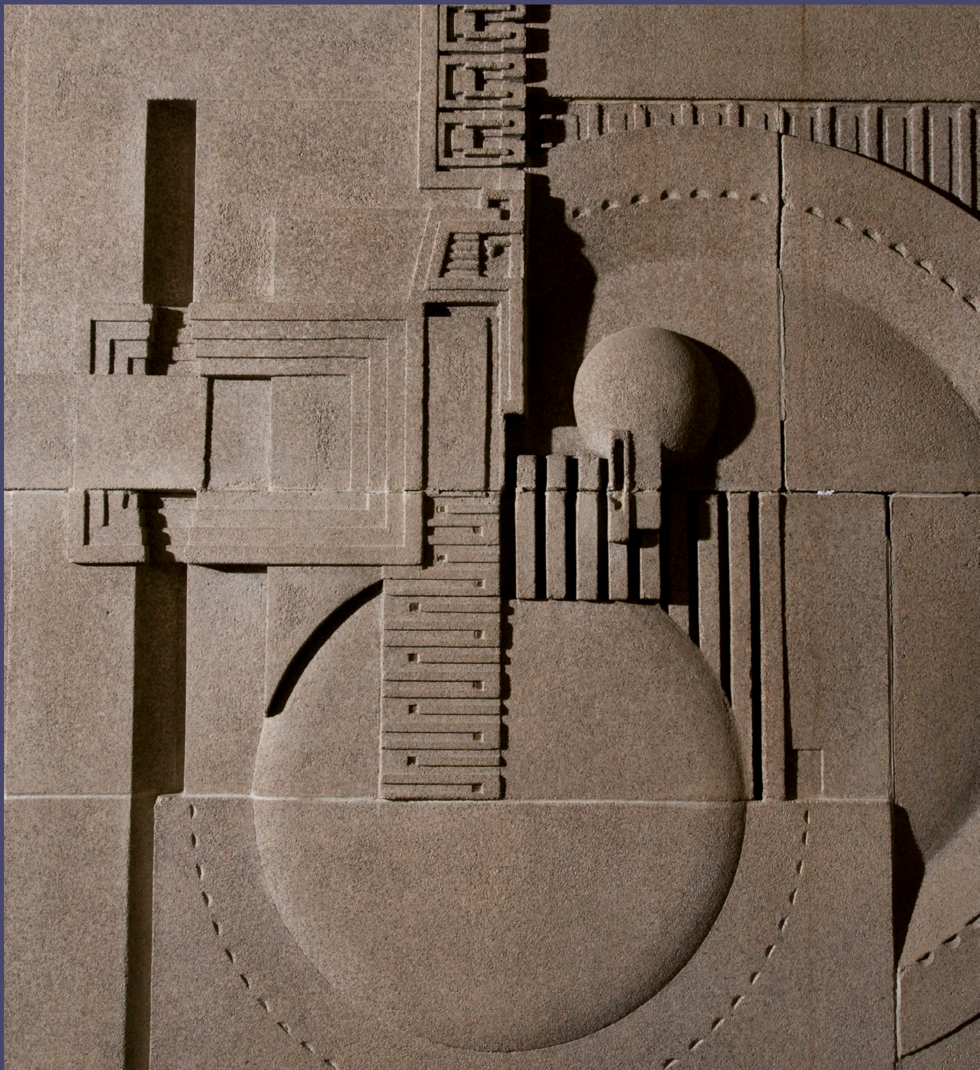

The Getty Conservation Institute

Conserving Concrete Heritage: An Annotated Bibliography

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LOS ANGELES

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The Getty Conservation Institute works to advance conservation practice in the visual arts, broadly interpreted to include objects, collections, architecture, and sites. It serves the conservation community through scientific research, education and training, model field projects, and the dissemination of the results of both its own work and the work of others in the field. And in all its endeavors, the GCI focuses on the creation and dissemination of knowledge that will benefit the professionals and organizations responsible for the conservation of the world's cultural heritage.

Front cover: Fireplace Detail. Hollyhock House, Los Angeles, California (Frank Lloyd Wright, 1919–21). Photography by Joshua White/JWPictures.com. Courtesy of Hollyhock House.

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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 means it is a ubiquitous part of the built environment in most parts of the world. Advances in reinforced concrete in the twentieth century captured the imagination 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 and experience with the conservation of concrete, but there is still much work to be done to secure better conservation outcomes that are more compatible with accepted practice. Access to information about the material, its history, deterioration, 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 those interested in the conservation of concrete by identifying specific resources on the subject. Additionally, by examining the literature on conserving concrete heritage, it will promote understanding of the current state of knowledge of the subject, demonstrate the scope of current technical information available in the field, and assist with identification of gaps in the existing literature and research.

This annotated bibliography covers mass concrete, reinforced concrete, cast-in-place concrete, post-tensioned prestressed concrete, and precast concrete. The references selected for inclusion have been drawn largely from *Conserving Twentieth-Century Built Heritage,* a bibliography first prepared by the Getty Conservation Institute in 2011 and revised in 2013. The list was updated 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. Citations selected for annotation were limited primarily to English-language publications. It is acknowledged that this bibliography may not be comprehensive at this stage.

The literature cited herein is largely specific to the conservation of concrete rather than concrete repair generally, a topic on which there is a very large body of literature. This is not to say that information addressing concrete repair generally is not relevant. It unquestionably is. Rather, it is recognized that there are additional considerations that must be taken into account when dealing with a building or structure of heritage significance. At this stage, this bibliography does not identify all of the critical texts from the repair sector that would be of use to conservation practitioners; this may be a useful addition and could be considered at future stages. That said, a limited number of more general texts that were determined to be directly applicable to the conservation of concrete have been included.

This bibliography is organized in five chapters, which echo the usual steps in the conservation process and have been used in key books on concrete conservation. They are outlined below. Publications that span more than one category are noted in all relevant chapters, but full annotations appear only with the first mention.

Chapter 1: History and Development of Concrete

This chapter includes citations to literature on the history and development of concrete. Understanding the history of a building or structure and its constituent materials is the first step in the conservation process. Texts contemporaneous with the development of concrete, as well as more recent research, are included.

Chapter 2: Concrete Deterioration and Damage

Although the mechanisms of concrete deterioration are largely understood and well researched, and there is a significant body of literature on this subject, the number of publications specific to the deterioration mechanisms and resultant decay in early types of concrete buildings and structures is limited. This chapter contains citations for resources focused on the deterioration of significant concrete buildings and structures. References include a limited number of sources on non-historic buildings, laboratory research, and the deterioration of civil structures that were determined to be of specific relevance to historic concrete.

Chapter 3: Historic Concrete Diagnostics, Monitoring, Nondestructive Testing, Investigation, and Assessment

Understanding the cause of deterioration and failure is a vital step in the conservation process. Assessing the modes of failure on a concrete building can entail a multitude of complex test methods focused on the building's physical properties. Nondestructive testing (NDT) and diagnostics are common in the discovery phases of an investigation; however, few publications exist which examine applicability of NDT to concrete buildings and structures that are of heritage significance. Semi-destructive tests typically play a role in diagnosing problems and their causes, but these can have conservation implications. This chapter includes resources that model sound diagnostics processes and methods.

Chapter 4: Approaches to Conserving Historic Concrete

This chapter includes resources focused on conservation approaches and methodologies for the repair and maintenance of concrete buildings. It includes case studies that highlight a range of such approaches. The literature covers all phases of the repair process including the role of maintenance as a conservation action. The sources demonstrate a sound conservation approach and include general guidance, methodologies specific to concrete conservation, and case studies.

Chapter 5: Conservation and Repair of Historic Concrete

This chapter contains citations to resources focused on the physical conservation of concrete heritage. They cover a range of repair types including cleaning, patch repair, chemical treatments, and other repairs typical of a conservation project. Selected case studies and specific repair typologies are included in this chapter, illuminating the successes and failures of the past two decades.

CHAPTER 1

History and Development of Concrete

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.

This report on the history of the development of Meridian Hill Park, Washington, DC (constructed 1915–36), was written in preparation for conservation and repair works. It focuses on the development of the concrete technologies used at Meridian Hill Park, looking in detail at preparation techniques, exposed aggregate finishes, and the use of reinforcement. John J. Earley, who developed and adapted techniques to achieve the desired concrete finishes at the site, is an important part of this story. The report documents three phases of the project, identifying the developments and advances in knowledge that were made during each period. From 1915 to 1916, when initial experimentation was undertaken, mock-ups were produced and the start of construction at the west wall occurred. From 1917 to 1918, techniques were developed to improve color, texture, and form. They included important steps such as the grading of aggregate and the 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 report concludes with some brief thoughts on the approach to future conservation and repair works at this site.

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, produced in 1969 by the National Concrete Masonry Association (NCMA), documents the history of this organization alongside the history and development of concrete block (with a focus on the United States). The first half of the book 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 second half of the book is divided into chapters addressing areas of particular importance and key developments for the concrete block industry. These are: lightweight aggregates, low-pressure curing, autoclave curing, transportation and handling, concrete masonry machinery, and specifications. The text is very detailed, with information provided on specific industry figures, manufacturers, and products, along with the relevant dates. This book provides detailed documentation of the concrete block industry from the start of the nineteenth century to 1969. The final chapter predicts a growing industry of fewer, but larger, producers of a high-quality product and fully automated production lines.

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

This doctoral thesis has three main aims: to fill an apparent technical gap in contemporary literature on reinforced concrete, to document the historical importance of the construction revolution brought about by the creation of reinforced concrete, and to focus on key contributions to the development of reinforced concrete. The thesis 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 entitled: "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." This thesis covers 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 of the development of reinforced concrete, identifies and discusses important aspects of the science and engineering, and includes calculations and technical drawings.

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 the historic use of concrete 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 are used to illustrate various issues that relate to the historic development of materials, such as the development of formwork and the use of high alumina cement. The conservation of concrete is discussed briefly in terms of site investigation and assessment, and repair and remediation, followed by discussion of the treatment of corrosion damage. Brief references are made to the treatment of other common defects.

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

Originally published in 1959, the second edition of *Concrete* (2004) includes a new foreword by Kenneth Frampton and an introduction by Réjean Legault. This historical account of the early period of reinforced concrete is described by Frampton as three books brought together as one. Part 1 provides an authoritative background on the material and discusses its development, focusing primarily on France in chapter 1, and on 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 during the nineteenth and early-twentieth centuries. It explores the relationship between the role of 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—whom Collins describes as the grandfather of reinforced concrete—and his role in the development of the new structural approaches made possible by reinforced concrete. He presents Perret as a pioneering figure in modern architecture The revised edition closes with three previously unpublished essays, two of which are on Perret. In the third, "The New Brutalism of the 1920s," Collins portrays Perret as the pioneer of the expressive and honest use of reinforced concrete, long before Le Corbusier's *béton brut*. This invaluable book traces the early architectural development of reinforced concrete as it relates to emerging forms of modernism. Contemporary black and white photographs of many pioneering concrete buildings provide a wonderful resource for those interested in tracing the fate of these seminal concrete buildings.

Cowden, Adrienne Beaudet. 1993. *Historic Concrete: An Annotated Bibliography*. NPS Reading List. Washington, DC: U.S. Dept. of the Interior, National Park Service, Preservation Assistance Division.

This bibliography on historic concrete brings together key texts covering the period 1900 to 1950, with the exception of the first chapter, which includes texts written as early as 59 B.C. It has been divided into four chapters that 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. *Concrete Architecture*. London: Laurence King.

The opening line, "This book is a celebration of concrete" (p. 8) is a good representation of the contents. A detailed introduction is followed by illustrated case studies that are divided into four chapters: "Home," "Work," "Play," and "Landscape." Although the case studies are about recent structures, built in the 1990s and early 2000s, the introduction to each chapter references earlier, twentieth-century works. The introduction, "The Challenge of Concrete," provides a detailed history of concrete from its beginnings. Croft identifies the main phases of concrete development, key figures, and the important role of the development of cement technology. One of the main focuses of the introduction, as indicated by the title, is the generally negative public and professional perceptions of concrete and the resulting impact on the material's use and popularity. Even architects who were early users of exposed concrete—including Frank Lloyd Wright—are quoted expressing negative views of the material. Croft notes that there was a breakthrough in the use of exposed concrete in the post Second World War period, partly because it was a readily available material, but also out of an interest in modernization and a desire to break with the past.

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 on 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 its development, and introduces the key figures involved in the development of different aspects of this compound material. Rather than following a straightforward chronology for the development of reinforced concrete, different aspects of a reinforced concrete structure are introduced and discussed separately, including monolithic structures and development of the mushroom slab, reinforced concrete columns, and concrete bridges. This is followed by information on the types of testing conducted to better understand the systems, their physical properties, and capabilities.

Gaudette, Paul E., and Deborah Slaton. 2007. *Preservation of Historic Concrete*. Preservation Briefs 15. Washington, DC: National Park Service, Heritage Preservation Services.

This Preservation Brief, produced by the United States National Park Service, provides an overview of the historic use of concrete in the United States. It introduces the history of the use of concrete and its manufacture with many illustrated case studies. The characteristics of concrete are briefly discussed. Detail is given on the mechanisms and modes of deterioration of concrete, and causes of the various modes of deterioration and their impacts on concrete structures are evaluated. A section on planning for concrete conservation highlights the importance of investigation and analysis prior to undertaking any repair work. The most comprehensive section discusses the methods of maintenance and repair. Fieldwork and site issues that may impact the repair process are also discussed. These include surface preparation, formwork and molds, selection of repair materials, and repair techniques. The brief provides a good introduction to the preservation of historic concrete.

