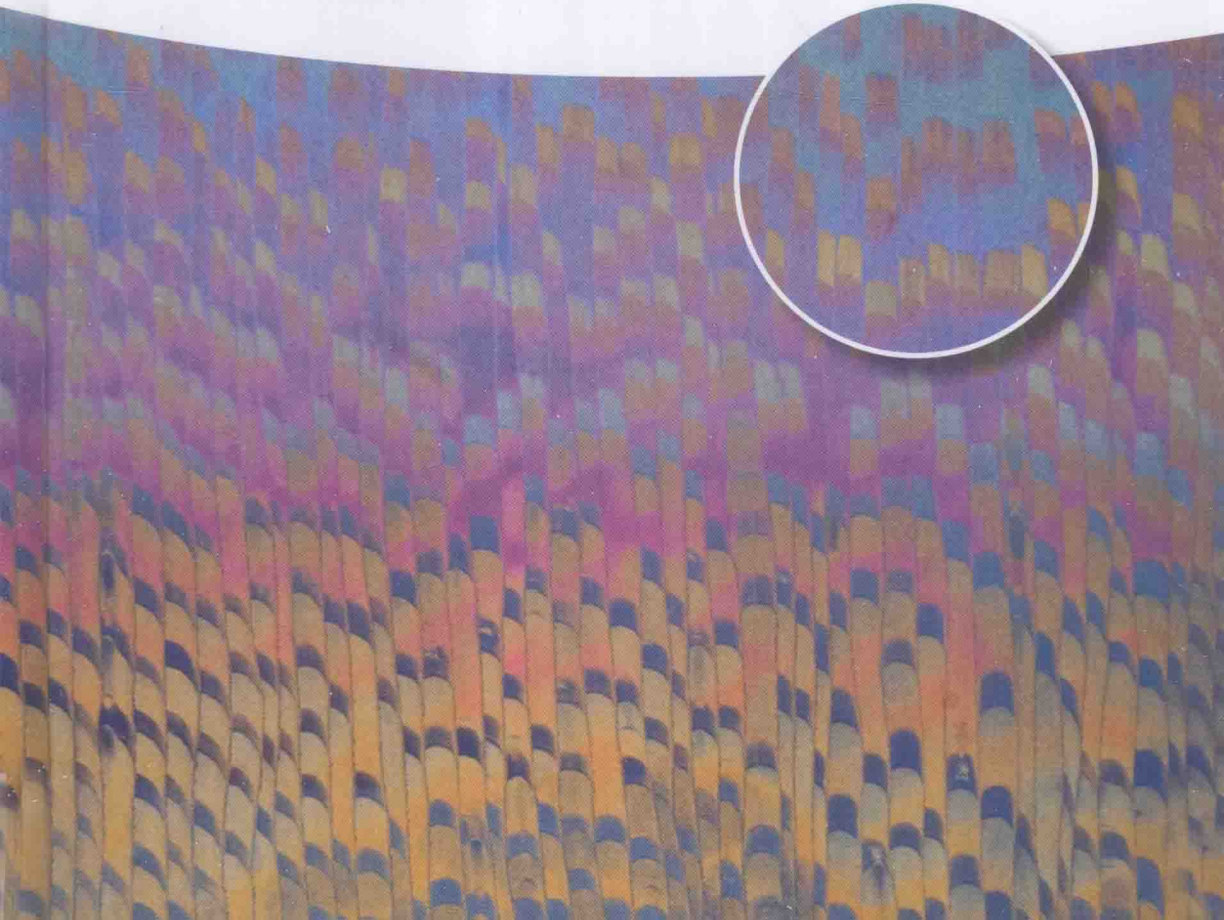
WILEY-VCH

Luca Bertolini, Bernhard Elsener, Pietro Pedeferri,
Elena Redaelli, Rob Polder

Corrosion of Steel in Concrete

Prevention, Diagnosis, Repair

Second, Completely Revised and Enlarged Edition



Luca Bertolini, Bernhard Elsener, Pietro Pedeferri, Elena Redaelli, and Rob Polder

