



Alkali-Aggregate Reaction and Structural Damage to Concrete

Engineering Assessment, Repair and Management

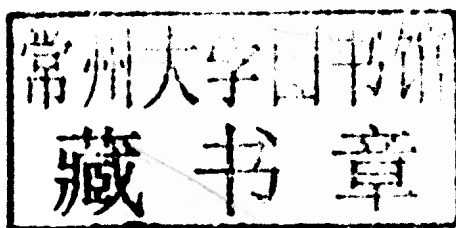
Geoffrey E. Blight & Mark G. Alexander



Alkali-Aggregate Reaction and Structural Damage to Concrete

Engineering assessment, repair
and management

Geoffrey E. Blight
Mark G. Alexander



CRC Press

Taylor & Francis Group

Boca Raton London New York Leiden

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

A BALKEMA BOOK

CRC Press/Balkema is an imprint of the Taylor & Francis Group, an informa business

© 2011 Taylor & Francis Group, London, UK

Typeset by Vikatan Publishing Solutions (P) Ltd, Chennai, India

Printed and bound in Great Britain by Antony Rowe (A CPI-group Company),
Chippenham, Wiltshire

All rights reserved. No part of this publication or the information contained herein may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, by photocopying, recording or otherwise, without prior permission in writing from the publisher. Innovations reported here may not be used without the approval of the authors.

Although all care is taken to ensure integrity and the quality of this publication and the information herein, no responsibility is assumed by the publishers nor the author for any damage to the property or persons as a result of operation or use of this publication and/or the information contained herein.

Published by: CRC Press/Balkema

P.O. Box 447, 2300 AK Leiden, The Netherlands

e-mail: Pub.NL@taylorandfrancis.com

www.crcpress.com – www.taylorandfrancis.co.uk – www.balkema.nl

Library of Congress Cataloging-in-Publication Data

Applied for

ISBN: 978-0-415-61353-8 (Hbk)

ISBN: 978-0-203-09321-4 (eBook)

Alkali-Aggregate Reaction and Structural Damage to Concrete

Author biographies

GEOFFREY BLIGHT



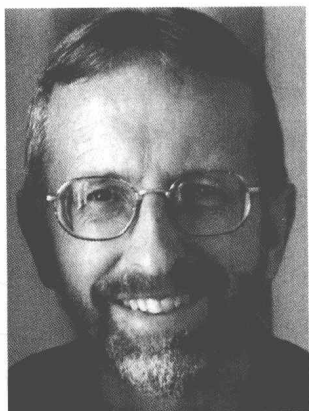
Geoffrey Blight completed his Bachelor's and Master's degrees in Civil Engineering at the University of the Witwatersrand, Johannesburg and his PhD in Geotechnical Engineering at the Imperial College of Science and Technology, London, in 1961. The early years of his career were spent at the South African National Building Research Institute, Pretoria, where he was engaged in research on design, operation and safety of mine waste storage facilities, including waste rock dumps and hydraulic fill tailings storage facilities.

In 1969 Geoff Blight was appointed to the Chair of Construction Materials in the Department of Civil Engineering at Witwatersrand University. The field of study encompassed geotechnical engineering and concrete technology.

In 1978 he was commissioned to study and diagnose the cause of cracking occurring in a series of 15 to 17 year old reinforced concrete structures supporting the Johannesburg motorway system, and diagnosed the cause as AAR. Since then, he has researched and investigated several cases of deterioration by AAR, and has published widely on the subject. He and his co-author, Mark Alexander, spent a number of years in joint research on AAR and other aspects of the durability of concrete.

He was a corresponding member of the committee that produced the British Institution of Structural Engineers' guides on the structural effects of AAR published in 1989 and 1992 and, since 2002, has been a corresponding member of the RILEM Technical Committees TC 106 and TC 191 – ARP which have been investigating various aspects of AAR.