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

This publication from the Institute of Civil Engineers contains fourteen papers on different aspects of the history and development of concrete. The papers are written by several different authors active in the field of concrete construction. Each paper focuses on a different time period and/or key subject, with most focused on developments during the twentieth century. The group of papers 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 and contrast developments in other countries.

Jonge, Wessel de, and Arjan Doolaar, eds. 1998. *The Fair Face of Concrete: Conservation and Repair of Exposed Concrete*. Preservation Technology Dossier 2. Eindhoven: 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. The publication is divided into three sections: "History and Development," "Diagnose and Remedy," and "Case Studies." The papers in "History and Development" provide a good introduction to 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 electro-chemical techniques as a means of repairing historic concrete. The nine case studies present conservation works undertaken to exposed reinforced concrete structures that date from 1920 to 1968. Three case studies of particular note are those on the Bahá'i 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 two 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 full façade and undertake a full replacement. Pörtner discusses the same case studies, but advocates a contrasting approach, which is to undertake minimal patch repairs. This volume provides insights into the early years of the conservation of historic concrete.

Kemp, Emory Leland. 1982. *History of Concrete, 30 B.C. to 1926 A.D.: Annotated*. ACI Bibliography, no. 14. Detroit: American Concrete Institute.

This annotated bibliography was produced by the American Concrete Institute as part of an effort to increase interest in the history of concrete. The project was initiated in 1976, the year of the United States bicentennial. It used the same age criteria as many bicentennial history projects by 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; however, 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.

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

This book is a comprehensive text focusing on the diagnostics and repair of architectural concrete from the 1890s onward. It begins with a comprehensive history of architectural concrete in Great Britain, from early typologies, materials, and construction methodologies to advancements and improvements of materials, standards, and construction through the 1970s. Chapters 3 and 4 focus on structural assessments, condition assessment, and survey methodologies to identify and catalogue concrete deterioration. 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 is given to 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. A number of maintenance options are discussed with coatings being the main focus. The key concept is that by understanding factors affecting concrete durability, one can better plan construction projects. Preventive maintenance and proactive repairs can provide a significant cost savings over the life of a building and extended 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 key is to shift the industry paradigm from "respond and repair" to "predict and prevent" (p. 259), which is a necessary approach in heritage conservation.

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. The purpose of the book is to assist the investigator in identifying the type of system that has been used in a structure and to 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 that have been used. The sixth chapter is a bibliography. The text is supplemented by a significant amount of technical data, and numerous drawings and illustrations. 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." This book is a first edition. The authors note that there are gaps in the information and that further editions will be published as more information is sourced.

Morris, A. E. J. 1978. *Precast Concrete in Architecture. London*: George Godwin.

This book on precast concrete is intended to provide guidance to those wishing to achieve high-quality design in precast concrete; it is not a technical guide. Morris also wishes to bring attention to aspects of the field that are often misinterpreted or overlooked. In the first three sections of the book, he documents the history of the development of precast concrete through the 1970s. In the final section, comprising the second half of the book, he 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 in chronological order, 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 and developments of precast concrete in the United States through 1950. Part 2, "The 1950s and '60s: An Era of Consolidation," focuses on the construction of the Alton Estate West (Roehampton Lane Flats), London (1953–58), which marks a time of change for the precast industry; precast concrete cladding and systems development are two of the key topics discussed. In the second part of this section, Morris addresses developments in Britain and in the United States in the 1960s and gives many examples of precast concrete architecture from this period. In part 3, "Technology of the 1970s," Morris looks back on predictions he had made for the industry in 1966. He 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, IL: Prestressed Concrete Institute.

This book is a compilation of a series of articles published in *PCI Journal* between 1978 and 1980 in celebration of the Prestressed Concrete Institute's twenty-fifth anniversary. All are focused on North America, with the majority of them specifically addressing developments within certain states or regions, including Florida, Tennessee, Colorado, and the western United States, as well as Canada. A few focus more specifically on people within the industry and their contributions to the development of prestressed concrete. The final three articles, each a continuation of the one before, were written to fill important gaps in the history and development of prestressed concrete that were not covered elsewhere in this 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: Ashgate/Variorum.

This publication brings together a collection of sixteen papers originally published in a range of journals and magazines during the twentieth century. Each addresses a topic relevant to the history and development of reinforced concrete. Some focus on the work of specific pioneers in the field: Smirke, Wilkinson, Hennebique, Mouchel, and 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 in the volume 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, Ohio (the first reinforced concrete skyscraper); early concrete bridges in California; and early reinforced concrete structures in New South Wales, Australia. An introduction to the volume links the papers, providing 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.

Odgers, David, ed. 2012. *Practical Building Conservation: Concrete*. Farnham: 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 with the deterioration and assessment of concrete structures, and best practices for their conservation. 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, fair-faced finishes, and coatings are addressed in relation to 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 is provided at the end of each chapter. A collection of eight case studies covers a wide variety of treatments and approaches. These include traditional repair, proprietary systems, combined traditional and innovative repairs, large-scale repairs to mass concrete, cathodic protection of reinforced concrete, repairs to concrete in a marine environment, repairs using precast panels, and finally repairs to concrete mosaic finishes. The book closes with a brief overview of care and maintenance. Odgers addresses the conservation of this complex material in a manner that is useful and accessible to beginning and seasoned professionals alike.

Onderdonk, Francis S. 1998. *The Ferro-Concrete Style: Reinforced Concrete in Modern Architecture: With Four Hundred Illustrations of European and American Ferro-Concrete Design*. Santa Monica: Hennessey + Ingalls. First published 1928 by Architectural Book Publishing Co.

Written in 1928, this book supports the emerging use of reinforced concrete and, more specifically, the potential for development of a new ferro-concrete architectural style. This is primarily an account of then-current trends and methods for utilizing reinforced concrete as both a decorative and structural architectural material. While there is some reference to previous materials and styles, this book is focused on current developments and gives few specific historical details. Onderdonk provides many well-illustrated examples of the specific architectural styles and features under discussion. Throughout the text, quotes from important figures—including Frank Lloyd Wright, John J. Earley, and John Ruskin—support his theories. This book is divided into five chapters: “The Possibilities of Reinforced Concrete,” “Surface Treatment and Sculpture,” “Concrete Tracery,” “The Parabolic Arch,” and “The Ferro-Concrete Style.” A wide variety of methods and techniques for achieving specific forms and finishes are discussed along with simplified technical details.

Palley, Reese. 2010. *Concrete: A Seven-Thousand-Year History.* 1st ed. New York: The 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 is focused on developments within the twentieth century and beyond, with the last six chapters addressing different contributors, such as Thomas Edison and Henry M. Flagler, as well as particular historical uses of concrete, such as military or artistic uses. Much of the discussion on the use of concrete in the twentieth century as a whole focuses on its military uses, particularly in relation to the Second World War. The book is written in a narrative style, with some of the contents reflecting the author's interests rather than a traditional set of key moments or figures in the history of concrete. Palley addresses some of the reasons that the use of concrete throughout history has been sporadic rather than continuous, as well as many of the social factors that have influenced its place in history.

Peterson, J. L. 1954. History and development of precast concrete in the United States. *Proceedings—American Concrete Institute* 50 (2): 477–96.

Peterson 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 their precast unit sizes, information on the production of the units, and on the construction techniques employed. Many of the examples represent important developments in the technology and use of precast concrete. Peterson concludes with a prediction of the future of precast concrete, identifying the increased availability of large truck cranes and increased size and efficiency of transit-mix trucks as important advances encouraging further developments in the precast industry.

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. Each of the sections that follow 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 of social change in the twentieth century. The three case studies in this section are less about specific buildings than they are about the development of concepts and design ideas. The next section looks at the Hennebique system and its importance in the evolution of the uses and abilities of reinforced concrete. Four supporting case studies on specific European domestic and industrial buildings are followed by a fifth that addresses key buildings of Dutch modernism. A section on invention of the mushroom column identifies how this technology enabled advances in design and the use of internal space. Industrial and commercial case studies from Europe and the United States describe the use of this technology. The final two sections of this chapter address technological advances that have enabled new ways of using space. The case studies from the first of these two sections are on specific architects and engineers and their contributions to certain forms of architecture, rather than individual buildings. The case study buildings in the final section bring us up to architecture of the present day.

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. Prudon concludes with an overview of several of the techniques available for the repair and conservation of historic concrete.

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. It was intended to fill a gap in the literature that Raafat dates to 1928 (p. 12). Though written primarily from an American 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. Rafaat introduces the key pioneers and looks at the 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 Book Company.

This is a technical publication specifically aimed at experienced engineers. Published in 1912, it provides an overview of contemporary theories and understanding of reinforced concrete in the United States, as well as a history of reinforced concrete. The first section addresses the history of the development of reinforced concrete. It includes 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.

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 convention in the fall of 2005. The papers cover a number of specialized topics on prestressed concrete, focusing on developments and uses over the previous fifty years. Topics include the early uses of prestressed, pretensioned, and post-tensioned concrete in Europe and North America; the development of construction techniques, codes, and standards; and the uses of 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 of the volume examine two important figures in the history of prestressed concrete: Gustave Magnel and Ned H. Burns.

Shand, P. Morton. 1932. Steel and concrete, a historical survey. *Architectural Review* 72: 169–79.

Writing in 1932, Shand asserts that the introduction of steel and concrete building materials altered the roles of engineers and architects and argues that as a result, engineers play a more critical role than architects. The 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 expanded from a paper on rock-faced concrete block published ten years previously.[1] Simpson dates the development and popularization of the manufacture and use of this material 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 block included the development and standardization of Portland cement, and intensive advertising of manufacturing machines and of concrete block itself. One of the great selling points for rock-faced concrete block was that it was inexpensive, and quick and easy to produce. Concrete block is noted as being particularly popular in areas where there was not easy access to other construction materials such as timber, brick, and stone. 1905 saw the formation of organizations such as the Concrete Block Machine Manufacturers' Association and the National Association of Cement Users. Despite the popularity of rock-faced

1 Pamela H. Simpson. 1989. Cheap, quick, and easy: The early history of rockfaced concrete block building. *Perspectives in Vernacular Architecture* 3: 108–18.

concrete block among the masses, Simpson identifies several sources that indicate that the material was far less popular among architects and the elite, who regarded it as a poor imitation of stone. One of the key problems identified with the use of concrete block was its weight, which seems to be the major factor that eventually led to its loss of popularity; by the late 1920s and 1930s concrete block 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, is focused on the United Kingdom. It is divided into periods related to the development of concrete, starting as early as 5600 BC, although the majority of the publication focuses on the development of modern concrete from 1750 AD onward. The modern history of concrete is presented in sections entitled: "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 of the key players in the development of concrete and provides illustrated, case-study examples including several firsts, such as construction of the first all-concrete house in 1835.

Urquhart, Dennis. 2013. *Historic Concrete in Scotland. Part 1, History and Development.* Short Guide 5. Edinburgh: Historic Scotland. http://conservation.historic-scotland.gov.uk/historic-concrete-short-guide.pdf.

This is the first section 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 use of rammed earth (clay) construction in many parts of Scotland to mass concrete. This guide is focused on pre-1945 concrete; however, there is also a note on post-1945 concrete identifying some of the constraints and developments of this period. Codes of practice are discussed throughout the guide; 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 (see p. 27 below) and 3 (see p. 72 below) of this Short Guide. A detailed appendix provides a list of pre-1945 concrete buildings in Scotland, noting each structure's type, date, location, and additional comments.

CHAPTER 2

Concrete Deterioration and Damage

Berkowski, P., and G. Dmochowski. 2014. Examples of concrete structural elements in early 20th century buildings in Wrocław (Poland)—Case studies. 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, 699–706. Boca Raton, FL: CRC Press.

This study presents an approach to assessing the suitability of nineteenth- and early-twentieth-century reinforced concrete structural elements for extended service life. Some of the structures concerned are deemed historic. Extending service life is a common demand in engineering today. Repair and strengthening while following ICOMOS charters poses challenges for engineers and conservation professionals. The rehabilitation process should address both the structural elements and the heritage value. Diagnosis and repair options are outlined in EN 1504, but when repair and strengthening are applied to heritage structures there are limitations in use. The authors emphasize the need to review existing documents and understand historic construction materials. Case studies investigate foundation structures, monolithic floor slabs, reinforced concrete slab floors, precast balcony slabs, structural framing systems, and arch framing structures. Overviews of the structural elements, in situ conditions, challenges, and repair solutions are provided. As the one-hundred-year-old concrete structural elements were not exposed to any destructive external influences, the study concludes that their structural and operational characteristics could support continued service life and a change in function.

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.

