emerald PUBLISHING

ice Publishing

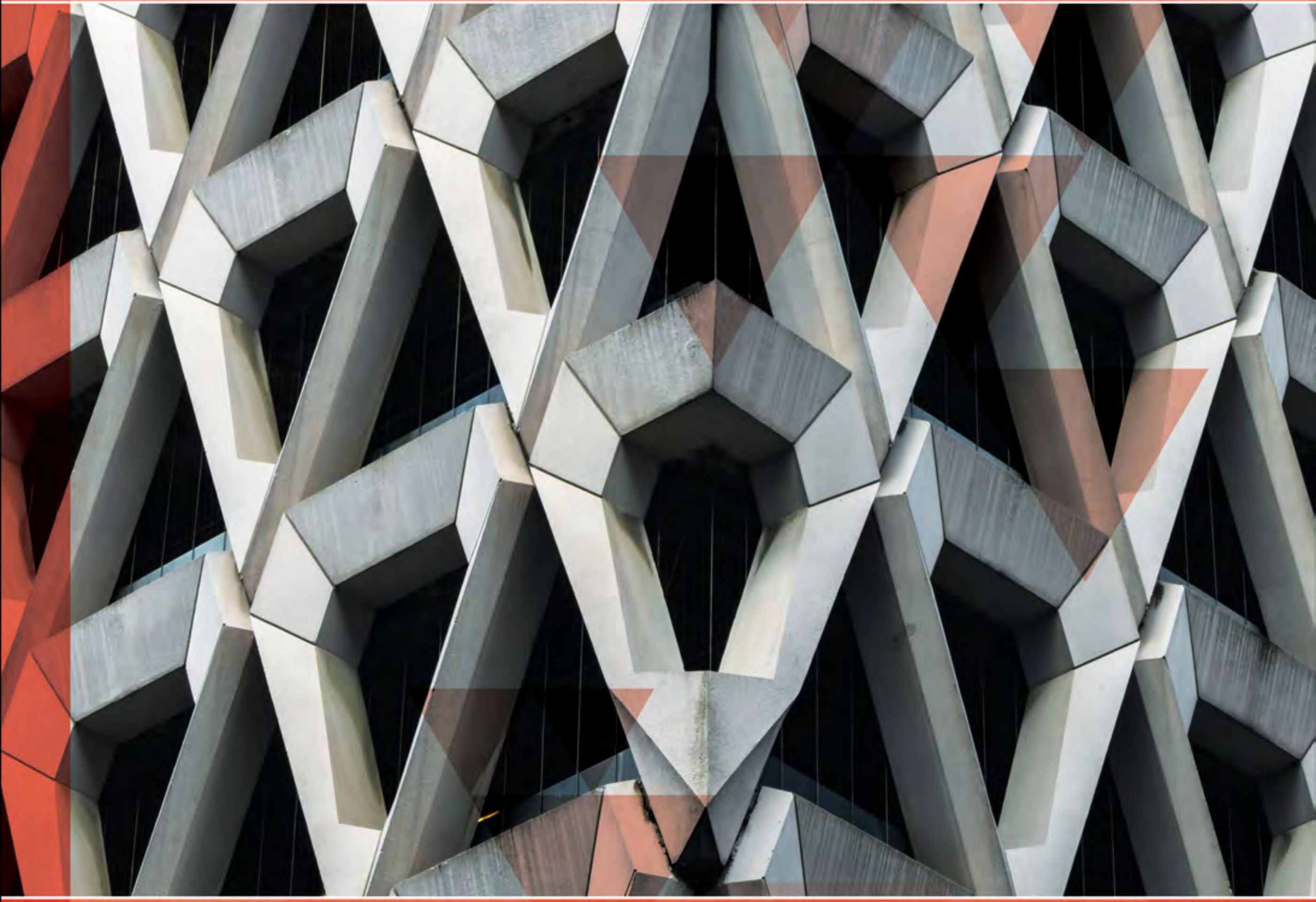
ice | handbooks

ICE Handbook of

Concrete Durability

A practical guide to the design of resilient concrete structures

Second edition



Edited by Marios Soutsos

ICE Handbook of Concrete Durability

emerald PUBLISHING

ice Publishing

ICE Handbook of Concrete Durability

A practical guide to the design of resilient concrete structures

Second edition

Edited by

Marios Soutsos

Queen's University Belfast

Published by Emerald Publishing Limited, Floor 5, Northspring,
21-23 Wellington Street, Leeds LS1 4DL.