Corrosion of Steel in Concrete

Prevention, Diagnosis, Repair

Second, completely revised and enlarged edition

WILEY-
VCH

WILEY-VCH Verlag GmbH & Co. KGaA

The Authors

Prof. Luca Bertolini
Politecnico di Milano
Department of Chemistry,
Materials, and Chemical
Engineering "G. Natta"
Piazza Leonardo da Vinci 32
20133 Milano
Italy

Prof. Bernhard Elsener
ETH Zürich
Institute for Building Materials
ETH Hönggerberg
8093 Zürich
Switzerland

Dr. Elena Redaelli
Politecnico di Milano
Department of Chemistry,
Materials, and Chemical
Engineering "G. Natta"
Piazza Leonardo da Vinci 32
20133 Milano
Italy

Prof. Rob Polder
TNO Technical Sciences/
Built Environment
P.O. Box 49
2600 AA Delft
The Netherlands

Delft University of Technology
P.O. Box 5048
2600 CA Delft
The Netherlands

Cover:
The picture used on the cover is a painting on a titanium surface, created by Prof. Pietro Pedeferri. We thank his heirs for the kind permission to use this work of art.

Library of Congress Card No.: applied for

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

Bibliographic information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available on the Internet at <http://dnb.d-nb.de>.

Composition Toppan Best-set Premedia Ltd., Hong Kong
Printing and Binding Markono Print Media Pte Ltd, Singapore
Cover Design Bluesea Design, Simone Benjamin, McLeese Lake, Canada

Print ISBN: 978-3-527-33146-8
ePDF ISBN: 978-3-527-65172-6
ePub ISBN: 978-3-527-65171-9
mobi ISBN: 978-3-527-65170-2
oBook ISBN: 978-3-527-65169-6

Printed in Singapore
Printed on acid-free paper

Luca Bertolini, Bernhard Elsener, Pietro Pedeferri, Elena Redaelli, and Rob Polder

Corrosion of Steel in Concrete

Related Titles

Sharma, S. K. (ed.)

Green Corrosion Chemistry and Engineering

Opportunities and Challenges With a Foreword by Nabuk Okon Eddy

2012

ISBN: 978-3-527-32930-4

Schütze, M., Wieser, D., Bender, R. (eds.)

Corrosion Resistance of Aluminium and Aluminium Alloys

2010

ISBN: 978-3-527-33001-0

Bernold, L. E., AbouRizk, S. M.

Managing Performance in Construction

2010

ISBN: 978-0-470-17164-6

Krzyzanowski, M., Beynon, J. H., Farrugia, D. C. J.

Oxide Scale Behavior in High Temperature Metal Processing

2010

ISBN: 978-3-527-32518-4

Revie, R. W.

Corrosion and Corrosion Control, Fourth Edition

2010

ISBN: 978-0-470-65366-1

Kreysa, G., Schütze, M. (eds.)

Corrosion Handbook – Corrosive Agents and Their Interaction with Materials

13 Volume Set

2009

ISBN: 978-3-527-31217-7

Galambos, T. V., Surovek, A. E.

Structural Stability of Steel

Concepts and Applications for Structural Engineers

2009

ISBN: 978-0-470-03778-2

Heimann, R. B.

Plasma Spray Coating

Principles and Applications

2008

ISBN: 978-3-527-32050-9

Geschwindner, L. F.

Unified Design of Steel Structures

2008

ISBN: 978-0-471-47558-3

Roberge, P. R., Revie, R. W.