This article addresses the use of impressed current realkalization for eight reinforced concrete columns, which support the cupola of the bell tower at the church of Sant'Antonio Abate (1926–30) in Valmadrera, Italy. A thorough technical description of realkalization is provided, followed by an investigation into the conditions that affect corrosion. The repair limitations of this particular project are highlighted. Performing patch repairs on these columns was deemed impractical due to the highly carbonated condition. Removal of contaminated concrete would have undermined the structural stability of the columns. 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 for hydroxyl ion build-up at the steel and various depths of the concrete was performed. It was determined that the alkalinity increased up to 10mm from the surface of the concrete inward, and that there was also an increase at the steel surface. The results were successful in providing an extension of service life. This project illustrates best practices and acknowledges the challenges within the field of conservation and concrete repair. Trials of electrochemical treatments should always be performed; however, they are of particular importance on landmark buildings.

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

This report by the British Cement Association provides advice and guidance on approaches to concrete buildings in which alkali-silica reaction (ASR) is suspected. It details the types of site investigation and testing that should be undertaken, outlines the requirements of a good site observation, identifies the correct sampling procedure, discusses in detail the available laboratory tests for the identification of ASR, and looks at the possible risk of future reaction. It is clear that no single observation can positively identify the presence of ASR and associated damage. The results of any investigation, incorporating site and laboratory observations, must be assessed as a whole, then the level of probability that ASR is present and causing damage can be determined. Throughout the text, it is observed that the presence of ASR does not necessarily mean that it has caused damage, and other potential damage factors should not be ruled out. The text is well illustrated with diagrams, photographs, flow charts, graphs, and tables to aid the understanding of the processes involved. Detailed appendices provide additional information on some of the processes described within the text. Appendix D provides a list of “common rock and mineral aggregates” that may “contain potentially alkali-silica reactive components” (p. 34).

Brocklebank, Ian. 2005. Concrete, carbonation, and corrosion. *Journal of the Building Limes Forum* 12: 35–45.

This is an introduction to the potential problems of deterioration in reinforced concrete. It also identifies some of the repair solutions available. The author addresses the issue that the field of research related to the repair of reinforced concrete 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*, 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; each is assessed for its appropriateness in a conservation context. Brocklebank notes that in some cases, work undertaken in a conservation-appropriate manner may invalidate a manufacturers’ standard guarantee.

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

This book provides the 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. Though not specific to heritage structures, this book provides an understanding of corrosion diagnostics in reinforced concrete structures. Staggering statistics on the economic loss caused by chloride-induced corrosion to highway bridge structures in the United States—$150 billion at the time of the first edition—are used to illustrate the need to understand, diagnose, and mitigate the corrosion process. Chapter 2 discusses the corrosion process, types of corrosion, and the basics of electrochemical cells. Chapter 3 focuses on the causes of corrosion, primarily carbonation and chloride attack, and the subsequent damage to reinforced concrete. Chapter 4 outlines the condition evaluation process 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; 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 inhibitors. Chapter 6 is dedicated to providing an understanding of electrochemical repair 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. 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 methodology, outlining why an owner or consultant may 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 herein, which if applied to historic concrete buildings, lead the investigator to be predictive in the evaluation process. Finally, Broomfield concludes with a chapter addressing building for durability in new construction, and methods and preventive treatments that are available today.

———. 2007. Repair Guidance Note 1: Corrosion of steel in concrete. *Concrete* 41 (4): 13–15.

This is the first part 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 guide summarizes the major causes of corrosion-related defects 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 is described and the relevant reference within the standard is identified. The corrosion process is described and the required conditions for it to occur are identified.

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

This is part 2 of 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 is a summary of all of the major causes of deterioration and decay in concrete. The causes are divided into three groups: design and construction defects, environmental influences, and structural damage. The causes of 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. The environmental influences identified are staining, erosion, efflorescence, freeze-thaw damage, and chemical attack. Each of the above is described in brief 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, England: 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 the risk of corrosion to the embedded steel. The digest describes the carbonation process and how the depth of carbonation can be measured, outlines various factors influencing the depth and rate of carbonation, indicates the possible effects produced in hardened concrete, and briefly discusses maintenance of concrete structures. Lab and field tests are described and European Standards are noted. This is an older text, but it provides a solid description of the reactions occurring in the concrete.

Building Research Establishment. 1991. *Sulphate and Acid Resistance of Concrete in the Ground*. BRE Digest 363. Watford, England: Building Research Establishment, Building Research Station.

This BRE Digest refers to sulphate and acid attack on concrete below ground. The document recommends the type of cement and quality of concrete to provide resistance to sulphate and acid attack in new structures. Sites are classified on the basis of their sulphate concentration, but recommendations also take into account water movement, acidity, and their individual effects on various forms of cast in situ and precast construction. Though this focus is on subgrade conditions, the information can be valuable for assessing foundations, piers, stanchions, and other components that make up the substructure of historic building construction.

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 in chapter 1: History and Development of Concrete.

Concrete Society. 1999. *Alkali-Silica Reaction: Minimising the Risk of Damage to Concrete: Guidance Notes and Model Specification Clauses*. 3rd ed. Concrete Society Technical Report No. 30. London: Concrete Society.

The first editions of the Concrete Society's guidance notes on alkali-silica reaction (ASR) were written in 1987. They were based upon the best-known information available in the construction industry in the United Kingdom. When written, ASR was a relatively rare phenomenon in the United Kingdom. This guidance note provides technical information on minimizing the risk of ASR and the levels of precaution necessary to minimize risk. Alkali contents of cements and the various additives are discussed in detail, as are reactive aggregates and testing protocols for identifying them. Concrete mix designs that limit ASR risk are provided along with mix-design calculations and a useful flow chart to determine risk and necessary precautions. Outline specifications are provided, which aim to minimize risk so the engineer can integrate this information in concrete construction documents. Non-reactive aggregates, water requirements, admixtures, and pigments are all discussed in minor detail. While this guidance note is dated, and there are more advanced methods of mitigating ASR risk today, ASR it is still seen in construction. The information provided here should be supplemented with more recent publications.

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, Inc.

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 that will assist in the identification of deterioration in concrete. The authors began this research in 2003 and at the date of this paper had compiled more than sixty entries. Their definitions are supplemented by images that illustrate each type of deterioration and by descriptions of conditions at specific twentieth-century buildings where each of these phenomena is present. Likely causes of deterioration are also identified.

Everett, L. H., and K. W. J. Treadway. 1980. *Deterioration Due to Corrosion in Reinforced Concrete*. BRE Information Paper 12/80. Watford, England: Building Research Establishment.

This BRE Information Paper provides research on observed corrosion-related deterioration in concrete. It identifies chlorides and the carbonation process as the drivers of corrosion. Assessment procedures provided are reflective of the date of publication. Structural concrete cracks versus corrosion-related cracking are discussed. The paper emphasizes that once corrosion-related cracking has been identified, the type of corrosion (Cl or CO2) must be determined. It provides a sequence that describes how the plotting of the chloride or carbonation data can be used as a rough guide for long-term performance, with percentages of contaminants charted against levels of corrosion risk. The age, depth of carbonation, and chloride content all provide a baseline for assessment of future durability. The results of the testing methodology and subsequent analysis may influence repairs. This early paper compiles data from five earlier BRE studies and provides an introduction to durability, service life, and the importance of durable repairs.

Jester, Thomas C., ed. 2014. *Twentieth-Century Building Materials: History and Conservation*. Los Angeles: Getty Conservation Institute. First published 1995 by McGraw Hill.

This book is examines a wide range of materials that can be found in twentieth-century buildings. Originally published in 1995, it was among the early works to highlight the complexities of modern building materials and systems. This work will assist the practitioner in identifying common materials, understanding how they deteriorate, and determining conservation, repair, and replacement approaches. The section on concrete-based materials covers (1) concrete block, (2) cast stone, (3) reinforced concrete, (4) shotcrete, (5) architectural precast concrete, and (6) prestressed concrete. The history and origins of the specific materials, developments including failures of these materials, manufacturing and/or mix-design information, and typical uses and installation methods are discussed. Each chapter, with the exception of prestressed concrete, has a section on failures, condition assessments, and material-specific treatments. Discussions of conservation approach and methodology are brief, and assume best practices are being carried out. Knowledge of in situ diagnostics, forensics, and laboratory techniques are required and noted within the text. Typical methods of conservation and repairs are described and replacement is discussed when necessary. This text is a valuable introduction to the various cement-based materials and their conservation.

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

This book addresses the many ways in which concrete and masonry buildings fail and discusses the reasons and modes of failure. The author's objective is to inform new design by highlighting past failures and solutions. Presented mostly as a series of modern (post-1950) case studies, eight issues of failure are addressed. Of most relevance to historic concrete are the following sections. The chapter on efflorescence provides an introduction to the issues associated with salts in concrete structures. The chapter on surface defects includes a discussion of surface finish treatments. Various types of concrete placement or formation are also discussed in this chapter, including cast-in-place using formwork, precast, self-compacting, and fiber-reinforced concrete. The chapter on discoloration identifies the importance of the composition and consistency of the concrete for 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. Calcium chloride as an additive, the alkali-silica reaction, carbonation, and salts are also discussed in this chapter. The seventh chapter looks at structure as a source of 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. This book does not specifically deal with historic concrete; however, it is a useful resource as an overview of defects in concrete structures.

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 of carbonation by looking at eight French case studies. Carbonation tests using a pH indicator (phenolphthalein) were undertaken prior to restoration works at each of the case study sites. In some cases additional data was available for comparison, such as microscopic analyses. 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—wind and humidity apparently being key and connected elements. In this study, the cases with the highest carbonation depths did not have corroded rebar. In several cases, carbonation was found to progress from both inner and outer surfaces, influenced in one example by the use of a lower quality, more porous cement 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*, 247–53. Buenos Aires: Editarq.

A research project was launched in France in 1993 under the auspices of the Cercle des Partenaires du Patrimoine to understand the origin of visible alterations on concrete buildings and structures. This paper looks at the five, key nonstructural mechanisms that trigger deterioration in concrete: carbonation, chloride alterations, sulfatic deterioration, frost-defrost cycles, and alkali-aggregate reactions. In this study, eighteen different types of visual defects or visible alterations were identified and are listed. Of these, the visual alterations found to most frequently affect French historic monuments are the losses of cement parts related to the corrosion of the reinforcement structure, cracks, black streaks, and biological overlays. The paper proposes a five-stage diagnosis procedure for assessing the type of maintenance or restoration work required where there is visible alteration. Trials were undertaken in 1996 and again in 2001 to identify methods to deal with some of the main alteration types encountered. The results were inconclusive and a third program, almost entirely devoted to trialing new technologies, was launched in 2002. The first conclusions of this further study are that the new technologies appear to be promising.

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 *Study and Conservation of Composite Artefacts.* Vol. 4 of *Metal 07: Interim Meeting of the ICOM-CC*

Metal Working Group, Amsterdam, 17–21 September 2007, edited by Christian Degrigny, 30–35. Amsterdam: Rijksmuseum.

The intent of this study was to characterize the physico-chemical processes of corrosion reactions occurring from a metallic core outward in relation to carbonation of three historic buildings. The paper attempts to predict conditions occurring at the reinforcement in order to be preventive in the repair approach. Long-term corrosion patterns of iron embedded in mortars were assessed at both passive and early stages of corrosion. Corrosion rates instigated by carbonation are often low and difficult to measure, and the carbonation front and oxide layer create highly resistive surface layers after ten years of corrosion activity. Two distinct zones were identified in the corrosion pattern: a dense product layer (DPL) of iron oxyhydroxides and magnetite in contact with the metal, and the transformed medium (TM) of iron oxyhydroxides and minerals characteristic of the mortar. The later layer is due to a dissolution of corrosion products. Samples were removed from three field sites, ranging from forty-seven to sixty-eight years in age. Three types of tests were performed: (1) carbonation with phenolphthalein, (2) on-site electrochemical methods, such as potential mapping, resistivity, and corrosion rate measurements, and (3) laboratory analysis, including SEM, EDS, and Raman microspectroscopy. The 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 rebar, thus affecting the corrosion rate. The results have yet to be paralleled with electrochemical techniques; however, they indicated that pH testing with phenolphthalein can be flawed and that homogeneity of corrosion is difficult to consider.

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

See annotation in chapter 1: History and Development of Concrete.

Prudon, Theodore H. M. 1981. Confronting concrete realities. *Progressive Architecture* 62 (11): 131–37.

See annotation in chapter 1: History and Development of Concrete.

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

This is a guide to dealing with common durability problems associated with corrosion-damaged concrete. The text provides a fundamental understanding of corrosion and corrosion-related repairs in reinforced concrete structures. This is not in-depth and is intended to enlighten owners and non-specialists. It encourages the hiring of a corrosion expert. Section 2 of the document provides inspection and evaluation procedures. These are provided to help determine conditions that may lead to failure. Physical and laboratory evaluations, in situ NDE, and destructive evaluation procedures are outlined. Section 3 tackles the question of how to appropriately commission inspections for a structure and how to determine when repairs are needed. Repair type and advice is provided in section 4. The document emphasizes that little 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.

Urquhart, Dennis. 2014. *Historic Concrete in Scotland. Part 2, Investigation and Assessment of Defects*. Short Guide 5. Edinburgh: Historic Scotland. http://conservation.historic-scotland.gov.uk/short-guide-5.pdf.