ICE Publishing is an imprint of Emerald Publishing Limited

Other ICE Publishing titles:
Concise Guide to Reinforced Concrete Design to Eurocode 2
Patrick Purcell. ISBN 978-0-7277-6572-7
Designing and Constructing Prestressed Bridges
Jiří Stráský and Radim Nečas. ISBN 978-0-7277-6385-3
Design of Fire-resistant Concrete Structures
Kristian Dahl Hertz. ISBN 978-0-7277-6444-7

A catalogue record for this book is available from the British Library

ISBN 978-0-7277-6375-4

© Emerald Publishing Limited 2023

Permission to use the ICE Publishing logo and ICE name is granted under licence to Emerald from the Institution of Civil Engineers. The Institution of Civil Engineers has not approved or endorsed any of the content herein.

All rights, including translation, reserved. Except as permitted by the Copyright, Designs and Patents Act 1988, no part of this publication may be reproduced, stored in a retrieval system or transmitted in any form or by any means, electronic, mechanical, photocopying or otherwise, without the prior written permission of the publisher, Emerald Publishing Limited, Floor 5, Northspring, 21-23 Wellington Street, Leeds LS1 4DL.

This book is published on the understanding that the authors are solely responsible for the statements made and opinions expressed in it and that its publication does not necessarily imply that such statements and/or opinions are or reflect the views or opinions of the publisher. While every effort has been made to ensure that the statements made and the opinions expressed in this publication provide a safe and accurate guide, no liability or responsibility can be accepted in this respect by the authors or publisher.

While every reasonable effort has been undertaken by the authors and the publisher to acknowledge copyright on material reproduced, if there has been an oversight, please contact the publisher and we will endeavour to correct this upon a reprint.

Cover photo: Welbeck Street car park, London. Magnus Bjermo/Shutterstock

Commissioning Editor: Michael Fenton
Development Editor: Cathy Sellars
Production Editor: Sirli Manitski

Typeset by Nova Techset
Index created by Sunrise Setting

Contents

About the editor

Marios Soutsos has been Professor of Structures/Materials in the School of Natural and Built Environment at Queen's University Belfast (QUB) since 2012. Prior to this, he was a lecturer/reader in Structures and Concrete Technology at the Centre for Engineering Sustainability, School of Engineering, University of Liverpool. He has had industrial experience in Cyprus, Libya, Saudi Arabia and Bahrain prior to returning to academia. His principal research experience is in construction materials, and his current research interests include high-strength concrete, cement replacement materials, chemical admixtures, concrete rheology, the use of recycled demolition aggregate in concrete products, repair materials, heat of hydration effects in concrete structures, as well as alkali-activated binders. Research funding sources include the Engineering and Physical Sciences Research Council (principal investigator for two EPSRC research grants and co-investigator for two EPSRC/EU research grants), the Department of the Environment (co-investigator for the DoE funded Cardington concrete frame project), The Onyx (Veolia) Environmental Trust, the Northwest European Regional Development Fund Programme, Carbon Trust Applied Research Grants, FP 7 Collaborative Research and Invest Northern Ireland.

He is an author or co-author of more than 120 technical publications (including more than 40 refereed journal papers and 80 refereed conference publications). He is a senior editor for *Construction and Building Materials* (Elsevier) and member of the editorial advisory board for *Magazine of Concrete Research* (ICE). He is a co-editor for two other books: *Properties of Fresh and Hardened Concrete Containing Supplementary Cementitious Materials* (Springer) and *Construction Materials: Their Nature and Behaviour, Fifth Edition* (CRC Press). He has contributed chapters to three other books: 'Chapter 18: Special concretes' in *ICE Manual of Construction Materials* (Thomas Telford), 'Chapter 1: Introduction: Key issues in the non-destructive testing of concrete structures' in *Non-destructive Evaluation of Reinforced Concrete Structures, Volume 1* (Woodhead Publishing) and 'Chapter 3: Estimation of on-site compressive strength of concrete' in *Non-Destructive Assessment of Concrete Structures: Reliability and Limits of Single and Combined Techniques* (Springer).