Corrosion Inspection and Monitoring

2007

ISBN: 978-0-471-74248-7

Preface to the Second Edition

Since this book was first published, durability of reinforced concrete structures has continued to receive worldwide interest of materials scientists and designing engineers. Although some of the open questions raised in the preface of the first edition have found reasonable explanations in the past decade, others are still unanswered and new issues have arisen. For example, the need for sustainability has, on the one hand, increased the demand for durable structures and, on the other hand, promoted the development and use of new materials with lower environmental impact whose durability properties need to be verified. The increased demand for maintaining large numbers of existing structures and prolonging their service life poses technical and economical challenges of a larger scale. At the same time, increased experience with regard to repair techniques and materials must be incorporated in asset management on the scale of, for example, road networks. Challenges for the next decade are science-based models for the prediction of service life of new and existing structures and reliable accelerated tests that are able to provide durability-related design parameters both for concrete (e.g., with regard to resistance to carbonation or chloride penetration) and for steel (e.g., relating to the chloride threshold for corrosion initiation).

In the second edition of this book, all chapters have been revised and updated with recent findings and new perspectives. The structure of the book has been maintained, so that it may serve as a reference for students and materials scientists, who may learn from the explanation of corrosion and degradation mechanisms, as well as people involved in the design, execution, and management of reinforced concrete structures, who may concentrate on the parts of the book dealing with practical aspects of assessment, monitoring, prevention, and protection techniques.

With this second edition we also have a new co-author, Elena Redaelli, but, sadly, we lost Pietro Pedeferri, who passed away on 3 December 2008. Pietro strongly wanted the first edition of this book, and he was the driving force for its realization. He dedicated his life to the study of electrochemistry and corrosion science and technology, making important contributions to several aspects of corrosion and protection techniques, such as localized corrosion of stainless steels, cathodic protection, corrosion in the human body, corrosion in the oil industry, surface treatments of titanium, and corrosion and protection of steel in concrete. Corrosion of steel in concrete became a major field of interest for him in the 1980s.

Looking for a durable solution to prevent corrosion of reinforcing steel in motorway bridges exposed to chloride contamination due to de-icing salt application, he proposed the technique of *cathodic prevention*, and in explaining the advantages of cathodic prevention over cathodic protection, he developed the graph shown in Figure 20.4, now internationally acknowledged as *Pedeferri's diagram*. This graph definitely expresses Pietro's spirit as a researcher as well as a teacher, showing that he was able to transfer in a simple, although rigorous, manner a complex matter as the way of dealing with depassivation and repassivation of steel in chloride-contaminated concrete. Pietro Pedeferri contributed to the understanding of several mechanisms involved in the corrosion behavior of steel reinforcement in concrete, and his knowledge permeates the whole book, even in this new edition.

The front cover is a tribute to Pietro Pedeferri as an artist. In fact, he was able to conjugate his research studies on the anodic oxidation of titanium with his creativity, and he developed a unique technique for electrochemical painting of titanium. Mixing acids, electrical currents, flow of liquids, and his poetic inspiration, he generated beautiful and colorful drawings.

The Authors, January 2013

Preface to the First Edition

Over the millennia, concrete prepared by the Romans using lime, pozzolana and aggregates has survived the elements, giving proof of its durability. Prestigious concrete works have been handed down to us: buildings such as the Pantheon in Rome, whose current structure was completed in 125 A.D., and also structures in marine environments have survived for over two thousand years. This provides a clear demonstration that concrete can be as durable as natural stone, provided that specific causes of degradation, such as acids or sulphates, freeze–thaw cycles, or reactive aggregates, are not present.

Today, thanks to progress made over the past few decades in the chemistry of cement and in the technology of concrete, even these causes of deterioration can be fought effectively. With an appropriate choice of materials and careful, adequately controlled preparation and placement of the mixture, it is possible to obtain concrete structures which will last in time, under a wide variety of operative conditions.

The case of reinforced concrete is somewhat different. These structures are not eternal, or nearly eternal, as was generally supposed up until the 1970s. Instead, their service life is limited precisely because of the corrosion of reinforcement. Actually, concrete provides the ideal environment for protecting embedded steel because of its alkalinity. If the design of a structure, choice of materials, composition of the mixture, and placement, compaction and curing are carried out in compliance with current standards, then concrete is, under most environmental conditions, capable of providing protection beyond the 50 years typical of the required service life of many ordinary structures, at least in temperate regions. In fact, cases of corrosion that have been identified in numerous structures within periods much shorter than those just mentioned can almost always be traced to a failure to comply to current standards or to trivial errors in manufacturing of the concrete. However, under environmental conditions of high aggressiveness (generally related to the presence of chlorides), even concrete which has been properly prepared and placed may lose its protective properties and allow corrosion of reinforcement long before 50 years have elapsed, sometimes resulting in very serious consequences.