MARK ALEXANDER



Mark Alexander completed his Bachelor's, Master's and PhD degrees in Civil Engineering at the University of the Witwatersrand, Johannesburg and lectured in Construction Materials at Witwatersrand University for several years. In 1992 he was appointed to the Chair of Civil Engineering at the University of Cape Town where he has further developed his interests in concrete durability, including repair and rehabilitation of deteriorated concrete structures. He has published extensively and is active in international scientific circles. He co-authored the Book "Aggregates in Concrete" published by Taylor and Francis in 2005. He is currently Vice President of RILEM* and is scheduled to assume the RILEM Presidency in 2012.

* Reunion Internationale des Laboratoires et Experts des Matériaux.

Acknowledgements

The authors wish to salute the many engineers and scientists who have contributed to the understanding that we have of the AAR phenomenon in 2010, 70 years after it was first formally described by T.E. Stanton in the U.S.A. in 1940. We particularly acknowledge the great early contributions in the 1950's and 60's by Harold Vivian in Australia, Sydney Diamond in the U.S.A. and Gunnar Idorn in Denmark. In our own country, Bertie Oberholster led the field with his early investigations of the unexplained cracking of concrete structures in the Western and Eastern Cape Provinces. There are many other pioneers in the field that we have not mentioned, but we salute them all.

We also thank all the engineers and scientists who in later years, up to the present, have taken the trouble to share their experiences and ideas on combating and preventing the effects of AAR, thus adding to the pool of common knowledge of the subject. We particularly want to thank the co-authors of our papers on AAR. It was the efforts of all those mentioned above that made the writing of this book possible.

In Geoff Blight's case, the City Engineer and Deputy City Engineer of Johannesburg, Eric Hall and John Stewart, as well as the consulting civil engineer, Wally Schutte first involved him, in 1978, in this fascinating field. He thanks them for doing so.

Mark Alexander in his formative years as a young researcher, was most fortunate in having Geoff Blight, first as a supervisor and then as a colleague in the enabling environment at Witwatersrand University. No one could have wished for a more supportive and stimulating supervisor! He is very grateful for the opportunities then afforded him.

Both authors have had the good fortune to enjoy the support of dedicated and outstanding technicians. At the University of the Witwatersrand, Bob van der Merwe, Frans Wiid and Bob Anderson were indispensable to the success of our research. At both Witwatersrand and Cape Town, in addition to lab staff, many students have assisted from time to time in investigating various aspects of AAR. One of these was Yunus Ballim, who went on to become head of Civil Engineering and is now Deputy Vice-Chancellor of the University of the Witwatersrand. We are grateful to Yunus for his enthusiasm and support for writing this book.

We thank Alex Elvin, Professor of Civil Engineering at the University of the Witwatersrand, for contributing Section 4.8.6 on recent developments in instrumentation.

Maryanne Kelly prepared the diagrams and patiently made the seemingly endless changes, additions and deletions that were part of the process.

We both acknowledge and are extremely grateful for our families' unwavering support.

Geoff particularly thanks his wife Rhona for patiently typing yet another major manuscript from his almost illegible drafts.

Mark likewise acknowledges the patient and unswerving support of his wife Lyn over the years.

Unless otherwise acknowledged, all of the photographs were taken by Geoff Blight.

Geoff Blight
Johannesburg, September 2010

Mark Alexander
Cape Town, September 2010

List of mathematical symbols

ROMAN LETTERS

A	cross-sectional area [mm ²]
B, b	breadths [mm]
c	cohesion of concrete [MPa]
C	compressive force [kN]
or C	structural capacity [stress, force or moment units]
D	structural demand [stress, force or moment units]
D	diameter [mm]
E	elastic modulus [MPa, GPa]
f	direct stress (f_y = yield stress) [MPa, GPa]
f(u) or F()	function of quantity in ()
H, h	heights [mm]
K	function of Poisson's ratio ν
L, l	lengths [mm]
P	load [kN, MN]
p ^{II}	pore water suction [kPa]
p _f	probability of failure [dimensionless]
r	radius of water meniscus [mm or nm]
RH	relative humidity [dimensionless]
s _d	standard deviation [MPa]
T	tensile force [kN]
or T	surface tension of water [N/mm, kPam]
V	ultrasonic pulse velocity [m/s, km/s]
V _u	shear force at failure [N, kN]
W _f	failure load [kN]
\bar{x}	mean value