List of contributors

Chris Atkins, Mott MacDonald, UK
Salim Barbhuiya, University of East London, UK
PA Muhammed Basheer, University of Leeds, UK
John Bickley, JA Bickley Associates, Canada (†)
Klaas van Breugel, TU Delft, The Netherlands
Jorge de Brito, Universidade de Lisboa, Portugal
John Broomfield, Broomfield Consultants, UK
Peter A Claisse, Coventry University, UK (†)
Oguzhan Copuroglu, TU Delft, The Netherlands
Dave Cullen, Jacobs, UK (†)
Philip Ebbatson, HKA, London, UK
R Doug Hooton, University of Toronto, Canada
Kenneth C Hover, Cornell University, Ithaca, USA
Jeremy Ingham, Consultant, London, UK
Iqbal Johal, Galvanizers Association, UK
Fragkoulis Kanavaris, Arup, UK
Jon Knights, Jon Knights Materials Consulting, UK
Konstantin Kovler, Technion – Israel Institute of Technology, Israel
Robert C Lewis, Ferroglobe Plc, UK
Desmond Makepeace, Galvanizers Association, UK
Bryan Marsh, Arup, UK
Alexander Mezhov, Technion – Israel Institute of Technology, Israel
John Myers, Missouri S&T, USA
Antonio Nanni, University of Miami, USA
Sreejith Nanukuttan, Queen's University Belfast, Northern Ireland
Alan Poole, AB Poole & Associates, UK
John L Provis, University of Sheffield, UK
John Reddy, Ecocem Materials Ltd, Republic of Ireland
Alan Richardson, Northumbria University, UK
Marco Rossini, University of Miami, USA
Eric Schlangen, TU Delft, The Netherlands
Asia Shvarzman, Antex Western, Winnipeg, Canada
Kosmas Sideris, Democritus University of Thrace, Greece
Rui V Silva, Universidade de Lisboa, Portugal
Robert Viles, Fosroc International Limited, UK (†)
Don Wimpenny, Jacobs, UK
Kai Yang, University of Leeds, UK
Guang Ye, TU Delft, The Netherlands

Acknowledgements

The editor would like to thank the following for their contributions to the first edition of this book:

Mustafa Sahmaran
David Cochrane
Douglas Gremel
Lindon Sear
Michael D Connell
Scott Humphreys

The following contributors have sadly passed away since the publication of the first edition or during the preparation of the second edition:

John A Bickley
Dave Cullen
Peter A Claisse
Robert Viles
Odd E Gjorv
Ken Day

Their contribution of knowledge, experience and guidance extended well beyond the confines of this book and their passing is an irreplaceable loss, keenly felt across the concrete community.

About this book

Significance of durability for reinforced concrete construction

Far more concrete is produced than any other manufactured material. It is the basic material for the construction industry, which employs 7% of the workforce worldwide and over half in some countries. One tonne of concrete is produced every year per head of population on the planet.

Over 100 years ago in 1907, Knudson showed in his paper entitled 'Electrolytic Corrosion of Iron and Steel in Concrete' that the passage of a small current through the reinforcement in concrete would cause corrosion. His opinion that stray currents were the cause of the problem was shared by most researchers at the time, but within a few years, Rosa, McCollum and Peters had concluded that 'the presence of chlorides always facilitated trouble' ('Electrolysis of Concrete', 1912). At the time this was written, the chlorides that did the damage were almost always from seawater. It was not until half a century later that winter salting of roads became widespread and soon after that, the extensive deterioration of highway structures was observed. This corrosion is the most significant of a wide range of different problems that affect modern structures, and these problems are discussed in this book.

Clients now expect their structures to last longer, with service lives of over 100 years being demanded in some cases. To avoid the liability for long-term repairs, they are looking for a 'warranty' from construction companies and, in many cases, give them contractual responsibilities for long-term maintenance. Contractors can, therefore, no longer bid based on the cheapest solution. They must consider the long-term durability of the structure to avoid spending their profits on repairs.

Durability is a very difficult area for design. A structural engineer can decide on the size and shape of components and carry out the necessary calculations (or get a computer to do them) to determine their load-bearing capabilities with great accuracy. No such process is possible for durability. The mix design of concrete can be specified and the exposure conditions determined (often not very accurately), but the only things that these affect directly are the properties of the matrix, such as the hydrate structure, the pore size and the fluid chemistry. These affect only the transport properties, and it is these that finally determine the durability of the structure. The link between what we can control and the result we get is, therefore, extremely complex and can be determined only by experimental or probabilistic methods.

To add further complications to a complex problem, how we make and use concrete is currently going through a series of fundamental changes. These have been driven partly by costs but primarily by environmental concerns. Cement production is responsible for approximately 5% of the world's carbon dioxide emissions. To put this into context, note that carbon dioxide emissions for concrete are 20 times less per tonne than for steel, but the quantities of concrete used are vastly greater. Thus, there is enormous pressure to replace as much of the cement as possible with other materials. The use of such materials and their effects on durability are discussed in detail in this book.

The final issue is that of workmanship. Despite many advances in quality control, the plans and specifications produced by the designer are often not accurately followed. The depth of cover concrete, which protects the steel from the exterior environment, often ends up less than that specified. Also, the curing, which should prevent the concrete from drying out after it is poured, is often not effective. Drainage systems for road bridges are notorious for failing to keep the damaging salt water away from vulnerable concrete surfaces. These factors combine to cause even the best designs to fail if inadequate provision is made to prevent, or allow for, poor construction.