This is the second volume of a three-part Short Guide produced by Historic Scotland. Part 1 (p. 18 above) introduced the history and development of pre-1945 concrete. This part addresses concrete defects and decay, and site and materials investigation and assessment. The investigation and assessment techniques addressed in this publication are intended as an overview. The concrete defects discussed in the text are ascribed to many different factors. These include poor workmanship, the use of poor-quality materials, poor detailing, excess free lime, high alumina cement, alkali-silica reaction, and environmental impacts such as the effects of acid rain and climate conditions. Defects specific to reinforced concrete are also described, such as the effect of carbonation of the concrete 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 are emphasized. The most commonly utilized nondestructive and destructive or invasive techniques for the investigation and analysis of historic concrete are described, providing the reader with an overview of each of the different processes. This publication leads to the final part of the three-part series, which deals with the maintenance and repair of historic concrete (p. 72 below).

CHAPTER 3

Historic Concrete Diagnostics, Monitoring, Nondestructive Testing, Investigation, and Assessment

American Concrete Institute. 2015. *ACI Manual of Concrete Practice, 2015*. 8 vols. Farmington Hills, MI: American Concrete Institute.

This publication is produced annually by the American Concrete Institute (ACI). The 2015 edition is composed of seven volumes plus an index. It is a comprehensive reference set on concrete that includes concrete code requirements, specifications, guides, and reports. It contains more than 240 standards and reports. Clear diagrams and photographs illustrate the text. The index volume contains a glossary of ACI terminology. The index provides a clear way of navigating to the relevant section with all relevant articles listed under clear topic headings such as "drying shrinkage," "precast concrete," and "repair." In the context of this bibliography, it is noted that there are no entries related to conservation or preservation in the index, although reference is made to historic structures. Users are directed to section 364.1R-07, "Guide for Evaluation of Concrete Structures before Rehabilitation." Under restoration, the notation says to "see repair." Within the repair section, none of the material is written directly in relation to conservation.

Ayón, Angel. 2009. The Guggenheim at fifty: Notes on recent preservation work. *DOCOMOMO Journal* (41): 73–79.

This article discusses the conservation works undertaken at Frank Lloyd Wright's Solomon R. Guggenheim Museum in New York City 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 constructed from data collected through laser-surveying technology. This model was used to analyze the structure under different environmental conditions and to identify the requirements for structural repairs or stabilization. All repairs were undertaken in accordance with the project's preservation 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 the work undertaken to reduce internal and external moisture-related issues is also discussed.

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 Torre Velasca, a significant, brutalist, reinforced concrete building in Milan (built 1956–58). Distinctive materials include mortar and cement plaster containing crushed Verona marble. Conservation methodology, condition analysis, and accurate diagnosis were needed for a repair approach to deal with corrosion of the structure. Both nondestructive and semi-destructive testing was carried out with in situ tests including half-cell, resistivity, and cover testing. Laboratory testing included XRD, TGA, FT–IR, and SEM. After preliminary research, the authors identified previous repairs, but could not visually determine those 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. This paper provides information on testing and methodologies for assessing corrosion risk. The key tests here indicate that conditions differ between the structural concrete and the decorative elements. Correlations between cover, carbonation, potential, and resistivity provide evidence that the upper levels of the exposed concrete building and precast elements are at a higher risk than the structural concrete. Areas at higher locations with more exposure are more prone to deterioration. Previous cracking (repair) was not a direct correlation of corrosion. No repair method was offered, but the holistic diagnostic approach is valuable.

Bianco, Alessia. 2004. Impiego delle PhD per la valutazione delle risorse dell'edilizia storica in calcestruzzo armato: Il caso dell'edilizia in "muratura confinata" dei primi del novecento a Reggio Calabria [The use of nondestructive testing for the evaluation of the resources of historic buildings in reinforced concrete: The case of buildings with "confined masonry" from the early 1900s in Reggio Calabria]. In *Architettura e materiali del Novecento: Conservazione, restauro, manutenzione: Atti del Convegno di studi, Bressanone 13–16 luglio 2004*, edited by Guido Biscontin and Guido Driussi, 369–77. Scienza e beni culturali 20. Marghera-Venezia: Arcadia ricerche.

This article is in Italian. It focuses on an early reinforced concrete block structural system. Various housing types are discussed. Nondestructive test methods were used to carry out a condition analysis, including cover survey, impact hammer, ultrasonic pulse velocity testing, concrete pull-off testing, and thermographic imaging.

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

See annotation in chapter 2: Concrete Deterioration and Damage.

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 Sir 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 new concrete repair standard, BS EN 1504. The specification of works was written to be as fully compliant to 1504 as possible given the additional needs stemming from its heritage listing. An investigation and predictive analysis was used in various locations to determine time to deterioration 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 removal in mind. Different treatments were applied throughout three phases of work to the three structures, based upon 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 complexities of the façade 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 with 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 methodical approach set forth in BS EN 1504 to diagnose the failures, provide a treatment rational, and guide assessment of the treatment types provides a best practices approach to historic concrete repair.

Building Research Establishment. 1991. *Sulphate and Acid Resistance of Concrete in the Ground*. BRE Digest 363. Watford, England: Building Research Establishment, Building Research Station.

See annotation in chapter 2: Concrete Deterioration and Damage.

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 Cohen's report is a landmark 1914 concrete-frame, high-rise building located in Newark, New Jersey. The building is on the National Register of Historic Places and is, therefore, subject to landmark compliance. However, the building has been derelict for many years. A neighborhood revitalization effort required a survey to determine condition and salvageability of the building prior to 2010. A follow up was necessary after the Virginia earthquake in 2011. The testing program on the building outlines nondestructive evaluation procedures in conjunction with a coring program. The report identifies challenges in dealing with early concrete structures and the need to alter testing protocol when actual site conditions and safety dictate accessibility. The main testing and visual components identified for the testing program were compressive strength, sounding for delaminations, rebound hammer, and cover and carbonation depth. Visual indicators of deterioration, crack surveys, and water penetration were noted. Conditions are summarized; however, limited conclusions are provided.

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 identify 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, other surfaces were prepared by sandblasting or removal of the concrete cover 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. *Journal of Construction and Building Materials* 34: 201–210.

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 Saint Vincent's (Robert Toussaint, 1928–30). The church's structure is reinforced concrete; the outer finish in many areas uses a material known as Pauchot reinforced artificial stone. The authors recommend a two-stage investigation approach in which a 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 the Second World War, an earthquake that occurred in 1983, and the effects of a local stream causing subsidence are identified as potential causes of the deterioration, particularly 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 rebars, and replacement using a less-porous mortar as a potential approach to the repair work.

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. The paper 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 repair process. Four case studies of monumental American structures are presented. A corrosion testing program was integrated with an overall condition evaluation; durability modeling was performed from the data collected from the evaluation. The case studies provide examples that 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 microcracking can be established and appropriate treatments that address long-term corrosion mitigation can be considered.

Dagher, H. J., and S. Kulendran. 1992. Finite element modeling of corrosion damage in concrete structures. *ACI Structural Journal* 89 (6): 699–708.

The premature deterioration of concrete structures due to corrosion of the reinforcement is a multibillion-dollar problem. This article provides numerical models to predict mechanical damage in concrete (bridge decks) resulting from the volume expansion of the corrosion product. Various models and inputs are included. The smeared crack approach is used to develop a versatile numerical model for corrosion damage in concrete. This includes: (1) model crack formation and propagation, (2) the capacity to accept and change crack formation around the reinforcing bars, (3) the ability to incorporate live and dead loads, initial shrinkage, and temperature cracks, and (4) visual representations of crack and delamination formations. While the article is useful in understanding finite elemental modeling, and the various parameters involved in corrosion-related crack formation and subsequent damages to a bridge deck, it is largely out of date (circa 1992). This methodology has advanced significantly in the last two decades and can be applied to many different types of structures. This approach could prove useful in predicting failures based on corrosion scale as well as determining patterns of failure.

Gillard, Anne, Luc Courard, and Pierre Paquet. 2011. Churches and concrete in Liège district: History, architecture and pathologies. *Restoration of Buildings* *and Monuments: An International Journal = Bauinstandsetzen und Baudenkmalpflege: Eine internationale Zeitschrift* 17 (1): 3–13.

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 a planned approach to repair, as outlined by EN 1504–9, where investigation, analysis, and root cause and failure identification are conducted prior to choosing a repair method. Defects identified through visual inspection of the churches fall into three main categories: concrete defects, structural defects, and miscellaneous degradations. Corrosion of the reinforcements as a result of carbonation was determined to be the most common cause of deterioration. Cracks were present in almost all of the structures. Each structure was classified according to its general condition. Three levels of classification were defined: "bad," if the structure or its occupants' safety is in danger; "satisfactory," if further investigation is urgently required but defects do not appear to affect the structure or pose safety concerns; and "good," if any deterioration is 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 these defects is needed.

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.

This article describes scientific research and investigation into deterioration in a 1941 reinforced concrete air raid shelter located at the military airfield at East Fortune, East Lothian, Scotland. The aims of this research were to characterize the construction of the shelter in terms of methods and materials, record the condition, investigate the movement of moisture through the structure, create an understanding of the deterioration processes at work using the evidence collected, and assess conservation options. Corrosion of the rebars 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. No exact conservation methods are identified for this site; however, BS EN 1504 is discussed and a summary table provides various conservation options, along with assessments of their advantages and disadvantages.

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

See annotation in chapter 1: History and Development of Concrete.

Linton, Linnea M. 2005. Delaminations in concrete: A comparison of two common nondestructive testing methods. *APT Bulletin* 36 (2–3): 21–27.

This article summarizes a research project comparing the usefulness of hammer and impact-echo tests in searching for delaminations 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 that were prepared with laminations in recorded positions; the control slab had no laminations. It was intended that 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 the accuracy of the tests and a comparison of the feasibility 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 delaminations. Use of the impact-echo test alone is not recommended because it was shown to have a higher percentage of error when locating areas that are not delaminated.

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

See annotation in chapter 1: History and Development of Concrete.

Macdonald, Susan, and New South Wales Heritage Office. 2003. *The Investigation and Repair of Historic Concrete*. Parramatta: NSW Heritage Office.

This guide addresses the history and use of architectural concrete in Australia. It is 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. The guide emphasizes that an inappropriate approach can lead to a failed repair. A number of reference charts are provided for ease in 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.

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 in chapter 2: Concrete Deterioration and Damage.

Marie-Victoire, Élisabeth, and Annick Texier. 2003. Alterations in old concretes. In *Architectural Culture around 1900: Critical Reappraisal and Heritage Preservation*, 247–53. Buenos Aires: Editarq.

See annotation in chapter 2: Concrete Deterioration and Damage.

Matthews, Stuart. 2012. *Structural Appraisal of Existing Buildings for Change of Use*. BRE Digest 366. 4 vols. Watford, England: Building Research Establishment.

This is an expanded and updated version of a BRE Digest that was originally published in 1991. Directed at engineers, it is a guide on undertaking structural appraisals when a change of use is proposed for an existing building. Although not specifically targeted at historic buildings, the methodology is equally applicable to those of identified historic significance. Although it is focused on the United Kingdom, the publication also makes reference to relevant EN Eurocodes. 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 the potential deterioration mechanisms and other issues such as climate change. It also includes an extensive bibliography of related building standards, codes, and guidelines.

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 *Study and Conservation of Composite Artefacts.* Vol. 4 of *Metal 07: Interim Meeting of the ICOM-CC Metal Working Group, Amsterdam, 17–21 September 2007*, edited by Christian Degrigny, 30–35. Amsterdam: Rijksmuseum.

See annotation in chapter 2: Concrete Deterioration and Damage.

Noyce, Paul A., and Gina L. Crevello. 2013. Early concrete testing and interpretation for long-term preventive measures. *Materials Performance* 52 (11): 54–57.

This is shortened version of a National Association of Corrosion Engineers conference paper. The premise of the paper is that if a concrete structure is assessed for corrosion early enough in its life cycle, a dramatically different approach can be taken to the maintenance and repair process. 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 understanding concrete and corrosion-related failures. This article identifies the numerous test methods used to understand concrete deterioration and highlights the complexities of understanding the data generated from electrochemical test methods. Emphasis is placed on having qualified testing professionals determine whether the data acquired has been affected by construction conditions, is accurate, or is influenced by other items.

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

See annotation in chapter 1: History and Development of Concrete.

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: Associazione Italiana Prove non Distruttive Monitoraggio Diagnostica.

This article explains an integrated approach to studying the behavior of a five-story concrete structure that was constructed shortly after World War II; original drawings and documentation have been lost. Ground penetrating radar was used to determine the embedded steel on structural elements and crack monitoring was undertaken to understand movement patterns. The building has projecting balconies and bow-windows, where 45-degree cracks had formed on the vertical piers. For this project, limited funding was available and the nondestructive evaluation (NDE) program assisted in determining construction history and condition without extensive invasive investigations. The 3D radar scanning allowed the investigators to determine reinforcement patterns and beam elements, and the long-term crack monitoring provided evidence that the structure had both seasonal movement 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 NDE techniques, the article indicates the usefulness of integrated NDE testing programs to determine building construction and behavior.

Prudon, Theodore H. M. 1981. Confronting concrete realities. *Progressive Architecture* 62 (11): 131–37.

See annotation in chapter 1: History and Development of Concrete.

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

See annotation in chapter 2: Concrete Deterioration and Damage.

