



Corrosion and Protection of Reinforced Concrete

Brian Cherry
Warren Green



CRC Press
Taylor & Francis Group

Corrosion and Protection of Reinforced Concrete



Taylor & Francis

Taylor & Francis Group

<http://taylorandfrancis.com>

Corrosion and Protection of Reinforced Concrete

Brian Cherry and Warren Green



CRC Press

Taylor & Francis Group
Boca Raton London New York

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

First edition published 2021
by CRC Press
2 Park Square, Milton Park, Abingdon, Oxon, OX14 4RN

and by
CRC Press
6000 Broken Sound Parkway NW, Suite 300, Boca Raton, FL
33487-2742

CRC Press is an imprint of Taylor & Francis Group, LLC

© 2021 Taylor & Francis Group, LLC

Reasonable efforts have been made to publish reliable data and information, but the author and publisher cannot assume responsibility for the validity of all materials or the consequences of their use. The authors and publishers have attempted to trace the copyright holders of all material reproduced in this publication and apologize to copyright holders if permission to publish in this form has not been obtained. If any copyright material has not been acknowledged please write and let us know so we may rectify in any future reprint.

Except as permitted under U.S. Copyright Law, no part of this book may be reprinted, reproduced, transmitted, or utilized in any form by any electronic, mechanical, or other means, now known or hereafter invented, including photocopying, micro-filming, and recording, or in any information storage or retrieval system, without written permission from the publishers.

For permission to photocopy or use material electronically from this work, access www.copyright.com or contact the Copyright Clearance Center, Inc. (CCC), 222 Rosewood Drive, Danvers, MA 01923, 978-750-8400. For works that are not available on CCC please contact mpkbookspermissions@tandf.co.uk

Trademark notice: Product or corporate names may be trademarks or registered trademarks, and are used only for identification and explanation without intent to infringe.

ISBN: 978-0-367-51760-1 (hbk)
ISBN: 978-0-367-51761-8 (pbk)
ISBN: 978-1-003-08130-2 (ebk)

Typeset in Sabon
by SPi Global, India

Contents

<i>Preface</i>	xv
<i>Authors</i>	xix
1 Steel-reinforced concrete characteristics	1
1.1 <i>Concrete and reinforced concrete</i>	1
1.2 <i>The structure of concrete</i>	2
1.3 <i>Cements and the cementing action</i>	2
1.3.1 <i>General</i>	2
1.3.2 <i>Heat of hydration</i>	6
1.3.3 <i>Rate of strength development</i>	7
1.4 <i>Supplementary cementitious materials – blended cements</i>	9
1.4.1 <i>General</i>	9
1.4.2 <i>Fly ash</i>	10
1.4.3 <i>Slag</i>	11
1.4.4 <i>Silica fume</i>	11
1.4.5 <i>Triple blends</i>	11
1.5 <i>Aggregates</i>	11
1.5.1 <i>General</i>	11
1.5.2 <i>The design of a concrete mix</i>	12
1.5.3 <i>Estimation of fine aggregate content and mechanical properties</i>	16
1.6 <i>Mixing and curing water</i>	16
1.7 <i>Admixtures</i>	17
1.7.1 <i>Air entraining admixtures</i>	18
1.7.2 <i>Set retarding admixtures</i>	18
1.7.3 <i>Set accelerating admixtures</i>	18
1.7.4 <i>Water reducing and set retarding admixtures</i>	18
1.7.5 <i>Water reducing and set accelerating admixtures</i>	19
1.7.6 <i>High range water reducing admixtures</i>	19
1.7.7 <i>Waterproofing agents</i>	19
1.7.8 <i>Other</i>	20
1.8 <i>Steel reinforcement</i>	20