In the past, there was a clear division between the structural engineers, who prepared the designs, and the concrete technologists, who often became involved only when durability problems arose. This came about due to conflicting pressures on the syllabus in civil engineering courses. However, designers are now finding that durability considerations have become a central part of the process and must be considered at every stage from concept to completion. Those wishing to study the topic have found the relevant information to be fragmented, partly due to the huge volume of research that has been published in the numerous journals that cover the area. Much of the information is also presented in terms of complex physical and chemical theories. This book is a compilation of essays by a selection of leading practitioners covering the full range of durability topics at a level that can be understood by engineers without the need to study the science in great detail.

Structure and contents

This book has 16 chapters with contributions from 39 practitioners and academics. The contents of the chapters are as follows.

1. Introduction
This chapter introduces the reader to concrete durability and aims to convey the need for all those involved in the design or construction of reinforced concrete structures to have a basic understanding of all the degradation processes.

2. Pore structure and transport processes
This chapter describes how the characteristics of the pore structure of cement-based materials play a fundamental role in governing the transport processes in concrete, and hence, its durability.

3. Physical deterioration mechanisms
This chapter reviews the range of mechanisms that result in the physical degradation of concrete. Specific deterioration types and mechanisms described include abrasion, erosion, cavitation, frost, exfoliation and fire.

4. Chemical deterioration mechanisms
This chapter reviews the range of mechanisms that result in the chemical degradation of concrete. Specific deterioration types and mechanisms described include weathering and leaching, acid and alkali attack, sulfate attack, delayed ettringite formation, salt attack, alkali–aggregate reaction and corrosion of the steel reinforcement.

5. Material selection to improve durability
This chapter describes construction materials that can be used to improve the durability of reinforced concrete structures. These include chemical admixtures,

mineral admixtures (pulverised fly ash, ground granulated blastfurnace slag, condensed silica fume (microsilica) and metakaolin) and alternative reinforcing materials to conventional steel reinforcement (black bars) (epoxy-coated steel reinforcement, galvanised steel reinforcement, stainless steel reinforcement and glass-fibre-reinforced polymers).

6. Construction processes to improve durability
This chapter describes how, for concrete to be durable, the designer's intentions must be translated into the actual structure. The concrete must be produced to give a consistent final in situ product, allowing for any variations in the constituent materials, production conditions and site practices.

7. Design aspects that can reduce risks from deterioration mechanisms
This chapter describes the considerations needed at the design stage to maximise the protection that can be achieved both using suitable design aspects and through appropriate materials measures.

8. Durability performance tests
This chapter describes tests that cover two main areas, namely physical and chemical material tests. It will assist the designer and specifier in choosing the correct test to determine durability for a given service life, which is related to the expected overall durability of the structure.

9. Performance-based specifications for concrete
This chapter mainly deals with performance specifications from the North American perspective, although the international literature has also been reviewed. The chapter concludes that a multi-step plan is needed, with possibly nine steps, to realise the transition from prescription to performance specifications.

10. Modelling and predicting the effects of deterioration mechanisms
This chapter describes and discusses the potential of some numerical models in tackling specific threats to durability. The deterioration of concrete is often a very slow process in which chemical, physical and mechanical mechanisms proceed simultaneously and may interact as well. Thus, modelling is very complex.

11. Case studies: Durability problems, repair strategies or proper consideration in durability design?
This chapter presents case studies of durability problems that have arisen in major structures to raise awareness of the extent and cost of repairs that may be needed for the structures to remain operational. One hundred years or more of service life is achievable with careful selection of concrete mix proportions and constituent materials as demonstrated by the East Sea Bridge in Shanghai.

12. Repair methods
This chapter describes a wide range of options for repairing and rehabilitating damaged reinforced concrete structures. Selecting the optimum combination of repair techniques requires a well-designed and executed condition survey.

13. Non-destructive testing and structural health monitoring
Several in situ tests for assessing the mechanical, permeation, corrosion and integrity characteristics of concrete in structures are reviewed in the first part of this chapter. The second part focuses on sensing techniques, which are classified as electrical or optical.

14. Durability of concretes based on non-Portland cements
This chapter addresses the durability of concretes based on non-Portland cements, with a particular focus on four key binder types: calcium aluminate, calcium sulfoaluminate, alkali-activated and magnesia-based cements.

15. Durability of concrete made with aggregates recycled from construction and demolition waste
This chapter reviews the durability of concrete made with aggregates recycled from construction and demolition waste. It also presents the design of slabs and beams made from reinforced recycled aggregate concrete in conformity with Eurocode 2.

16. Lessons learnt by expert witnesses involved in construction disputes
This chapter discusses, through examples, the recurrent themes that have been identified as contributing to the causes of disputes involving a failure of design or workmanship for construction projects involving concrete structures.