Sabnis, Gajanan M., ed. 1985. *Rehabilitation, Renovation, and Preservation of Concrete and Masonry Structures*. Publication SP 85. Detroit: American Concrete Institute.

This book is a compilation of twelve papers that were produced for American Concrete Institute conventions in 1981 and 1982. Eight of the papers are relevant to the conservation of historic concrete. "Nondestructive Evaluation in Rehabilitation and Preservation of Concrete and Masonry Materials," by James Clifton, contains useful appendices listing a wide range of nondestructive tests and discusses their applications, advantages, and limitations. "Inspection, Analysis, and Restoration of

MIT Kresge Auditorium," by Edward Cohen, Norval Dobbs, and William Combs, describes in detail the assessment, testing program, and monitoring work undertaken at the auditorium, along with the restoration and repair work completed. "Verification of Structural Adequacy," by Dov Kaminetzky, includes a study testing the success of visual inspections for identifying the structural stability of three reinforced concrete structures. "Repairs of Concrete Columns, Spandrels, and Balconies on a High-rise Housing Complex in Chicago," by Stella Marusin, looks at the restoration of an exposed-frame, reinforced concrete, high-rise apartment block, detailing the site and lab investigations, selection of repair materials, and repair techniques. "Cathodic Protection for Reinforced Concrete Structures," by Kenneth Hover, describes in detail the development and processes of this preventive technique. "Restoration of a Concrete Clarifier Structure," by Stephen Tsui, presents a case study describing investigation, testing, and rehabilitation work to treat severe decay, including cracking, scaling, spalling, and leakage. "Subzero Degree Fahrenheit Temperature Repairs of Concrete with Epoxy Mortar," by Floyd Dimmick, documents a case from material selection to conclusions and recommendations. "Repairs and Restoration of Reinforced Concrete Columns," by R.L. Nene, is a brief discussion of the use of gunite as a repair material.

Silman, Robert. 2000. The plan to save Fallingwater. *Scientific American* 283 (3): 70–77.

This article, written from an engineering perspective, deals with the structural investigation begun at Frank Lloyd Wright's Fallingwater in 1995. It 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 time of 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 ex-situ tests on a small piece of reinforcing steel were also 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 as soon as possible (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 outward appearance of the building. The proposed repairs are described and illustrated. Repairs were scheduled for the winter of 2001–2002, as part of a larger restoration project.

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 and patching and coating materials for use in 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 of the repair materials are discussed and the testing program is described in detail. In 2006, following discussions with a group of manufacturers, six were invited to identify a single product for each of the three requirements: crack fillers, patching material, and coating material; all materials were required 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 of the products stood out as performing particularly well. 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 on 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 of an acrylic crack filler and coating and a polymer-modified patching compound were selected for implementation. The conservation work began in 2007 and was due for completion mid-2008.

Urquhart, Dennis. 2014. *Historic Concrete in Scotland. Part 2, Investigation and Assessment of Defects*. Short Guide 5. Edinburgh: Historic Scotland. http://conservation.historic-scotland.gov.uk/short-guide-5.pdf.

See annotation in chapter 2: Concrete Deterioration and Damage.

CHAPTER 4

Approaches to Conserving Historic Concrete

American Concrete Institute. 2015. *ACI Manual of Concrete Practice, 2015*. 8 vols. Farmington Hills, MI: American Concrete Institute.

See annotation in chapter 3: Historic Concrete Diagnostics, Monitoring, Nondestructive Testing, Investigation, and Assessment.

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.

See annotation in chapter 2: Concrete Deterioration and Damage.

Ayón, Angel. 2009. The Guggenheim at fifty: Notes on recent preservation work. *DOCOMOMO Journal* (41): 73–79.

See annotation in chapter 3: Historic Concrete Diagnostics, Monitoring, Nondestructive Testing, Investigation, and Assessment.

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 in chapter 1: History and Development of Concrete.

Chao-Ching Fu. 1995. Problems of historicity in the conservation of the pioneering reinforced concrete buildings in Taiwan. In *Structural Studies of Historical Buildings IV, Volume 1: Architectural Studies, Materials and Analysis*, edited by C. A. Brebbia and B. Leftheris, 53–60. Southampton: 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 colonization by Japan in 1895, Japanese architectural professionals brought new architectural materials and building types to Taiwan. These works are considered to be of great importance as they mark the arrival of "real modern development of Taiwanese architecture" (p. 54). Key factors in the deterioration of these buildings are improper restoration works, destructive alterations, and environmental conditions including 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: (1) potential discrepancies between historicity and durability, (2) lack of availability of original building drawings and documents, and (3) contradiction between the requirements of preservationists and building owners.

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.

This thought-provoking paper addresses the need to create an inventory and history of concrete structures designed by engineers rather than architects. It establishes this need through case studies on the repair and reuse of four significant landmark exposition halls built between 1949 and 1960 in Turin. 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 that an integration of science, engineering, art, and culture is preferred. The author explores how values are assessed when a structure has moved away from the realm of high 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 United States National Park Service, and DOCOMOMO. Criteria for landmark listings are provided. The four case studies on the reuse of functionally obsolete, oversized, engineer/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. http://www.wmf.org/dig-deeper/publication/preserving-textile-block-florida-southern-college.

This report was produced following a meeting of conservation professionals in April 2009 at Florida Southern College (FSC), the site of a collection of twelve Frank Lloyd Wright designed buildings (constructed 1938 to 1959). The meeting topic was the conservation of these buildings and others constructed using Wright's experimental concrete textile block system, which comprises individual, hand-molded, interlocking concrete blocks. Three groups of conservation challenges with the textile block system 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 the fundamental characteristics of the block system need to be preserved. To do this the original composition and production method of the blocks needs to be replicated. Due to the potentially short life span of the system, the owner must accept the ongoing task of conservation, and where necessary replacement, over the lifetime of the building. Undertaking the replacement of blocks is particularly tricky due to the interlocking nature of the components. The author suggests creating a "Textile Block Conservation for Dummies" publication that can be used by people undertaking repairs to these buildings (p. 24). However, this does not remove the need for a good understanding of the processes that have led to each specific area of deterioration. A set of recommendations provide a guiding structure for future conservation work.

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.

See annotation in chapter 3: Approaches to Conserving Historic Buildings.

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 the discussions that occurred during a meeting organized by the Getty Conservation Institute (GCI), which convened a multidisciplinary group of experts in the field of concrete conservation; the meeting was organized under the auspices of the GCI's Conserving Modern Architecture Initiative. The report provides a summary of the meeting's presentations, discussions, and outcomes, as well as a proposed plan of action. Three key areas were addressed at the meeting: (1) potential research to advance the conservation of concrete, (2) possibilities for creating and disseminating information to fill knowledge gaps, and (3) areas for potential education and training activities. Research priorities are divided into three categories including investigation, diagnostics, and analysis; conservation and repair methodology; and process, repair materials, and case studies.

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 between repairing modern and historic concrete buildings and highlights the special considerations when dealing with historic concrete. As Gaudette 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. The article states that in order to properly understand the original materials and construction of a historic concrete building, the 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 life span may be selected for historic concrete structures where this enables a less-visible intervention.

Gaudette, Paul E., and Deborah Slaton. 2007. *Preservation of Historic Concrete*. Preservation Briefs 15. Washington, DC: National Park Service, Heritage Preservation Services.

See annotation in chapter 1: History and Development of Concrete.

Gillard, Anne, Luc Courard, and Pierre Paquet. 2011. Churches and concrete in Liège district: History, architecture and pathologies. *Restoration of Buildings and Monuments: An International Journal = Bauinstandsetzen und Baudenkmalpflege: Eine internationale Zeitschrift* 17 (1): 3–13.

See annotation in chapter 3: Approaches to Conserving Historic Buildings.

Heinemann, Herdis A., R. P. J. van Hees, and T. 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 the World Heritage designation was received, a three-year conservation project began at Fort Bezuiden Spaarndam. This paper is an evaluation of the conservation works that were undertaken. It breaks down each phase of the work and identifies where the work could have been approached differently. The main failing seems to be that the work was undertaken with a repair approach rather than a conservation approach; the concrete was primarily understood as a structural material, not a historic material. The authors note that the general lack of expertise in the conservation of historic concrete must be addressed.

Heinemann, Herdis A., H. Zijlstra, and R. P. J. van Hees. 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 the conservation of concrete. Dilemmas and possible solutions are explored in two Dutch case studies. Rather than focusing on specific methodologies for the conservation of concrete, this 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 by the paper is the limited number of experts in this field, not only those who consider and understand the conservation of the material, but also "the related disciplines, such as construction history, conservation philosophy, concrete durability and concrete repair" (p. 66).

Jonge, Wessel de. 1997. Concrete repair and material authenticity: Electrochemical preservation techniques. *APT Bulletin* 28 (4): 51–57.

This article demonstrates the use of realkalization on four concrete structures, three being landmark buildings. The overarching theme is the need to preserve the Zonnestraal Sanatorium. The ideology of the avant-garde and the transitory nature of the modern architectural movement are discussed in relation to original design intent. The discussion includes the physical and philosophical approaches of repair that may alter the authenticity of the original structure. A less-obtrusive stabilization and/or intervention is preferred. By assessing successful realkalization projects, de Jonge makes a case for its applicability as a concrete conservation methodology. Realkalization has no visual impact upon the concrete surface, while preserving and extending service life; thus, the article demonstrates its benefits as a repair approach on the Zonnestraal Sanatorium. It includes a brief description of concrete deterioration and a technical description of realkalization. It concludes by emphasizing that while electrochemical treatments are promising, the team must be fully versed in their application, advantages, and challenges. In the case of the sanatorium, realkalization was determined to be a suitable repair method.

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

See annotation in chapter 1: History and Development of Concrete.

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

This book is a record of the proceedings of a seminar, "Conservation of Le Corbusier's Work in Concrete," which took place at Chandigarh, India, in 2002. A small invited group was present. The 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. Two papers on each of the following four topics are included: the Chandigarh experience, conservation in France, techniques of restoration, and Le Corbusier's concrete. The specific paper topics include: an introduction to Le Corbusier's work at Chandigarh and restoration work completed; a 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* 28 (4): 37–44.

This article focuses on the conservation of Britain's postwar concrete architectural heritage. It notes that of the building materials and systems that came into use in Britain in the previous century, reinforced concrete is the most widespread and poses some of the most urgent conservation problems. Macdonald 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 relationship between reconciling 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. 2003. *Concrete: Building Pathology*. Oxford: Blackwell Science.

See annotation in chapter 1: History and Development of Concrete.

Macdonald, Susan. 2015. Conserving Concrete Heritage, An Experts Meeting to Identify Research Needs to Advance the Field: Background Paper. In *Conserving Concrete Heritage Experts Meeting: The Getty Center, Los Angeles, California, June 9–11, 2014, edited by Alice Custance-Baker and Susan Macdonald, 32–43. Los Angeles: Getty Conservation Institute.* http://hdl.handle.net/10020/gci_pubs/conserving_concrete_heritage.

This paper was produced in advance of a concrete conservation experts meeting to provide background information and stimulate discussion on research that will advance this area of conservation practice. The experts meeting was organized under the auspices of the Getty Conservation Institute (GCI)'s Conserving Modern Architecture Initiative. The background paper was not intended to be a definitive treatise on the state of concrete conservation. It recognizes that there may be omissions and that there is considerable expertise on the subject outside of the GCI. It notes that a series of assumptions underlie the GCI's approach to conserving concrete, including an assumption that current concrete repair techniques have not adequately addressed conservation needs. The paper's primary focus is on reinforced concrete. The GCI hopes to identify the areas of conflict between existing repair options and conservation needs, as well as the actions needed to remove the barriers to improving current methods of repair, thereby improving the state of concrete conservation. Sections address challenges to conserving concrete, the current status of concrete conservation, potential actions to improve the status quo, and research that would advance the conservation of concrete.

Macdonald, Susan, and New South Wales Heritage Office. 2003. *The Investigation and Repair of Historic Concrete*. Parramatta: NSW Heritage Office.

See annotation in chapter 3: Historic Concrete Diagnostics, Monitoring, Nondestructive Testing, Investigation, and Assessment.

Marie-Victoire, Élisabeth, A. 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 use of acoustic emissions (AE) monitoring on naturally carbonated slabs versus the use of linear polarization resistance (LPR) on artificially carbonated slabs. 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. As it is imperative to understand corrosion activity for either diagnostic purposes or to assess a repair, this study meant to investigate AE for this purpose. LPR testing can be influenced by treatments; therefore, AE monitoring was utilized for comparative purposes. Microcracking related to corrosion can be detected by AE over corrosion activity itself, but all studies to date were on chloride contaminated concrete rather than carbonated concrete. Panels used for AE testing were taken from the Raincy Notre-Dame Church (1921–23) and the newly cast concrete slabs were built in accordance with EN 1604. The LPR measurements indicated low rates of corrosion activity. When compared, both methods indicated low rates of activity, and variations in corrosion activity were distinguished. LPR readings were instantaneous while AE testing took about an hour. No clear correlation of the data between the two methods was observed. AE testing can detect corrosion in carbonated concrete; however, the data was difficult to interpret. AE may be able to pick up the signals of corrosion activity earlier in the initiation phase than EC techniques. LPR testing, on the other hand, provided consistent and accurate data when compared to the autopsied samples.