GREEK LETTERS

α	l.c.	alpha	ratio or coefficient [dimensionless]
β	l.c.	beta	ratio or coefficient [dimensionless]
γ	l.c.	gamma	shear strain [dimensionless]

ϵ	l.c.	epsilon	direct strain [dimensionless, $\text{mm/m} = 1 \times 10^{-3} = \text{millistrain}$ $\text{mm/km} = 1 \times 10^{-6} = \text{microstrain}$]
η	l.c.	eta	viscosity [Pas, kNm/s]
μ	l.c.	mu	micro as in $\mu\text{m} = \text{micrometre}$ or $\mu\epsilon = \text{microstrain}$
ν	l.c.	nu	Poisson's ratio [dimensionless]
π	l.c.	pi	ratio of perimeter to diameter of a circle [dimensionless]
ρ	l.c.	rho	density or unit mass [kg/m^3 or g/cm^3]
σ	l.c.	sigma	direct stress, strength or pressure [$\text{kPa} = \text{kN/m}^2$, $\text{MPa} = \text{N/mm}^2$]
or σ			standard deviation of C or D
τ	l.c.	tau	shear stress or shear strength [kPa , MPa]
τ_u, τ_f			shear stress at failure
ϕ	l.c.	phi	angle of shearing resistance of concrete [degrees of arc]

Contents

<i>Author biographies</i>	xi
<i>Acknowledgements</i>	xiii
<i>List of mathematical symbols</i>	xv

I Alkali-aggregate reaction (AAR) and its effects on concrete – an overview	1
1.1 AAR and its visible characteristics	1
1.2 The chemical characteristics of AAR	3
1.3 Guarding against AAR	3
1.4 Main types of AAR and the appearance of fractures caused by AAR	5
1.4.1 Alkali-silica reaction (ASR)	5
1.4.2 Alkali-silicate reaction	6
1.4.3 Alkali-carbonate rock reaction (ACR)	6
1.5 Chemical mechanisms of AAR	7
1.6 Necessary and sufficient requirements for AAR to occur	8
1.6.1 Alkalis	8
1.6.2 Reactive silica	10
1.6.3 The environment and moisture	10
1.7 What is still to come	13
References	15
Plates	16
2 Diagnostic investigations and tests and their interpretation	23
2.1 Investigation of the cause of cracking in a concrete structure	23
2.1.1 Planning the site inspection	24
2.1.2 Observations on the structure	25
2.1.3 Preliminary assessment of the site inspection	25
2.1.4 Sampling of concrete	26

2.2	Petrology of AAR-susceptible mineral and rock types	27
2.2.1	Mineral constituents	27
2.2.2	The alkali-silica reaction	31
2.3	Assessing aggregates for AAR-potential	32
2.3.1	Initial screening tests	33
2.3.2	Indicator tests	33
2.3.3	Performance tests	38
2.3.4	RILEM technical committee contributions	38
2.3.5	Drawing conclusions from tests for AAR-susceptibility	40
2.4	Aggregate petrography	40
2.4.1	Petrographic composition and examination of aggregates	41
2.4.2	Analysis techniques	42
2.4.3	Assessing residual ultimate expansion of concrete in structures	43
	References	43
	Plates	45
3	Effects of AAR on engineering properties of concrete – results of laboratory determinations	47
3.1	Laboratory specimens and cores taken from structures	47
3.2	The process of cracking	48
3.3	Differences between laboratory specimens and cores taken from AAR-affected structures	50
3.4	The testing of cores and laboratory-prepared cylinders or prisms	53
3.4.1	Stresses in a cylinder subject to compression between rigid platens	53
3.4.2	Load-controlled and strain-controlled testing	55
3.4.3	Measuring the elastic modulus and Poisson's ratio for concrete in compression	55
3.4.4	Measuring the direct tensile strength	57
3.4.5	Measuring the indirect or splitting tensile strength	58
3.5	The strength of disrupted or disintegrated concrete	58
3.6	Elastic properties, compressive, indirect and direct tensile strengths of AAR-affected concrete	61
3.7	Creep of AAR-damaged concrete under sustained load	65
3.8	The effects on expansion of compressive stress	67
3.8.1	Restraint on expansion imposed by reinforcing	67
3.8.2	Restraint on expansion imposed by adjacent structures or structural elements	69
3.9	Fracturing of reinforcing steel in AAR-affected structures	71