Soutsos M
ISBN 978-0-7277-6375-4
https://doi.org/10.1680/icehcd.63754.001

Chapter 1
Introduction

Marios Soutsos
Queen's University Belfast, UK

1.1. Potential durability problems

Concrete is, due to its versatility, comparative cheapness and energy efficiency, of great and increasing importance for all types of construction throughout the world. Concrete structures can be durable and long lasting but to be so, due consideration needs to be given at the design stage of the effect on the concrete of the environment that the structure will be exposed to. Degradation can result either from exposure to the environment exposed, for example, frost damage, or from internal causes within the concrete, such as the alkali–aggregate reaction. It is also necessary to distinguish between degradation of the concrete itself and loss of protection and subsequent corrosion of the steel reinforcement. ACI Committee 201 [1] defines concrete durability as: 'Its resistance to deteriorating influences which may through inadvertence or ignorance reside in the concrete itself, or which are inherent in the environment to which it is exposed.'

Initially, concrete was regarded as having an inherently high durability, but more recent experiences have shown that this is not necessarily the case, unless durability design forms an integral part of the design and construction process. There is a need to consider all potential deterioration mechanisms at the design stage before selecting and specifying an appropriate concrete mixture from a durability perspective. Prescriptive specifications for concrete based on a permissible maximum water-to-cement ratio and minimum cement content have received much criticism in recent years. They may even have inadvertently allowed designers and contractors to avoid considering or implementing all the available information required for a sound design for durable construction.

Unexpected maintenance and repairs arising very early in the specified service life of structures have led to enormous financial burdens to clients. The US Department of Defense funded a major research project entitled 'Concrete Durability – a Multibillion-Dollar Opportunity' to determine whether the problem with concrete durability was a technical or an institutional problem [2]. It concluded that

> Most of the knowledge exists which, if properly applied, would produce durable concrete. The lack of proper application may be attributed to a lack of knowledge by practitioners and the system's failure to make durability the responsibility of the organization which can most directly provide it – the contractor.

It is not so much the lack of knowledge within the design team but the failure to recognise the magnitude of potential durability problems, which may incur high maintenance and repair costs. If structures are not properly maintained, subsequent strengthening is not always an option, so that they may have to be demolished. This was the case with the Churchill Way flyovers in Liverpool, which were demolished between September and December 2019. The flyovers were closed in September 2018 pending a structural safety review, which found that they were 'no longer adequate to carry vehicles or pedestrians'.

Figure 1.1 Multistorey car park in Colchester that was pulled down in 1995 because concrete corrosion problems were beyond economic repair

Hopefully, such structures showing signs of structural distress will be identified in good time and demolished safely rather than collapsing suddenly with loss of life. The latter was unfortunately the case with the Morandi Bridge in Genoa, a section of which collapsed in August 2018 killing 43 people and leaving 600 people homeless. The collapse also exposed the state of disrepair of Italian motorways in general, but especially those in Liguria, a region of north-western Italy, whose capital is Genoa.

Some examples of durability problems that have appeared in the *New Civil Engineer*, the monthly journal of the Institution of Civil Engineers, in the past decades and durability problems reported in newspapers and websites are briefly described to convince the reader that durability needs to be considered seriously and at the design stage of the construction project.

1.2. Concrete condemned: The Queen Street car park in Colchester

A multistorey car park in Colchester was pulled down in 1995 because concrete corrosion problems were beyond economic repair (Figure 1.1) [3].

The Queen Street car park was put up only in 1971 under a design and build contract by the now defunct contractor Shears-Neal. By 1985, evidence of corrosion in precast concrete units on the in situ concrete frame prompted Colchester Borough Council to commission consultant Eastwood & Partners to report on the structure. Eastwood found that 3% of units were affected and made repair recommendations to prolong its life by 5 years. In 1992, the car park, which sits over a live bus station, was closed for safety reasons. Eastwood reported that 40% of the units were then affected. Refurbishment costs were put at £1.5 million, rebuild at £3 million and demolition at £350,000. The council opted for demolition.

1.3. Repairs to a heavily used bridge in Runcorn carried out without disrupting traffic

Problems on the 34-year-old 27-span crossing with its striking 330-m central lattice steel arch were first identified in 1989 [4]. The three-span bridge itself, with its concrete deck, was in reasonably good condition, thanks to owner Cheshire County Council's £1 million a year maintenance programme. However, all the concrete approaches were in a less favourable state (Figure 1.2). Each is made up of four in situ longitudinal deck beams carried generally on a single central pier with an integral cross head. The ever familiar story of road salt seeping down through leaking deck expansion joints to attack beams, cross heads and piers was all too evident on both sides of the Mersey.