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 preservation of twentieth-century built heritage. The testing was performed on hollow panels removed from a landmark church. The aims of the program were to establish penetration profiles of the inhibitors to determine if there was migration to the steel and to determine if the realkalization increased alkalinity of the concrete. The concrete was characterized and corrosion condition was established prior to undertaking the testing program. After the application of the inhibitors, it was concluded through SEM, optical microscopy, electrodes, and ionic chromatography that there was no interaction between the cement paste and the inhibitors. Two questions were raised by the results: (1) Is the migrating power too low to penetrate the concrete? And (2) 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 (IC) realkalization and a galvanic-based realkalization method. The galvanic method did not provide enough energy to increase pH while the IC system was successful. This was the first step in a long-term study.

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

See annotation in chapter 1: History and Development of Concrete.

Prudon, Theodore H. M. 1981. Confronting concrete realities. *Progressive Architecture* 62 (11): 131–37.

See annotation in chapter 1: History and Development of Concrete.

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

This is the fourth part in a series of 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 the readers understanding of part 9 of the standard, which contains guidance on repair approaches. It explains the different sections of this part of the standard, and identifies what is and what 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.

Simpson, Lorne, Paul Gaudette, and Deborah Slaton. 2001. Centre Street Bridge lions: Rehabilitation and replication of historic concrete sculpture. *APT Bulletin* 32 (2–3): 13–20.

This article addresses the history and decision-making behind the conservation of the four cast concrete lions on the Centre Street Bridge in Calgary, Alberta, Canada. Each lion sits atop a kiosk at a corner of the bridge, which was constructed c.1915. Investigation works to assess the condition of the lions and to identify the mode of construction and the materials used began in 1999. Each of the lions was found to have been cast in five pieces, then constructed following masonry techniques with mortar construction joints. Each section was reinforced, but there was 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 repairs that were undertaken in the 1970s and 1980s at some length. The lions were found to be in a poor condition with high levels of cracking, delamination, and corrosion of the rebar. This was attributed to environmental conditions, highly porous cement, and unsuccessful previous interventions. The article details the conservation trials and the evaluation of 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 for the bridge is described. Three of the original lions were restored and are on display elsewhere. The fourth lion was in a 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.

Wright, Alan, and Peter Kendall. 2008. The listening mirrors: A conservation approach to concrete repair techniques. *Journal of Architectural Conservation* 14 (1): 33–54.

This article examines the conservation and stabilization efforts on three surviving listening mirrors that were constructed during the interwar period in Kent, United Kingdom. The conservation study was one of the largest projects funded by the Aggregates Levy Sustainability Fund and was guided by English Heritage. The aim of the project was to review conditions and to look at options for repair of the remotely located mirrors to ensure long-term stability. The team assessed three approaches: (1) do nothing, (2) stabilize by completing the most urgent repairs, and (3) a complete restoration. They chose stabilization, which allowed application of the most current methods of modern concrete repair. The work included sympathetic patch repairs, with matching form finish but distinct in color; an evaluation of the efficacy of corrosion inhibitors; and the use of impressed current cathodic protection utilizing photovoltaic battery cells to provide power to the remote site. The study concluded that thought and care are required in the detailing of all repairs for historic concrete, and understanding how a repair can visually and physically impact a landmark is as important as ensuring the repair is appropriate. The patch repairs were well matched in texture, but the color was differentiated to distinguish repairs from the original material and will age with time. Trials established that the use of corrosion inhibitors was ineffective. One of the two cathodic protection trials was effective. This work acted as a testing ground for alternative methods of historic concrete repair.

CHAPTER 5

Conservation and Repair of Historic Concrete

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.

This article examines cleaning and conservation work undertaken on the folded concrete beams of the Sydney Opera House. The beams are an important structural and design element and are of exceptional significance to the building. 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* (third edition, 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 this feature. 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 conservation and 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.

American Concrete Institute. Committee 546. 2014. *Guide to Concrete Repair: Reported by ACI Committee 546*. ACI 546R-04. Farmington Hills, MI: American Concrete Institute.

This comprehensive guide to concrete repair is produced by the American Concrete Institute (ACI). 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. Also discussed are design considerations such as material compatibility, feasibility, necessary considerations during the repair process, and the subsequent use of the building. The second chapter addresses concrete removal, preparation, and repairs, summarizing the methods available and the features of each method, as well as special considerations or limitations. It discusses the importance of surface preparation. The section on repair techniques includes discussion of the steps required for the repair of reinforcements, anchorage methods and materials, materials placement for various repair techniques, 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, and 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 ASTMs for testing these treatment systems. This section also discusses joint sealants, cathodic protection, chloride extraction, and realkalization. The final chapter discusses strengthening techniques for a variety of structural components as an alternative to replacement.

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 in the laboratory utilizing physical and chemical techniques, including chemical analyses, X-ray diffraction, and optical microscopy. The laboratory diagnosis is mainly in respect to the quality of the hardened concrete, notably composition, cement content, aggregate, and water-to-cement ratio. The quality of the material, as expressed through the results of the testing program, can assist with predicting future behavior of a concrete structure. This combined methodology can be used to choose the correct repair materials and evaluate risk. Concrete samples examined were taken from four structures that were between twenty and fifty years old. While none of the structures were of historical architectural significance, the analytical laboratory approach can provide information regarding estimation ratios of original construction materials, chemical attack, and concrete properties. Results can be used to determine the stability of the concrete. While the methods presented are useful, the investigations were entirely laboratory based.

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 clearly written 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 of the 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* (41): 73–79.

See annotation in chapter 3: Historic Concrete Diagnostics, Monitoring, Nondestructive Testing, Investigation, and Assessment.

Ban, M. 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 conservation challenges in the field of modern and contemporary heritage, and the lack of knowledge concerning the issue of aging concrete. It outlines the testing programs, the results, and the rationale behind 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 located in Vienna, Austria, and the Cologne Opera House in Cologne, Germany, are used to illustrate differences in nondestructive evaluations and preservation treatments for landmark concrete structures. The testing program for the Wotruba Church utilized nondestructive and low-grade, semi-destructive testing to ascertain condition. Testing included water absorption, surface strength, micro-structural analysis, carbonation, cover survey for reinforcement distribution, air permeability, and climate analysis. The Cologne Opera's testing program included an extensive site study and more invasive test methods: cover, petrographic analysis, microanalysis of thin sections, carbonation, adhesion pull-off strength, paint/binder analysis (for coatings), and carbonation resistance of coated areas. The combination of nondestructive and low-destructive evaluations proved useful in determining the concrete's condition in both cases. At the Wotruba Church, a methodology focused on academic research and less-invasive testing led to 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 is needed for understanding localized treatments, protective coatings, and the interactions between repair materials and historic concrete.

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 five different surface preparation techniques were trialed: polishing with abrasive rotating plates, 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 that these have 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. Polishing was not found to cause any damage to the concrete surface. Sandblasting and scarifying resulted in a low level of cracking but not at a level considered to be 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 (with the exception of the polished surface, which was not included in this part of the study). 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 techniques to hand-held breakers.

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* 36 (2–3): 3–11.

This article introduces thin-shell concrete structures and demonstrates some of the issues associated with this form of architectural design using two case studies, the Kresge Auditorium, Cambridge, Massachusetts, and the Loring Air Force Base, Limestone, Maine. Although the forms of deterioration may be similar to other concrete structures, the authors discuss how the deterioration of thin-shell concrete structures may be influenced by 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 and problems inherent to the roof coverings, as well as the solutions identified for improving their performance. These must take into account shell type and condition, expansion and contraction characteristics, internal and external environments of the building, aesthetics, and modern safety and performance requirements.

Bouichou, Myriam, Élisabeth Marie-Victoire, and Didier Brissaud. 2009. Comparative study of cleaning techniques to be used on concrete indoors. In *Concrete Repair, Rehabilitation and Retrofitting II: Proceedings of the 2nd International Conference on Concrete Repair, Rehabilitation and Retrofitting (ICCRRR), Cape Town, South Africa, November 24–26, 2008*, edited by Mark G. Alexander, 843–49. Boca Raton, FL: CRC Press.

This paper presents the results of interior concrete cleaning trials undertaken on Saint-Esprit Church (1934) in Paris, France. The authors recognize a need to develop specific methods for cleaning indoor concrete surfaces. Two techniques were trialed: a water injection-extraction technique and a variety of latex pads. The water-based technique works under vacuum and was undertaken at two separate pressures, 2bars and 20bars. Three separate families of latex pad products were tested (twelve types in total), with or without a content of ammonia and/or EDTA. Three factors were being examined during the trials: ease of use, efficiency of removal, and side effects. The water injection-extraction method was found to be easy to use and the cleaning produced “homogeneous and luminous” results (p. 845); no side effects were identified with this technique. The results of the latex pads were variable. It was found that large amounts of material were required for the application and it was relatively difficult to apply. Required residence time was highly variable. In some cases the latex had to remain in place for much longer than expected and adhesion was not consistent. Two of the groups—one with no ammonia content and a variable EDTA component, and the other with no EDTA component and with or without an ammonia content—showed homogeneous results, but the latter group achieved a higher level of cleaning. The samples were examined visually, by binocular microscopy, scanning electron microscopy, and FTIR spectrometry. A second set of trials was carried out on a different (bush-hammered) surface, but this is not discussed in this paper.

Bouichou, Myriam, Élisabeth Marie-Victoire, Alexandre François, Faisl Bousta, and Geneviève Orial. 2010. Elimination of biological covering on concrete: Tests in situ of different techniques. In *Concrete under Severe Conditions: Environment and Loading: Proceedings of the 6th International Conference on Concrete under Severe Conditions (CONSEC '10), Mérida, Yucatán, Mexico, 7–9 June 2010*, edited by Pedro Castro-Borges, 1181–88. Boca Raton, FL: CRC Press.

This paper documents a series of trials undertaken to identify the most appropriate technique for the removal of microbiological growth on the Jeanne Hachette Center, a 1970s concrete building in Paris, France. Two test areas were identified and divided into smaller testing areas, each for trialing a different technique or combination of techniques. The treatments included three different biocides based on quaternary ammonium salts, one including an additional isothiazolinone component (an organo-sulfurated molecule), and two water-based systems, one using a technique of injection and extraction under low-pressure vacuum and the other using super-heated steam delivered under pressure through a nozzle. The water-based systems were trialed individually. The biocides were tested in combination with the water-based methods or with manual dry brushing, each carried out two months after application. The results were assessed in terms of the ease of the application procedure and efficiency for removing the biological cover, which was measured both qualitatively and quantitatively. The dry brushing techniques were found to detach surface particles and were discontinued. The most successful immediate results were obtained by the steam cleaning, with full elimination of the biological cover. The test areas were revisited a year-and-a-half later and the observations were consistent with the earlier results. One year later the area was again revisited and all test areas showed an increase in biological activity, including the control areas. The conclusion is that the steam cleaning technique was most successful; however, it could be combined with a biocide applied at a later time to increase the longevity of the results.

British Standards Institution. 2009. *Products and Systems for the Protection and Repair of Concrete Structures. Definitions, Requirements, Quality Control and Evaluation of Conformity. General Principles for Use of Products and Systems.* 2nd ed. BS EN 1504–9: 2008. London: British Standards Institution.

Part 9 of British Standard (BS) EN 1504 sets out the general principles for the specification and use of repair products and systems for reinforced and unreinforced concrete. These principles, along with examples of protection and repair methods that apply them, are summarized in table 1. The table identifies a series of principles (e.g., protection against ingress), gives examples of methods of treatment (e.g., hydrophobic impregnation, filling of crack, applying membranes, etc.), and identifies the relevant part of the standard. When using this standard to make decisions surrounding the conservation of historic concrete, additional factors will need to be considered. This standard is concerned with the longevity and functionality of structures, but does not mention heritage values.

Brocklebank, Ian. 2005. Concrete, carbonation, and corrosion. *Journal of the Building Limes Forum* 12: 35–45.

See annotation in chapter 2: Concrete Deterioration and Damage.

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 in chapter 3: Historic Concrete Diagnostics, Monitoring, Nondestructive Testing, Investigation, and Assessment.

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 sea water 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 an in-depth knowledge of deterioration, durable repair options, and the experience necessary to choose the best solution while implementing the work in extreme conditions, including by helicopter.

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, England: BRE Press.

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

Cailleux, Emmanuel, Élisabeth Marie-Victoire, M. Bach, F. Feugeas, and A. 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, England: BRE Press.

This paper documents two investigations undertaken to quantify the success of corrosion inhibitors. At the time of writing, laboratory trials had shown successful results, but in situ tests had been inconclusive. This study focuses on the 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 (1959) during restoration works. Carbonation depth was similar on all four panels and was past the depth of the reinforcement, which was shown to have a corrosion oxide layer. One panel was used as a control, while a separate corrosion inhibitor was applied to each of the other three: a mineral inhibitor, a mineral and organic inhibitor, and an organic inhibitor. The first was identified being probably anodic, the other two as probably both anodic and cathodic. Each treatment was applied by the manufacturer to remove application error 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 rebar, and the organic inhibitor was found to have successfully penetrated. The panels were reassessed two years later. The mineral inhibitor had not penetrated further and was discounted from the trials. 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 noncorroded and precorroded steel samples were tested with the same inhibitors. The results appear to show that the corrosion inhibitors can work on noncorroded steel, but are not effective on precorroded steel.