1.8.1	<i>Background</i>	20
1.8.2	<i>Conventional steel reinforcement</i>	20
1.8.3	<i>Prestressing steel reinforcement</i>	24
1.9	<i>Fibre-reinforced concrete</i>	26
	<i>References</i>	26
2	Concrete deterioration mechanisms (A)	29
2.1	<i>Reinforced concrete deterioration</i>	29
2.2	<i>Cracking</i>	30
2.2.1	<i>General</i>	30
2.2.2	<i>Plastic settlement cracking</i>	32
2.2.3	<i>Plastic shrinkage cracking</i>	33
2.2.4	<i>Early thermal contraction cracking</i>	35
2.2.5	<i>Drying shrinkage cracking</i>	35
2.2.6	<i>Crazing</i>	36
2.2.7	<i>Alkali aggregate reaction cracking</i>	37
2.3	<i>Penetrability</i>	40
2.4	<i>Chemical deterioration</i>	41
2.4.1	<i>General</i>	41
2.4.2	<i>Alkali aggregate reaction</i>	43
2.4.3	<i>Delayed ettringite formation</i>	43
2.4.4	<i>Sulphate attack</i>	44
2.4.5	<i>Acid sulphate soils</i>	47
2.4.6	<i>Thaumasite sulphate attack</i>	48
2.4.7	<i>Acid attack</i>	48
2.4.8	<i>Aggressive (dissolved) carbon dioxide attack</i>	49
2.4.9	<i>Seawater attack</i>	51
2.4.10	<i>Leaching and efflorescence</i>	52
2.4.11	<i>Physical salt attack</i>	53
2.4.12	<i>Other chemical attack</i>	55
	<i>References</i>	56
3	Concrete Deterioration Mechanisms (B)	59
3.1	<i>Biological deterioration</i>	59
3.1.1	<i>Bacteria</i>	59
3.1.2	<i>Fungi</i>	61
3.1.3	<i>Algae</i>	61
3.1.4	<i>Slimes</i>	61
3.1.5	<i>Biofilms</i>	61
3.2	<i>Physical deterioration</i>	63
3.2.1	<i>Freeze-thaw</i>	63
3.2.2	<i>Fire</i>	65
3.3	<i>Mechanical deterioration</i>	67
3.3.1	<i>Abrasion</i>	67
3.3.2	<i>Erosion</i>	67

3.3.3	<i>Cavitation</i>	68
3.3.4	<i>Impact</i>	71
3.4	<i>Structural deterioration</i>	72
3.4.1	<i>Overloading</i>	72
3.4.2	<i>Settlement</i>	72
3.4.3	<i>Fatigue</i>	72
3.4.4	<i>Other</i>	74
3.5	<i>Fire damaged concrete</i>	74
3.5.1	<i>General</i>	74
3.5.2	<i>Effects on concrete</i>	75
3.5.3	<i>Visual concrete fire damage classification</i>	77
3.5.4	<i>Effect on reinforcement and prestressing steel</i>	79
3.6	<i>Examination of sites</i>	79
	<i>References</i>	83
4	Corrosion of reinforcement (A)	85
4.1	<i>Background</i>	85
4.2	<i>Portland cement and blended cement binders</i>	85
4.3	<i>Alkaline environment in concrete</i>	86
4.4	<i>Physical barrier provided by concrete</i>	86
4.5	<i>Passivity and the passive film</i>	87
4.5.1	<i>Background</i>	87
4.5.2	<i>Thermodynamics</i>	88
4.5.3	<i>Kinetics</i>	89
4.5.4	<i>Film formation</i>	90
4.5.5	<i>Film composition</i>	91
4.5.6	<i>Film thickness</i>	92
4.5.7	<i>Models and theories</i>	92
4.6	<i>Reinforcement corrosion</i>	92
4.6.1	<i>Loss of passivity and corrosion of steel in concrete</i>	92
4.6.2	<i>Uniform (microcell) corrosion and pitting (macrocell) corrosion</i>	93
4.6.3	<i>Corrosion products composition – chloride- induced corrosion</i>	94
4.6.4	<i>Corrosion products composition – carbonation- induced corrosion</i>	95
4.6.5	<i>Corrosion products development – visible damage</i>	95
4.6.6	<i>Corrosion products development – no visible damage</i>	96
4.7	<i>Chloride-induced corrosion</i>	97
4.7.1	<i>General</i>	97
4.7.2	<i>Passive film breakdown/pit initiation</i>	98
4.7.3	<i>Metastable pitting</i>	101
4.7.4	<i>Pit growth/pit propagation</i>	102
	4.7.4.1 <i>General</i>	102
	4.7.4.2 <i>Chemical conditions within propagating pits</i>	103