Figure 1.2 Concrete approaches to the Runcorn Bridge

The worst damage was beneath the Widnes approaches, which were widened in 1977 by adding a separately supported 5-m-wide strip of deck. Here the main culprit was a 500-mm-wide longitudinal infill slab that connected the original and extended sections of the deck.

Flexible joints supporting both sides of the infill were leaking, allowing chloride-rich surface water to run down. Chloride levels in the rectangular beam, which is up to 2 m deep, approached 2% by weight of cement. The concrete had spalled and delaminated and the link steel had been attacked. However, the four layers of the main densely packed 50-mm rebar were relatively unscathed.

Cathodic protection was installed in the chloride-riddled approach spans, which avoided the widespread demolition and reconstruction of the damaged spans for one of the River Mersey's most strategic crossings. Importantly, this was the first full-scale application of a micro-concrete gunite overlay, which claimed to solve the historic package of problems surrounding such specialised sprayed-concrete applications.

1.4. Terminal operation: Miracle cure for the Marsh Mills Viaducts

What to do about the Marsh Mills Viaducts became a major preoccupation of engineers in the West Country for more than 15 years once it was realised that the elegant concrete structures were condemned to a lingering but terminal decline [5]. The revelation that the Marsh Mills Viaducts were afflicted by the alkali–silica reaction (ASR), which would inexorably burst it apart, had come as a shock. The industry had assumed that ASR was a technically interesting cause of deterioration to concrete overseas but generally of only academic interest in Britain. The ASR deterioration of structures, such as Charles Cross car park in Plymouth and the foundations of electricity substations in the South West, had previously been dismissed as freak incidents. Cracking on the viaduct, which had already been monitored for 18 months when the situation was headlined by *New Civil Engineer*, was dismissed at the time by engineers at Devon County Council as something 'rather superficial'.

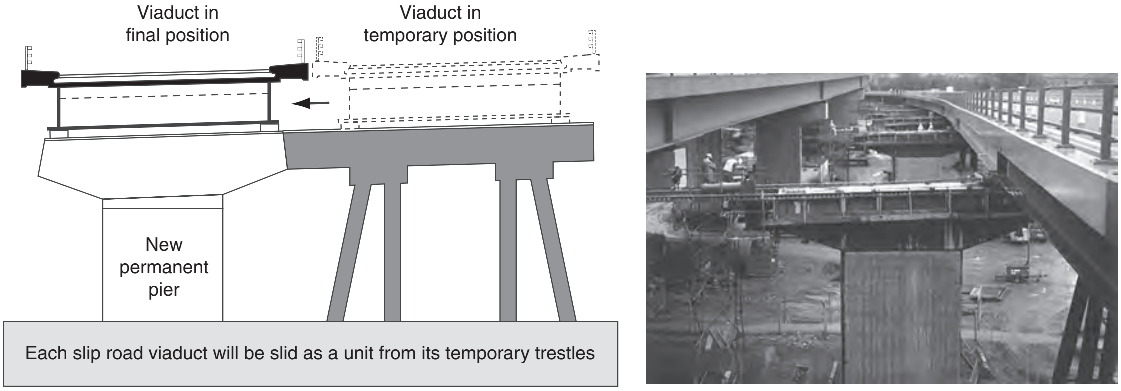
The trouble was caused by alkali-rich cement from the nearby Plymstock Works, which was used in combination with sea-dredged aggregates, and aggravated by road de-icing salt. Moisture is required for ASR, which produces an expansive gel that can burst concrete structures apart. The internal expansion causes a characteristic map cracking effect on the surface of a structure.

Discovery of the full extent of the problems at Marsh Mills prompted a nationwide examination of other highway structures. Many were found to be in trouble to a greater or lesser degree and several were replaced. As well as Marsh Mills, there were several other reinforced-concrete bridges on the 1969/70 vintage, grade-separated A38 highway between Exeter and Plymouth. Measures adopted were to observe and contain the problem with remedial works, such as weather shields, to extend the working life of structures until such time as replacements could be built.

Miracle cure? Bold innovation won Hochtief the contract to replace Plymouth's concrete cancer-crippled Marsh Mills Viaducts at a design and build cost of £12.25 million. The idea was simple. Its execution, however, was nerve-wracking. Traffic diversions could be avoided almost entirely, figured Hochtief and its designer Tony Gee & Partners; just assemble the new viaduct decks on temporary supports beside the old structures while building the permanent foundations and piers beneath them. Then, traffic could be transferred away for a few hours while each new viaduct was slewed sideways onto the permanent supports (Figure 1.3). Slewing in the viaducts involved the biggest such bridge jacking operation ever attempted. Each slip road deck was some 400 m long, weighed about 5250 tonnes and was supported on bearings sliding on tracks set on seven or eight intermediate piers. Just for good measure, the viaducts were each set out on a curve with a severe gradient and a crossfall.