Cailleux, Emmanuel, Élisabeth Marie-Victoire, Annick Texier, and G. Marchese. 2003. Experimental investigation of realkalisation treatments used for restoration of historical monuments made of reinforced concrete. In *Concrete Solutions: 1st International Conference on Concrete Repair, St.-Malo, France, 15–17 July 2003*, edited by Michael Grantham, 527–34. London: GR Technologie Ltd.

In this study, two realkalization treatments—one using an impressed current (R1) and the other a sacrificial anode (R2)—were conducted on carbonated precast panels removed from the Maison du Brésil, built by Le Corbusier in 1959. Laboratory testing established depth of carbonation, porosity, cement type, and native half-cell potentials prior to treatment. The testing program was meant to emulate on-site conditions. Post-treatment discussions noted discoloration of the concrete, most likely due to superficial gypsum and urban pollutions, and an increase in pH at the reinforcing steel. While the R1 treatment had up to a 15mm increase in pH around the reinforcing steel, R2 had a significantly lower change in pH due to lower current densities and fewer hours of total charge passed (Ah/m^2). While energized, the potential shifted and the depolarization process indicated that the steel had been passivated. Microstructural observations showed an emergence of alkali-silica gels not otherwise noted. Microstructural observations and the long-term effect of the realkalization on steel potential and corrosion rate will continue to be studied.

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

This is part of a series of 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 guidance note 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 concrete 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 provides brief guidance to several other sections of 1504–05, including terms and definitions, performance characteristics, and annexes. Came 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 current state of the art in cathodic protection (CP) of steel in concrete and the allied, but distinctly separate, field of cathodic protection of metals in masonry structures. The book is an excellent introduction to the topic, directed toward the practicing professional. The history of CP and concrete is interwoven with technical material, providing solid evidence that this is a proven technology with a more than forty-year track record. Chapter 1 provides an introduction to 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 within historic masonry structures, and provides examples dating back to Saxon times where corroding anchorage has caused damage to masonry. 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 CP systems available and most importantly design and protection criteria. NACE and BS EN 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 CP in practice. Chapter 6 deals with immersed cathodic protection design (earth or water) where there are fewer CP applications. Chapter 7 discusses the various factors a designer should consider to provide a successful CP 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 CP systems. Chapter 10 discusses power supplies utilized in impressed current cathodic protection (ICCP) 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 ICCP, electro-osmosis, and galvanic CP systems. Chapter 13 addresses the economic aspects of cathodic protection, cost savings, and life extension. In summary, cathodic protection protects the clients' 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 was 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 0.3mm were filled, and anticarbonation 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 meets 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.

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.

See annotation in chapter 3: Approaches to Conserving Historic Buildings.

Douglas, S. 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.

London's Royal National Theatre, designed by Denys Lasdun and built between 1969 and 1976, is a major British postwar structure and an internationally significant example of theater architecture. The Grade II* listed, cast-in-place, exposed concrete building features fiberglass molded "diagrid" soffits and a distinct Douglas fir board form finish. The author decries the use of the term brutalist to describe the National, noting that Lasdun described it as functional. Though initially condemned by critics and royals alike, the National exhibits an extremely high level of workmanship. The board-marking is used for intentionality of space, routing of pedestrian access, and expression of space. To further delineate use of space, brick is used for non-public spaces and non-load-bearing elements. Despite being constructed to robust standards, the National is beginning to show signs of deterioration. The current team is undertaking a proactive concrete conservation program to prolong the life of the structure and minimize future repairs. Exacerbated damage from previous proprietary repairs is occurring, which might have been avoided with higher-quality concrete repairs. The lack of skilled conservators able to repair concrete has introduced some challenges, including removal of unwanted marks, highlighting the board finish, and proper cleaning techniques. Additionally, as this theater is in almost constant use, it has been difficult to find windows of time during which the work can be performed. This case study illustrates both a growing public appreciation of concrete structures from this era and the challenges of their conservation.

Drewett, J., and N. 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, United Kingdom. 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 (ICCP) 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. The visible areas were repaired using shuttering and a proprietary repair mortar, and the non-visible areas were repaired using sprayed concrete (gunite). The use of the ICCP 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. The installation of the system was completed in 2010. In its design and installation, it was one of the most complex ICCP systems undertaken in the United Kingdom to date.

Farrell, David, and Kevin Davies. 2005. Repair and conservation of reinforced concrete. In *Historic Churches: The Conservation and Repair of Ecclesiastical Buildings*. The Building Conservation Directory Special Report Magazine, 12th annual ed., 17–19. Tisbury: Cathedral Communications Limited.

This article provides an overview of 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; examples of treatments and repairs are provided.

Frens, Dale H. 2002. Restoration of the concrete roof of the Mercer Museum in Doylestown, Pennsylvania. *APT Bulletin* 33 (1): 13–19.

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 on this building. The structural system and building envelope, including the roof, are of cast-in-place reinforced concrete. Interior floors, wall and ceiling surfaces, and windows are also of concrete. A survey undertaken in 1991 found the majority of the exterior concrete to be in good condition, although the roof, which is the focus of this article, was suffering many forms of deterioration. A year later, the author undertook a more detailed survey of the roof, which included the collection and analysis of samples of the concrete. 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 from escalating prices, but there was no agreement on the exact amount of work that would be completed. This form of contract required a high level of trust between the owner, architect, and contractor.

Gaudette, Paul E., and Harry J. Hunderman. 1997. Repair of Mies van der Rohe's Promontory: A multi phased approach to facade restoration. *APT Bulletin* 28 (2–3): 45–50.

This article documents the restoration project undertaken at the Promontory Apartment Building, Chicago, Illinois, 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 on 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 were a poor aesthetic match were also investigated. The main form of deterioration of the concrete resulted from corrosion of the steel reinforcement due to inadequate coverage; this appeared to occur in isolated areas. After the development and selection of the repair materials, which were designed to match original materials visually and to have similar physical characteristics, trials were undertaken on an area of the building and procedures modified where necessary 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 formwork rather than trowel placement. 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 coat was selected for the building. An alternate version of this article can be found in Wessel de Jonge and Arjan Doolaar, editors, *The Fair Face of Concrete: Conservation and Repair of Exposed Concrete* (see pp. 10–11 above).

Gillard, Anne, Luc Courard, and Pierre Paquet. 2011. Churches and concrete in Liège district: History, architecture and pathologies. *Restoration of Buildings and Monuments: An International Journal = Bauinstandsetzen und Baudenkmalpflege: Eine internationale Zeitschrift* 17 (1): 3–13.

See annotation in chapter 3: Approaches to Conserving Historic Buildings.

Gralińska-Grubecka, A., and J. W. 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 corrosion protection materials 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 differing requirements for concrete repair and 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 on the ease of application, workability, and finished appearance of each product. For the corrosion tests, each product was trialed on corroded and cleaned steel bars and underwent cycles of condensation, sulphur 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; observations and measurements were 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.

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

This is a critical book for those interested in concrete repair and the durability of such repairs. It notes that 50 percent of all concrete patch repairs will fail within ten years, with progressive deterioration occurring after the repair cycle. It is estimated by one contributing author that 50 percent of construction fees spent in Europe are on concrete repair, and that in the United States, over $8.3 billion per annum is spent on reinforced concrete corrosion failures. This book deals with diagnosing and understanding failing concrete, and the mechanisms that make repairs fail. Chapters 2 and 3 provide technical information on failed substrates and poor repairs. As the consequences of failing repairs becoming cyclic, the book progresses to include discussions of proven, durable repair methods such as cathodic protection (CP), electrochemical chloride extraction, and realkalization. Service life of repairs is plotted against material degradation, and durability predictions are provided to demonstrate service life extension. CP is highlighted as a successful repair method. Pros and cons of electrochemical treatments are provided, with scientific support of long-term durability. Less successful treatments, such as corrosion inhibitors are noted. Chapter 11 provides an overview of European Standards for concrete repair. Chapter 12 discusses concrete repair from a contractor's perspective, including information on how to quantify, tender, and bid the work. Chapter 14 is critical, as it summarizes the outcome of CONREPNET, a long-term durability study carried out in Europe that addressed mechanisms of failure, repairs, and repair performance. This study parallels a survey by the United States Corps of Engineers of repairs to their structures, which found that 50 percent of repairs were successful, 25 percent had failed, and 25 percent were exhibiting early failures. Successes and causes of repair failure are identified; in summary, many could have been avoided if skilled labor was utilized and more favorable weather conditions occurred during repair. The results of CP were encouraging, with a 60 percent success rate, and the failures were relatively minor system defects. Chapter 15 provides service life models for chloride-induced corrosion and discusses probabilistic performance-based predictive models. Finally, fiber-reinforced polymers and coating systems are introduced.

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

This article reports on the repair works undertaken at East Midtown Plaza, in New York City, 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 survey undertaken in 1991 showed the spalling to have reached a critical level. In fact, over 50 percent of the areas identified as spalling in the 1991 survey were cement 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 in the concrete deterioration, although it was not the sole cause. Further patching was considered to be a temporary option; therefore, the architects proposed recasting 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 treatment, a trial determined that the proposed scheme was feasible, with a slight modification. Due to insufficient coverage of the rebars, an additional inch of concrete was added to the top and base of each slab. To prepare the surfaces, the defective concrete was removed to an inch behind the rebar to allow the corrosion to be cleaned away and to 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.

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

This PhD thesis aims to achieve a dedicated conservation strategy for historic concrete and to aid the field's transition from concrete repair to concrete conservation. Heinemann asks three main research questions (p. 24): (1) How can historic concrete be preserved with its ascribed heritage values? (2) How can a proposed conservation strategy be evaluated for its impact on values and technical performance? And (3) How can technical demands be balanced with the preservation of heritage values when heritage values and durability issues originate in the same material properties? This thesis is organized in three sections. Part 1, "Understanding and Characterization of Historic Concrete," provides a full description and in-depth explanation of material properties of historic concretes and their failures. Part 2, "Interpretation and Evaluation of Historic Concrete," explores relationships between heritage values, historic concrete, and the state of conservation, while addressing how repairs can have a contraindication on values, which techniques should be used, and the impact of these repairs on durability and heritage service life. Part 3, "Development and Evaluation of a Dedicated Conservation Strategy," outlines the conservation aim and provides examples of different states of historic concrete. The work concludes by stating that no repair techniques exist that 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 field trialed and a conservation ethic must be applied to concrete buildings.

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

This two-volume set compiles documents from the American Concrete Institute, BRE (formerly the Building Research Establishment), the Concrete Society, International Concrete Repair Institute, NACE International (formerly National Association of Corrosion Engineers), SSPC: Society for Protective Coatings, and the United States Army Corps of Engineers. The manual is made up of seven sections: general, condition evaluation, concrete restoration, contractual, strengthening, protection, and special cases. This is a comprehensive resource on the subject of concrete repair.

Jerome, Pamela, Norman Weiss, and Hazel Ephron. 2006. Fallingwater part 2: Materials-conservation efforts at Frank Lloyd Wright's masterpiece. *APT Bulletin* 37 (2/3): 3–11.

This article is the second of two parts addressing the conservation works undertaken at Frank Lloyd Wright's Fallingwater (1939), in Pennsylvania, at the start of the twenty-first century. This article describes the implementation and results of the conservation works led by Wank Adams Slavin Associates (WASA). Details of the work undertaken to the roofs, terraces and skylights, concrete and stucco, stone, windows and doors, paints and coatings, and interiors are given. One of the concrete repairs described in detail is for a set of stairs suspended over the stream that were suffering from corroding reinforcement and spalling concrete. Patch repairs were determined to be insufficient for the level of damage. These 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 recasting 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. See also, Norman Weiss, Pamela Jerome, and Stephen Gottlieb. 2001. "Fallingwater part 1" (p. 73 below).

Jester, Thomas C., ed. 2014. *Twentieth-Century Building Materials: History and Conservation*. Los Angeles: Getty Conservation Institute. First published 1995 by McGraw Hill.

See annotation in chapter 1: History and Development of Concrete.

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

See annotation in chapter 1: History and Development of Concrete.

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 (FRP) composites, both generally and on architectural and historically significant concrete structures. The benefits of using modern materials must be carefully examined before any intervention is made and long-term durability must be assessed. Karydis notes that the use of FRPs 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. FRPs are the main alternative. They are minimally invasive, can be concealed, and are less destructive than gunite 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 that FRPs can be morally justified for use in strengthening twentieth-century, concrete heritage structures. The author turns to the Burra Charter to support this conclusion: "Traditional techniques and materials are preferred for the conservation of significant fabric. In some circumstances modern techniques and materials which offer substantial conservation benefits may be appropriate" (p. 12).

Loudon, Neil, and Colin George. 2008. Repair Guidance Note 11: Ongoing monitoring of concrete repairs. *Concrete* 41 (5): 14–15.

This Repair Guidance Note summarizes an approach for monitoring concrete repairs. It opens with a list of records related to repair works completed that should be considered when developing a monitoring program. The note then discusses monitoring of repaired concrete structures, either through installed monitoring systems or site assessments. Upon completion of repair works, a detailed inspection should be conducted as a benchmark. Testing and assessment of the repairs where there is evidence of failure is briefly discussed; specific testing methods and potential response approaches are identified. Finally routine maintenance is recognized as important for extending the life of the repairs and the building.