4.7.5	<i>Reinforcing steel quality</i>	105
	4.7.5.1 <i>Metallurgy</i>	105
	4.7.5.2 <i>Defects</i>	105
4.7.6	<i>Chloride threshold concentrations</i>	106
4.7.7	<i>Chloride/hydroxyl ratio</i>	108
4.8	<i>Carbonation-induced corrosion</i>	110
4.9	<i>Leaching-induced corrosion</i>	111
4.10	<i>Stray and interference current-induced corrosion</i>	112
	4.10.1 <i>General</i>	112
	4.10.2 <i>Ground currents</i>	113
	4.10.3 <i>Interference currents</i>	114
	4.10.4 <i>Local corrosion due to stray or interference currents</i>	114
	<i>References</i>	115
5	<i>Corrosion of reinforcement (B)</i>	119
5.1	<i>Thermodynamics of corrosion</i>	119
	5.1.1 <i>Background</i>	119
	5.1.2 <i>The driving potential – the nernst equation</i>	119
	5.1.3 <i>The potential – pH diagram</i>	123
5.2	<i>Kinetics of corrosion</i>	126
	5.2.1 <i>Background</i>	126
	5.2.2 <i>Polarisation</i>	126
	5.2.3 <i>Investigation of the corrosion state</i>	129
	5.2.4 <i>Pitting corrosion</i>	131
	5.2.5 <i>Oxygen availability</i>	133
	5.2.6 <i>Polarisation of the anodic process</i>	135
	5.2.7 <i>Resistance between anodic and cathodic sites</i>	136
	5.2.8 <i>Potential difference between anodic and cathodic sites</i>	137
5.3	<i>Reinforcement corrosion progress</i>	138
5.4	<i>Modelling chloride-induced corrosion initiation</i>	141
5.5	<i>Modelling carbonation-induced corrosion initiation</i>	145
5.6	<i>Modelling corrosion propagation</i>	146
	5.6.1 <i>Background</i>	146
	5.6.2 <i>Corrosion damage criterion</i>	146
	5.6.3 <i>Factors affecting corrosion rates</i>	147
	5.6.4 <i>Corrosion rates – chloride contaminated concrete</i>	147
	5.6.5 <i>Corrosion rates – carbonated concrete</i>	148
	5.6.6 <i>Length of corrosion propagation period</i>	149
	5.6.6.1 <i>Background</i>	149
	5.6.6.2 <i>General model</i>	150
	5.6.6.3 <i>Andrade (2014) model</i>	151
	5.6.6.4 <i>Andrade (2017) model</i>	151
5.7	<i>Design life achievement</i>	152
	<i>References</i>	153

6	Condition survey and diagnosis (A) –	
	on-site measurements	157
6.1	<i>Planning a condition survey</i>	157
6.2	<i>Visual inspection</i>	158
6.3	<i>Cracks</i>	160
6.4	<i>Delamination detection</i>	162
6.5	<i>Concrete cover</i>	163
6.6	<i>Electrochemical measurements</i>	164
6.6.1	<i>Electrode (half-cell) potential mapping</i>	164
6.6.2	<i>Polarisation resistance</i>	167
6.7	<i>Concrete resistivity</i>	170
6.8	<i>Other measurements</i>	172
6.8.1	<i>Rebound hammer</i>	172
6.8.2	<i>Ultrasonic pulse velocity</i>	173
6.8.3	<i>Ultrasonic pulse echo</i>	174
6.8.4	<i>Impact echo</i>	175
6.8.5	<i>Ground penetrating radar</i>	175
6.9	<i>Carbonation depth</i>	175
6.10	<i>Concrete sampling</i>	178
6.10.1	<i>General</i>	178
6.10.2	<i>Wet diamond coring</i>	178
6.10.3	<i>Drilled dust samples</i>	180
6.11	<i>Representativeness of investigations, testings, and sampling</i>	180
	<i>References</i>	181
7	Condition survey and diagnosis (B) –	
	laboratory measurements	183
7.1	<i>General</i>	183
7.2	<i>Cement (binder) content and composition</i>	185
7.3	<i>Air content</i>	186
7.4	<i>Water/cement (binder) ratio</i>	186
7.5	<i>SCM content and composition</i>	187
7.6	<i>Water absorption, sorption, and permeability</i>	188
7.7	<i>Depth of chloride penetration</i>	193
7.8	<i>Sulphate analysis</i>	195
7.9	<i>Alkali aggregate reaction</i>	196
7.10	<i>Alkali content</i>	197
7.11	<i>Delayed ettringite formation</i>	197
7.12	<i>Acid attack</i>	197
7.13	<i>Chemical attack</i>	198
7.14	<i>Microbial analysis</i>	198
7.15	<i>Physical deterioration determination</i>	198
7.16	<i>Petrographic examination</i>	198
7.17	<i>Compressive strength</i>	200