Motivation for this extreme solution came from the lane licence charges imposed by the Highways Agency. Overnight closure of any two lanes of the A38 would have cost the contractor £5000, rising to £18 000 a day at a weekend and a thumping £25 000 a day during the week. In effect, Hochtief saved these charges and spent the money instead on extensive temporary works. The crippled viaducts carried slip roads for the A38 up to 12 m above the Plym Valley. They were heavily trafficked and tightly constrained by obstacles, including the main railway line to Penzance, the River Plym and buried services, including most of the trunk gas, water and electricity supplies to Plymouth.

Figure 1.3 Replacing the Marsh Mills Viaducts [5]



(a)

(b)

Figure 1.4 The collapse of the Ynys-y-Gwas Bridge led to a ban on grouted tendons [6]

1.5. Lasting effect: The collapse of the Ynys-y-Gwas Bridge

Bridge owners have for many years been concerned about the corrosion of prestressing cables and the difficulty of inspection. These concerns were highlighted in December 1985 with the sudden collapse of a 32-year-old 18.3-m-span post-tensioned segmental road bridge in South Wales (Figure 1.4) [6]. The failure of the Ynys-y-Gwas Bridge was directly caused by tendons corroded by chlorides from de-icing salts. The salt penetration was eventually attributed to a combination of inadequate tendon protection, poor workmanship and ineffective deck waterproofing. Other key factors identified included the lack of an in situ top slab and joints opening under load.

Although possibly the most newsworthy, this is by no means the only bridge to have had problems. In September 1992, the Department of Transport's concern as an owner and client led to the announcement of a temporary ban on the commissioning of any new bridges of the grout duct post-tensioned type until specifications had been reviewed. Construction of some bridges already designed using bonded internal prestress was allowed to continue. The Department of Transport's decision, in effect, laid down a challenge to the UK concrete bridge industry to put its house in order and to demonstrate that it had done so. The response by the Concrete Society, supported by the Concrete Bridge Development Group, was to set up a working party in June 1992 to study the problem and prepare recommendations. In May 1994, the working party held a seminar that summarised the position at that time. Detailed discussions started with the Highways Agency in April 1995 with a view to making use of the revised design and construction procedures to allow a phased reintroduction of bonded post-tensioned bridges. Concrete Society Technical Report 47: *Durable Bonded Post-tensioned Concrete Bridges* was published in 1996 [7].

1.6. Thaumasite test for the Cotswolds

Fears that thaumasite sulphate attacks against concrete could hit thousands of house foundations prompted the government to commission a major in situ research project in 1998 [8]. The research took place at a site in the Cotswold village of Shipston-on-Stour, where cases of thaumasite in house foundations were discovered as long ago as 1990. The tests monitored 176 concrete specimens over periods of 3 and 10 years. Some 43 mix types were used with four different aggregates and ten different binders. A combination of precast and cast-in-place specimens were placed in two 11-m-long by 2.5-m-deep trenches.

The research was a clear indication of the government's increasing fears over the possible scale of the problem. The Highways Agency revealed ten cases of thaumasite on bridges on the M5 in Gloucestershire (Figure 1.5). A further 27 structures were understood to have been identified as vulnerable to thaumasite attack on country roads in Gloucestershire.

Figure 1.5 Thaumasite attack against a bridge in Gloucestershire

The subject of thaumasite attack was in the spotlight for almost a year [9–12]. The government's expert group produced, after an 8-month investigation, a guidance document on thaumasite attacks [13]. Articles on thaumasite, however, continued to appear months after its publication [14–17].

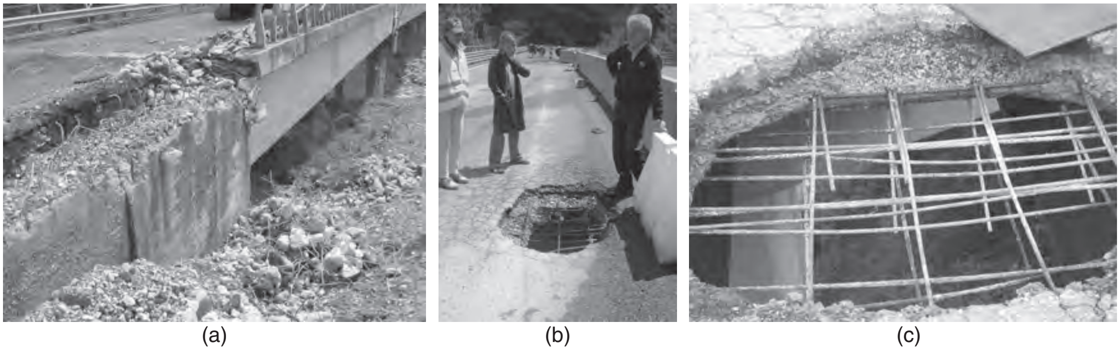
1.7. Joint detailing key to flat-slab collapse of Pipers Row car park

The Health & Safety Executive published its report into the 1997 collapse of the Pipers Row multistorey car park in Wolverhampton in 2004 (Figure 1.6) [18,19]. The research identified that lift slabs were susceptible to punching shear if the concrete had deteriorated in the slab/column zone.