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

See annotation in chapter 1: History and Development of Concrete.

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 Chatelleraut, 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 concretes. The three-arch bridge, which crosses the Vienne River, was built by the François Hennebique Company between 1899 and 1900; it is one of the earliest reinforced concrete bridges in France. The active bridge was in need of extensive repair. It was suffering from heavy corrosion, cracking, spalling, and leakage. Low-quality concrete was originally used, which was most likely due to a limited knowledge of concrete construction. Concrete cover was thin and construction defects were observed, but carbonation was generally low. Realkalization was performed for fifteen days. To track progress, phenolphthalein and thymolphthalein tests were performed on drilled powder samples, potential, resistivity and polarization resistance were mapped. Prior to treatment, two zones were assessed. These zones had pH values as low as 9 up to 7cm deep. Corrosion current and resistivity values indicated corrosion risk was negligible despite the carbonated condition. The conditions were observed just after treatment, two months after treatment, and one year after treatment. It was concluded that the effects of realkalization on this particular project were not successful. While there was an increase in pH at the reinforcing steel and a short-term decrease in corrosion activity, the challenges of ancient concretes with construction anomalies may prevent a successful outcome from the use of this technology.

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.

This article examines electrochemical (EC) testing methods in chloride contaminated and carbonated concrete at Notre Dame de Royan (1954–58), a historic landmark concrete church. Prior to testing, the program identified carbonation depth, chloride profiles, concrete cover, and reinforcement distribution. In order to measure rebar corrosion, EC 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 to the corrosion rate readings. It was determined that seasonal fluctuations did not impact the corrosion; however, the presence of moisture (e.g., 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 corrosion values. The testing program also indicated that the meters both overestimated and underestimated corrosion activity in passive or carbonated conditions. To overcome the unreliable results produced by these two devices, correction factors should be added or different devices used. Long-term monitoring should be considered over spot-testing programs for historic concretes.

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. It breaks down the two groups and gives brief descriptions of each of the most common types. For film formers, this includes acrylics, epoxies, silicones, and stearates. The penetrants group includes silanes, siloxanes, silicates, and siliconates. Silanes and siloxanes are identified as the most efficient penetrants; however, 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 in determining how a product will perform in the field. A method for undertaking on-site testing is given.

Meier, S. J., and F. H. Wittmann. 2011. Recommendations for water repellent surface impregnation of concrete. *Restoration of Buildings and Monuments: An International Journal = Bauinstandsetzen und Baudenkmalpflege: Eine internationale Zeitschrift* 17 (6): 347–56.

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 differences between the use of water repellents on modern and historic concrete and the parameters required for their application are identified. 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 penetration depth and effectiveness of the water repellent.

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

See annotation in chapter 1: History and Development of Concrete.

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

This case study presents the investigation, diagnosis, and subsequent conservation and repairs undertaken to 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 dalle de verre is arranged in precast concrete panels with glass inset, originally coated with an epoxy. The article explains in some 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 concrete panels. The methodology for achieving a conservation rather than large-scale replacement solution is outlined.

Raijiwala, Darshak B., Prashant S. Hingwe, and Vijay K. Babhor. 2009. Bacterial concrete—An ideal concrete for historical structures. In *Concrete Solutions: Proceedings of the International Conference on Concrete Solutions, Padua, Italy, 22–25 June 2009*, edited by Michael Grantham, Carmelo Majorana, and Valentina Salomoni, 185–89. Leiden: Balkema; Boca Raton, FL: CRC Press.

This paper presents an innovative new method for repairing cracks in existing concrete using microbiologically induced calcite precipitation. This study specifically focuses on the bacteria *Bacillus pasteurii.* It defines bacterial concrete as “a concrete which can be made by embedding bacteria in the concrete that are able to constantly precipitate calcite” (p. 185). Microbiologically enhanced crack remediation by microbiologically induced calcium carbonate precipitation is discussed. The method of applying the bacteria to the cracked concrete is not described in detail, but the technique for immobilizing bacteria using materials such as polyurethane polymer, lime, silica, and fly ash is. This is intended to protect the bacteria from the high pH of the concrete and to reduce its metabolic activity. The paper claims that this method reduces the potential expansion experienced by alkali-aggregate reaction by 20 percent, the effects of sulfate by 38 percent, and expansion from freeze-thaw by 45 percent.

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

This is part of 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 offers guidance on the 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 the principles for the treatment of corrosion as a result of carbonation or chloride attack. The note summarizes the factors that should be considered in a pre-repair assessment.

Rossetti, Vito Alunno, and Alessandro Dal Bò. 2004. Restauro e manutenzione dei calcestruzzi nelle architetture del novecento: Valutazione della affidabilità di materiali e sistemi oggi disponibili per il ripristino corticale attraverso lo studio dei parametri di rischio alla fessurazione e rischio al distacco [Restoration and maintenance of concrete in architectural works of the 1900s: Evaluation of the current reliability of materials and systems for cortical restoration through the study of risk parameters regarding cracking and delamination]. In *Architettura e materiali del Novecento: Conservazione, restauro, manutenzione: Atti del Convegno di studi, Bressanone 13–16 luglio 2004*, edited by Guido Biscontin and Guido Driussi, 211–19. Scienza e beni culturali 20. Marghera-Venezia: Arcadia ricerche.

“Frequent failures occur in many concrete repair works. The large number of premixed products and systems for repair works available in the market requires a critical revision of the technologies involved in order to guarantee an adequate durability for the repaired concrete surfaces. Seven of the most frequently used premixed repair mortars available on the Italian market have been characterized according to the recent European Standard, EN 1504, *Products and Systems for the Protection and Repair of Concrete Structures*, and other specific test methods. The objective was to evaluate the durability of the concrete repair with laboratory testing and field trials, through the measurement of the parameters that seem to affect most their performance. Cracking risk factor and delamination risk factor have been proposed as indices of risk of failure. A correct understanding of these two factors could help the design engineers to a proper selection of the repair system with reduced risk of failure.” NB: this text is in Italian. The author abstract is reproduced here.

Sabnis, Gajanan M., ed. 1985. *Rehabilitation, Renovation, and Preservation of Concrete and Masonry Structures*. Publication SP 85. Detroit: American Concrete Institute.

See annotation in chapter 3: Historic Concrete Diagnostics, Monitoring, Nondestructive Testing, Investigation, and Assessment.

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: FEUP Edições.

This study explores the durability of an impressed current realkalization treatment. Cast reinforced concrete slabs were artificially carbonated. These were then realkalized using a current density of 1A/m^2 of steel following the CEN/TS 14038-1 specification [CEN/TS 14038-1 2005]. The durability of the treatment was determined by several electrochemical measurements and analytical characterizations. These were 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 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; however, both the rest potentials and corrosion rate were almost back to their initial values. Results were confirmed through SEM observations, which revealed the presence of large corrosion spots on the steel rebars.

Simpson, Lorne, Paul Gaudette, and Deborah Slaton. 2001. Centre Street Bridge lions: Rehabilitation and replication of historic concrete sculpture. *APT Bulletin* 32 (2–3): 13–20.

See annotation in chapter 4: Approaches to Conserving Historic Buildings.

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

This paper summarizes the 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. She notes that 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 changes in the physical characteristics of the concrete as well as visual appearance.

The paper highlights the importance of having skilled site operatives and the correct safety measures in place during site operation.

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

This report is one of the products of the European Union funded CONREPNET project, a network intended to "improve the durability of concrete repairs through performance-based rehabilitation" (p. vii). This publication documents the results of a series of questionnaires completed by respondents from all parts of the industry. They are grouped as consultants, repairers, academics, and owners. The report is organized into chapters covering expectations of concrete repairs, performance of repairs in practice, current practice, and current research. Questionnaire respondents were asked to provide background on the structure, information on the original concrete deterioration that led to the repair, the repair type and 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. 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. The data collected for these projects includes 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*.

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.

This study aimed to realkalize aged concrete specimens using an aluminum alloy, set in a cellulose alkaline buffer. This study was in response to impressed current (IC) electrochemical (EC) realkalization treatments that require 200Amp.h.m2 to be passed to ensure that the historic/existing concrete is realkalized. While EC realkalization by IC is well established, dating back to the 1980s, the treatments can have electrochemical reactions, including dissociated alkaline solutions, diffusion of alkaline compounds, and migrations of ions between the anode and cathode, among other dissociative affects. The aluminum alloy provided current through galvanic reactions acting in a sacrificial manner. The duration of time required to pass current with a galvanic system was three times greater than using an impressed current system. Testing indicated that there was an increase in pH at the rebar immediately after testing (10.3), which was confirmed one year after treatment. 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. http://conservation.historic-scotland.gov.uk/shortguide5pt3concrete.pdf.

This is the third volume of a three-part Short Guide produced by Historic Scotland. Part 1 (p. 18 above) introduced the history and development of pre-1945 concrete. Part 2 (p. 27 above) 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 should be read in conjunction with the other two parts. This publication is intended as an introduction to the main concepts of conserving concrete heritage. The maintenance section of this volume 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 may be introduced at a later stage. The second section looks at repair methods and materials, providing an overview of the factors that must be considered 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. The selection of appropriate methods and techniques is discussed. Reinforcement corrosion is discussed and each of the main causes, plus the potential repair approaches and treatment methods available, are briefly described. Due to their significance to the built heritage of Scotland, a short section on the conservation of concrete maritime structures is included. A final table summarizes the key issues discussed in this guide.

Valença, J., C. Almeida, and E. S. Júlio. 2012. Concrete heritage: Tentative guidelines for the 'Patch Restoration Method'. In *Concrete Repair, Rehabilitation and Retrofitting III: Proceedings of the 3rd International Conference on Concrete Repair Rehabilitation and Retrofitting, (ICCRRR), Cape Town, South Africa, 3–5 September 2012*, edited by Mark G. Alexander, 1023–28. Boca Raton, FL: CRC Press.

This paper introduces the patch restoration method developed by a team in Portugal as an alternative to the standard patch repair method. The method was initially developed and tested under laboratory conditions, then applied in the field to the buildings of the Calouste Gulbenkian Foundation, in Lisbon, Portugal, as a case study. The paper highlights the importance of following all of the stages, from initial condition assessment and evaluation of the original concrete to development and application of a physically and aesthetically matched repair mortar, and ongoing evaluation of the patch repair. The methods used to characterize the original and repair mortars are digital image processing and the two-dimensional laser roughness analyzer. For the laboratory tests, a range of repair mortar test samples were prepared with different levels of pigment and different surface textures. Accelerated aging tests were performed in a carbonation chamber and the results of color changes, which were found to be minimal, are presented in this paper. The focus of the assessment of new repairs in this paper was on the visual appearance and color match.

Weiss, Norman, Pamela Jerome, and Stephen Gottlieb. 2001. Fallingwater part 1: Materials-conservation efforts at Frank Lloyd Wright's masterpiece. *APT Bulletin* 32 (4): 44–55.

This is the first of two articles addressing the conservation works undertaken at the start of the twenty-first century at Frank Lloyd Wright's Fallingwater (1939), in Pennsylvania. This article was written as the conservation works were getting underway. It provides an introduction to the site and the main material conservation issues. Moisture penetration is identified as the key cause of concrete deterioration at the site. The authors detail the main 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. This, combined with cracking at the corners due to a lack of expansion joints, allowed the penetration of moisture behind the surface 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 corrosion of the embedded steel and spalling concrete. Other building elements, including stone, windows and doors, roofs, terraces, paints and coatings, and interiors are described, as are maintenance histories and condition assessments undertaken by Wank Adams Slavin Associates (WASA) since 1988. During the period 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. See also, Pamela Jerome, Norman Weiss, and Hazel Ephron. 2006. "Fallingwater part 2" (p. 65 above).

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.

This is a case study of the conservation of Saint John and Saint Mary Magdalene, Goldthorpe, a historic concrete church in South Yorkshire, United Kingdom. Completed in 1918, the concrete structure is unusual in an area where brick was the traditional building material. The reason concrete was used for this specific project is unknown. By the 1950s, the tower was showing major decay and a hard impermeable layer of gunite 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; it also 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 at the church are described. The difficulty in locating a concrete repair contractor that is prepared to undertake work with a conservation emphasis is discussed.

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Alice Custance-Baker is a former consultant to the Getty Conservation Institute. Custance-Baker previously worked as an architectural conservator for Nicolas Boyes Stone Conservation, Edinburgh, and as the building materials analyst at the Scottish Lime Centre Trust, Fife, United Kingdom. She received her BSc Hons and MSc by Research in geology from the University of Edinburgh and has undertaken a wide range of conservation training, including participation in the International Centre for the Study of the Preservation and Restoration of Cultural Property (ICCROM) Seventeenth International Course on Stone Conservation.

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Kyle Normandin is a former senior project specialist at the Getty Conservation Institute, where he managed the Conserving Modern Architecture Initiative and the Eames House Conservation Project. Trained as a building conservator and architect, Normandin serves as the secretary general of the ICOMOS International Scientific Committee on Twentieth-Century Heritage and is the chair of the Docomomo International Scientific Committee on Technology. He has contributed numerous technical papers on the architectural conservation of cultural heritage.

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