7.18	<i>Reporting</i>	200
7.18.1	<i>Background</i>	200
7.18.2	<i>Commission/scope of services</i>	202
7.18.3	<i>Technical background</i>	202
7.18.4	<i>Site investigation</i>	202
7.18.5	<i>Hypothesis</i>	202
7.18.6	<i>Laboratory testing</i>	202
7.18.7	<i>Commentary on laboratory results</i>	202
7.18.8	<i>Conclusions and recommendations</i>	202
	<i>References</i>	203
8	Repair and protection (A) – mechanical methods	205
8.1	<i>Introduction</i>	205
8.2	<i>Crack repair</i>	206
8.3	<i>Repair and protection options</i>	208
8.4	<i>Patch repair</i>	209
8.4.1	<i>Stages in the process</i>	209
8.4.2	<i>Breakout</i>	210
8.4.3	<i>Rebar coatings</i>	212
8.4.4	<i>Bonding agents</i>	215
8.4.5	<i>Patching materials</i>	215
8.4.6	<i>Equipment and workmanship</i>	218
8.5	<i>Sprayed concrete (Shotcrete/Gunite)</i>	218
8.6	<i>Recasting with new concrete</i>	219
8.7	<i>Inhibitors</i>	220
8.8	<i>Coatings and penetrants</i>	224
8.8.1	<i>Anti-carbonation coatings</i>	224
8.8.2	<i>Chloride-resistant coatings</i>	225
8.8.3	<i>Penetrants</i>	226
8.9	<i>Structural strengthening</i>	227
8.10	<i>Pile jacketing</i>	228
	<i>References</i>	231
9	Repair and protection (B) – cathodic protection	233
9.1	<i>Introduction</i>	233
9.2	<i>History of cathodic protection</i>	236
9.3	<i>Impressed current cathodic protection</i>	237
9.4	<i>Galvanic cathodic protection</i>	237
9.5	<i>The application of cathodic protection</i>	239
9.6	<i>Impressed current anodes</i>	239
9.6.1	<i>Historic</i>	239
9.6.2	<i>Soil/water anodes</i>	240
9.6.3	<i>Mesh anodes</i>	241
9.6.4	<i>Ribbon/grid anodes</i>	242
9.6.5	<i>Discrete anodes</i>	242
9.6.6	<i>Arc sprayed zinc</i>	243