3.10	The possibility of bond failure in AAR-affected reinforced concrete structures	74
3.11	Review and summary of conclusions	76
	References	78
	Plates	80
4	Assessment of risk of structural failure based on the results of laboratory or field tests	83
4.1	Introduction, definitions and examples	83
4.2	An acceptable probability of failure	84
	PART 1 Statistical considerations	87
4.3	Statistical calculation of the probability of failure	87
4.4	Assessing demand D and capacity C	89
4.4.1	Assessing the demand D	89
4.4.2	Assessing the capacity C	90
4.5	A simple example of calculating p_f	91
4.6	Conclusions on statistical assessment of risk	92
	PART 2 Full-scale test loading	92
4.7	Full-scale test loading as a means of assessing risk	92
4.8	Instruments used for measurements in laboratory and in situ load testing	93
4.8.1	Determining principal and shear strains	94
4.8.2	Mechanical methods for measuring deflection and strain	95
4.8.3	Electrical methods for measuring deflection and strain	96
4.8.4	Measuring temperature	99
4.8.5	Measuring rotation or change of slope	100
4.8.6	Recent developments for in situ measurement of displacement, rotation and strain in structures	100
4.8.7	Testing by ultra-sonic pulse velocity (UPV)	103
4.9	Planning, preparing and performing an in situ load test on a structure	109
4.9.1	The history of the structure	109
4.9.2	Objectives, extent of testing and preliminary information-gathering	109
4.9.3	Detailed planning – choice of date and time, lighting and access	110
4.9.4	Loading system, stages of loading, predicted and actual movements and strains	110
4.9.5	Briefing the testing team	111

4.10	“Special” or “once or twice off” test loadings of complete structures	112
4.10.1	Motorway double-cantilever structures: (northern cold-temperate coastal climate)	112
4.10.2	Motorway portal frame (southern warm-temperate, water deficient continental climate)	115
4.10.3	Motorway bridge (northern cold-temperate climate)	120
4.10.4	Unreinforced concrete road pavement (southern mediterranean-type temperate climate)	120
4.10.5	Underground mass concrete plug	122
4.10.6	Industrial structural pavement	128
4.11	Routine periodic test loading of complete structures	131
4.11.1	Loading jetty over sea (southern moist tropical coastal climate)	131
4.11.2	Bridges on highway (north temperate climate)	132
4.12	Tests on relatively small components removed from site and tested in laboratory	134
4.12.1	Prestressed concrete railway sleepers (southern temperate semi-désert climate)	134
4.12.2	Beams sawn from flat slab bridges (northern cold-temperate climate)	135
4.12.3	Prestressed planks taken from road bridge (southern warm-temperate climate)	136
4.13	Review and conclusions	138
	References	142
	Plates	145
5	Repair and rehabilitation of AAR-affected structures	155
5.1	Types of repair or remedial treatment	155
5.2	Arresting the AAR process – experiments with surface treatments	156
5.2.1	Experiments in Iceland (cold climate) and France (cool temperate climate)	159
5.2.2	Laboratory experiments in South Africa (warm temperate, water-deficient continental climate)	161
5.2.3	Field experiments in South Africa	165
5.2.4	Additional observations and conclusions	174
5.2.5	Treatment of structures with lithium compounds	174
5.3	Restoring design-properties by resin-injection	175
5.3.1	General consideration of crack injection as a method of repair	175
5.3.2	Repair of sports stadium	176
5.4	Repair by externally applied stressing	182