Pipers Row was a punching shear failure and occurred when there was only a dead load, implying that there had been an apparent major reduction in strength. The failure was initiated by local deterioration of the concrete, confirmed both by examination of the debris and by subsequent rigorous structural analysis. The concrete in the collapsed top slab was of lower quality than elsewhere in the structure. It had been exposed to the elements for over 30 years and undoubtedly went through many freeze–thaw cycles. Frost action

Figure 1.6 Collapse of Pipers Row multistorey car park in Wolverhampton [18]

Figure 1.7 Deterioration of the concrete on (a) the parapet walls and (b, c) concrete deck of Fornello Viaduct



led to the concrete becoming friable all the way into the slab near an internal column and as far as the top steel, eventually leading to a complete loss of bond and anchorage. Rigorous analysis of Pipers Row clearly showed that the undeteriorated as-built strength had a safety margin of at least 1.5 against the worst possible in-service load.

1.8. Fornello Viaduct of the Orte–Ravenna (E45) highway

The European route E45 goes from Norway to Italy through Finland, Sweden, Denmark, Germany and Austria. It has a length of about 5190 km, and it is, thus, the longest north–south European route. Fornello Viaduct is part of the mountain highway connecting Orte to Ravenna in Italy. It was built in the early 1970s and has four 32-m spans of width 9.5 m in each direction. The deck consisted of four prestressed concrete girders and a reinforced-concrete slab of thickness 200 mm. Figure 1.7 shows the extent of the concrete deterioration in the parapets and reinforced-concrete slab. Studies of the deck indicated that the primary causes of deterioration were not only corrosion of the steel reinforcement but also freeze–thaw attack [20]. The studies were carried out in 2008 after it was decided that the reinforced-concrete deck should be demolished and replaced.

1.9. The Churchill Way flyovers in Liverpool were demolished in 2019

The Churchill Way flyovers were built in the 1960s and opened in the 1970s as part of Liverpool's abandoned inner ring road scheme. The flyovers linked Lime Street to both Dale Street and Tithebarn Street and ran directly behind the city's museums on William Brown Street. Remedial works were previously carried out in the 1980s, in 2005 and in 2013. They were closed in 2018 and a review was carried out which showed that they were 'no longer adequate to carry vehicles or pedestrians'.

The flyovers had been poorly built. Wooden moulds had been used to build the hollow-core post-tensioned concrete girders. In some parts, the wooden moulds were overloaded from the weight of the fresh concrete and broke open. Therefore, there was more concrete than was required, which increased the self-weight of the structures. The lack of access holes that allowed entry into the hollow cores of the girders meant that this went unnoticed. Moreover, the wooden formwork inside the flyover decks had rotted, and there were serious problems with drainage. The concrete cover was not adequate. For example, some cables and steel reinforcement were too near the surface. Corrosion of these led to concrete spalling. The structure was, as a result, 'overstressed' and cracks had appeared over some of the supports [21–23].

Liverpool Council decided that it would have been too costly and difficult to repair or replace the flyovers. They estimated that it would have cost £60 million to rebuild whereas demolition would have cost only

Figure 1.8 Removal of Liverpool's condemned Churchill Way flyovers [22]

£6.75 million. The latter was considered to be the safest and most economical option, even if the road network in the area had to be improved to help the traffic flow. New bridges were required to replace the pedestrian footbridges that crossed the busy main roads.

Demolition was a complex job since the flyovers were multi-span post-tensioned concrete girders (Figure 1.8). Taking down one part of any structure could have caused damage elsewhere. The concrete girders were cut in situ, lowered to the ground using heavy-lifting equipment and then cut into smaller sections and transported off site. This was to minimise the dust, noise, vibration and environmental impact to the surrounding area.

1.10. Collapse of the Morandi Bridge in Genoa in 2018

A 250-m-long deck section of the Polcevera Viaduct, more familiarly known as Genoa's Morandi Bridge, collapsed on 14 August 2018 killing 43 people (Figure 1.9) [24]. The viaduct was 1.1 km long and had three 90-m-tall towers. One of the three towers collapsed. The foundations of the tower were being strengthened

Figure 1.9 Collapse of the Morandi Bridge in Genoa in 2018 [25]

(a) (b)