9.6.7	<i>Conductive organic coatings</i>	243
9.6.8	<i>Remote (soil/water) anodes</i>	243
9.7	<i>Galvanic anodes</i>	246
9.7.1	<i>Remote (soil/water) anodes</i>	246
9.7.2	<i>Thermally sprayed metals</i>	247
9.7.3	<i>Zinc mesh with fibreglass jacket</i>	249
9.7.4	<i>Zinc sheet anodes</i>	249
9.8	<i>The actions of cathodic protection</i>	250
9.8.1	<i>General</i>	250
9.8.2	<i>Thermodynamics</i>	250
9.8.3	<i>Kinetics</i>	251
9.9	<i>Criteria for cathodic protection</i>	252
9.9.1	<i>Background</i>	252
9.9.2	<i>Potential criterion</i>	252
9.9.3	<i>Instantaneous off measurements</i>	254
9.9.4	<i>300 mV shift criterion</i>	255
9.9.5	<i>100 mV Potential decay (polarisation) criterion</i>	256
9.9.6	<i>AS 2832.5 criteria</i>	257
9.9.7	<i>ISO 12696 criteria</i>	258
9.9.8	<i>Other standards</i>	258
9.9.9	<i>CP criteria are proven</i>	259
9.10	<i>Selection and design of cathodic protection systems</i>	260
9.10.1	<i>General considerations</i>	260
9.10.2	<i>General design considerations</i>	262
9.10.3	<i>Current density</i>	262
9.10.4	<i>Anode layout</i>	263
9.10.5	<i>Power requirements</i>	263
	9.10.5.1 <i>General</i>	263
	9.10.5.2 <i>Anode resistance</i>	264
	9.10.5.3 <i>Circuit resistance</i>	264
	9.10.5.4 <i>Cathodic polarisation (back emf)</i>	265
	9.10.5.5 <i>Power supply</i>	265
9.11	<i>Stray current and interference corrosion</i>	265
9.11.1	<i>General</i>	265
9.11.2	<i>Regulatory requirements</i>	265
9.12	<i>Commissioning</i>	266
9.13	<i>System documentation</i>	267
9.13.1	<i>Quality and test records</i>	267
9.13.2	<i>Installation and commissioning report</i>	267
9.13.3	<i>Operation and maintenance manual</i>	268
9.14	<i>Operational</i>	268
9.14.1	<i>Warranty period</i>	268
9.14.2	<i>Monitoring</i>	268
9.14.3	<i>System registration</i>	268
9.15	<i>Cathodic prevention</i>	268
	<i>References</i>	271

10	Repair and protection (C) – electrochemical methods	275
10.1	<i>Galvanic electrochemical treatments</i>	275
10.1.1	<i>Background</i>	275
10.1.2	<i>Discrete zinc anodes in patch repairs</i>	275
10.1.3	<i>Distributed discrete zinc anodes</i>	279
10.1.4	<i>Performance limitations</i>	282
10.1.5	<i>Performance assessment</i>	284
10.2	<i>Hybrid electrochemical treatments</i>	287
10.2.1	<i>Background</i>	287
10.2.2	<i>First generation system</i>	288
10.2.3	<i>Second generation system</i>	290
10.2.4	<i>Performance assessment and limitations</i>	290
10.3	<i>Electrochemical chloride extraction</i>	294
10.4	<i>Electrochemical realkalisation</i>	297
10.5	<i>Repair and protection options – costs assessment approaches</i>	300
10.6	<i>Repair and protection options – technical assessment approaches</i>	302
10.6.1	<i>General</i>	302
10.6.2	<i>‘Do nothing’ option</i>	303
10.6.3	<i>Scenario analyses approach</i>	303
	<i>References</i>	308
11	Preventative measures	311
11.1	<i>Introduction</i>	311
11.2	<i>Concrete technology aspects</i>	311
11.2.1	<i>General</i>	311
11.2.2	<i>Mix design/mix selection</i>	312
11.2.3	<i>Mix selection process</i>	313
11.2.4	<i>Binder types</i>	313
11.2.5	<i>Water/cement (water/binder) ratio</i>	314
11.2.6	<i>Concrete strength</i>	315
11.3	<i>Construction considerations</i>	317
11.3.1	<i>General</i>	317
11.3.2	<i>The 5 Cs/pentagon of Cs</i>	318
11.4	<i>Coatings and penetrants</i>	322
11.4.1	<i>General</i>	322
11.4.2	<i>Organic coatings</i>	323
11.4.3	<i>Penetrants</i>	323
11.4.4	<i>Pore blocking treatments</i>	324
11.4.5	<i>Cementitious overlays</i>	326
11.4.6	<i>Sheet membranes</i>	326
11.5	<i>Coated and alternate reinforcement</i>	326
11.5.1	<i>General</i>	326
11.5.2	<i>Galvanised reinforcement</i>	327