5.4.1	Repair of cantilever projection supporting beam spans on either side	182
5.4.2	Repair of knee of reinforced concrete portal frame	184
5.4.3	Principle of increasing resistance to vertical stress by increasing horizontal stress	185
5.4.4	Strengthening column by means of stressed precast concrete encasement	187
5.5	Strengthening by glued-on steel plates	189
5.5.1	Experiments on external plating to strengthen concrete structures	189
5.6	Repair by partial demolition and reconstruction	192
5.6.1	Partial demolition and rebuilding of bridge piers	192
5.6.2	Refurbishing a bridge underpass	192
5.6.3	Partial demolition and rebuilding of highway structure	193
5.7	Repair and rehabilitation of concrete highway pavement	197
5.8	Repair or mitigation of effects of AAR in large mass concrete structures	197
5.8.1	Use of slot-cutting to relieve distress in hydroelectric power machinery	198
5.8.2	Effects of AAR on movements of arch dams	202
5.8.3	Slot-cutting for relief of swelling stress	204
5.9	Repair of broken reinforcement in AAR-damaged concrete	206
5.10	Review and conclusions	207
5.10.1	Arresting AAR	208
5.10.2	Repair by resin injection	208
5.10.3	Repair by externally applied stressing	208
5.10.4	Repair by external reinforcing	209
5.10.5	Partial demolition and reconstruction	209
5.10.6	Repair and rehabilitation of concrete pavements	209
5.10.7	Alleviation of AAR effects in mass concrete structures	209
5.10.8	Broken reinforcement	209
5.10.9	Repair and ongoing maintenance	209
	References	210
	Plates	214

6	Epilogue – A check-list of important structural consequences of AAR	227
6.1	AAR is a durability problem that is unlikely to cause structural failure	227
6.2	AAR results in the deterioration of concrete properties	227

6.3	In situ concrete properties can usually be expected to be considerably better than properties measured on cores in a laboratory	228
6.4	Compression members are relatively unaffected by AAR	228
6.5	Flexural members need more consideration	228
6.6	The performance of structural concrete pavements	228
6.7	Compressive stresses in AAR-affected concrete	229
6.8	AAR-damaged structures can reach and exceed their design service life with minimal repair and preventive maintenance	229
	<i>Subject index</i>	231

Alkali-aggregate reaction (AAR) and its effects on concrete – an overview

1.1 AAR AND ITS VISIBLE CHARACTERISTICS

The subject of the book is alkali-aggregate reaction and the structural damage it causes to concrete. The occurrence of AAR has been reported from every continent and both north and south hemispheres. It is a world-wide problem in concrete technology. The emphasis of the book is on engineering assessment, diagnosis and repair. There are many published conference and journal papers dealing with AAR, and the number of authoritative and specialized papers has increased substantially over the past three decades. For example, the number of papers presented to the Fifth International Conference on AAR in Concrete in 1981 was 32. At the 12th International Conference in 2004, 162 papers were presented. However, most of this literature is concerned with scientific rather than engineering aspects of AAR, i.e.: its chemistry, the nature of the various reactions, susceptible minerals, chemical kinetics, and factors influencing them, as well as the prediction of AAR-susceptibility. These scientific studies have been essential for our understanding of the AAR phenomenon and have assisted the cement and concrete industries to improve the performance of cement and aggregates and items made of concrete and to eliminate the use of marginal materials that may be AAR-susceptible.

The effects of AAR on the engineering performance of concrete artifacts and structures – whether of mass reinforced or prestressed concrete has been less well-covered in the engineering literature. At the 1981 AAR Conference, 4 of the 28 papers dealt with engineering aspects of AAR, while in 2004, 45 of the 162 papers were on engineering aspects. Hence not only has the number of engineering-orientated papers increased, but also their proportion (1 in 7 to 1 in 4.2). AAR has the primary effect of damaging concrete and causing some loss of performance in concrete structures, at the very least by the unsightly surface cracking it causes. The challenge to owners and operators of AAR-affected structures is how to assess these structures in terms of their engineering performance and safety, how to repair them and then how to manage the repaired structures. It must be recognised that, ultimately, civil or structural engineers have to assess, repair and manage the ongoing problems of AAR-affected structures. Owners of such structures will require reasonable assurance that their assets will retain their value and remain safe, functional and economic in terms of ongoing repair costs. Therefore, sound engineering knowledge of the mechanisms whereby concrete is damaged by AAR, its effects on the actual performance of concrete structures, as well as on assessment and repair techniques is needed.