The problem of corrosion in reinforced concrete structures is thus a very real one and must be given special consideration. It is, in fact, only since the early

1980s that research has devoted much attention to this problem. From those years on main physiological aspects related to behaviour of steel in concrete, such as the nature of the aqueous pore liquid present in the hardened concrete, the electrochemistry of steel in this environment, the mechanism of protection of steel by an oxide film, etc. have been established. Passing to the pathological side, research has explained the phenomenology and mechanisms of corrosion, established the conditions which give rise to it and the laws governing its evolution, and developed techniques for diagnosing and controlling it. In particular, it has been shown that the only circumstances that can give rise to corrosion are those when both depassivation occurs (e.g., due to carbonation or chlorides) and oxygen and humidity are present.

Several points still need to be clarified. For example: the atlas of pathological anatomy has been defined clearly with regard to corroding reinforcement, but only sketchily in relation to the surrounding concrete; the body of diagnostics allows the state of corrosion in a structure to be evaluated for the more common forms of corrosion, but is still incomplete in the case of hydrogen embrittlement in high-strength steels of prestressed structures or corrosion caused by stray current; the handbook of anticorrosionistic pharmacology includes a long list of methodologies of prevention (from inhibitors to coatings, to corrosion resistant reinforcement, to electrochemical techniques); however, their long-term effects or their possible negative side-effects are not always clearly known. Probably, the greatest shortcomings have to do with the basic aspects of corrosion. For instance, in the area of physiopathology: the species around the passive reinforcement in concrete are known, but those around corroding reinforcement are not; the influence of species on the passivity or corrosion of steel is known in qualitative terms, but very little is known of the entity of their interaction with the constituents of cement paste, and thus of their mobility in electrical fields or in various concentration gradients, in relation to the type of cement or to the characteristics of the concrete, etc.

In the field of construction, notable progress has also been achieved: the problem of corrosion, and more in general of the durability of structures in reinforced concrete, is very seriously taken into consideration; new laws are in place and new technologies and products are available.

But the above must not lull us into a false sense of security. It is true that today there is greater sensitivity to this problem, often being the subject of conferences, seminars and publications. New rules and standards do exist, though they are perceived as compulsory, being the result of legislation. Finally, new technologies and sophisticated products are being adopted, for example in the field of repair of structures damaged by corrosion. All these aspects do not, however, in themselves eliminate the errors, often trivial, that are at the basis of most failures today, and even less are they able to solve those cases where structures operate under conditions of high aggressiveness. Substantial progress will be made, also with regard to durability, only when our current technology, based on empiricism and common sense, evolves into a technology based on a thorough knowledge of degradation processes and of methods for their control.

Education, and thus teaching in particular, has a very important role to play, not only by making professionals sensitive to the durability problem, but also by giving them the tools necessary to solve it.

We hope that this text may be useful for those who work in the field of civil and construction engineering, as well as for those involved in the area of maintenance and management of reinforced concrete structures. Its aim is to provide the knowledge, tools and methods to understand the phenomena of deterioration and to prevent or control them. In some sections of the text, because of our professional background, we have gone into details of some electrochemical aspects. These explanations go beyond what is strictly required in civil and construction engineering and are not essential to an understanding of the other sections.

Finally, we wish to thank the European commissions that, by promoting the cooperative actions COST 509, 521 and recently 534, gave to several European researchers the opportunity to meet, collaborate and exchange views in the field of corrosion of steel in concrete. This book was born from that cooperation. We gratefully acknowledge all friends and colleagues on COST Actions, RILEM technical committees and European Federation of Corrosion working groups for providing data, papers and, most of all, for stimulating discussion.

The Authors, November 2003

Contents