11.5.3	<i>Epoxy coated reinforcement</i>	329
11.5.4	<i>Stainless steel reinforcement</i>	330
11.5.5	<i>Metallic clad reinforcement</i>	339
11.5.6	<i>Non-metallic reinforcement</i>	340
11.6	<i>Permanent corrosion monitoring</i>	341
	<i>References</i>	342
12	Durability planning aspects	345
12.1	<i>Significance of durability</i>	345
12.2	<i>Durability philosophy</i>	346
12.3	<i>Phases in the life of a structure</i>	346
12.4	<i>Owner requirements</i>	350
12.5	<i>Designer requirements</i>	350
12.6	<i>Contractor requirements</i>	352
12.7	<i>Operator/maintainer requirements</i>	352
12.8	<i>Limit states</i>	355
12.9	<i>Service life design</i>	357
12.10	<i>Durability assessment – buried aggressive exposure – 100-year design life</i>	359
12.11	<i>Durability assessment – marine exposure – 100-, 150-, and 200-year design lives</i>	359
	<i>References</i>	372
	<i>Index</i>	373



Taylor & Francis

Taylor & Francis Group

<http://taylorandfrancis.com>

Preface

The late Professor Brian Cherry was many things; a gentleman, a sailor, a scholar, and one of the most significant figures in the history of Australian engineering and engineering education. He was a man who had received the highest level of respect from all who knew him, and from all who had interacted with him professionally and socially. He inspired countless students, co-authors, practitioners, scientists, engineers, and researchers young and old.

Brian had a significant impact on the field of corrosion science and technology over many decades, and one of his passions in that regard was the ‘Corrosion and Protection of Reinforced Concrete’. Some time ago he began work on a monograph on this subject. I have had the honour and delight of working with him on it when he was alive and progressing it since his passing in 2018.

Professor Brian Cherry was always a firm believer in first understanding the fundamentals of any aspects of corrosion science, then the mechanisms, before embarking on engineering solutions to the management of corrosion including in steel reinforced concrete.

This monograph has been developed to provide a sound understanding of the mechanisms of the corrosion and protection of reinforced concrete. It is particularly designed for asset managers, port engineers, bridge maintenance managers, building managers, heritage structure engineers, plant engineers, consulting engineers, architects, specialist contractors, and construction material suppliers, who have the task of resolving problems of corrosion of steel reinforced, prestressed, and post-tensioned concrete elements. It is also considered a most useful reference for students at postgraduate level.

Since its development in the mid-19th century, reinforced concrete has become the most widely used construction material in the world. Extended performance is often expected of our reinforced concrete structures. Some like marine structures are in aggressive environments, they may be many decades old, of critical importance in terms of function or location and be irreplaceable, and as such repair, and protection is necessary during their service lives.

This monograph provides readers with not only a comprehensive general knowledge, necessary for an understanding of corrosion prevention and protection in reinforced concrete, but also information on specific problems of corrosion in concrete learnt from the practical experience of both authors. To achieve this, the Chapters in this monograph are structured along the following lines:

- In Chapter 1, the characteristics of steel reinforced concrete are discussed. This includes its structure, different cements (binders), important aggregate, and mixing water issues, the more common admixtures that are necessary, and the different forms of reinforcing steel including conventional, prestressed, and post-tensioned. Fibre-reinforced concrete is also considered.
- The environments in which we place our reinforced concrete structures mean that various deterioration processes affect their in-service durability, loss of functionality, unplanned maintenance/remediation/replacement, and in the worst cases a loss of structural integrity and a resultant safety risk. Degradation of concrete may involve one or more of mechanical, physical, structural, chemical, and biological causes. Cracks in concrete are routes for the ingress of aggressive environmental agents. The penetrability of hardened concrete is also relevant. Chapters 2 and 3 examine all these key factors.
- The most common form of damage to a reinforced concrete structure is caused by corrosion of the steel reinforcement. Key aspects of reinforcement corrosion in concrete are considered in Chapters 4 and 5. The high levels of protection afforded to steel reinforcement by suitably designed, constructed, and maintained concrete are discussed in these chapters. These include the physical protection provided to steel reinforcement by concrete, and the electrochemical protection provided by the passive iron oxide film produced on the steel surface by the concrete.

The passivity provided to steel reinforcement by the alkaline environment of concrete may however be lost if the pH of the concrete pore solution falls because of carbonation or if aggressive ions such as chlorides penetrate in sufficient concentration to the steel reinforcement surface. Carbonation of concrete occurs as a result of atmospheric CO_2 gas (and atmospheric SO_x and NO_x gases) neutralising the concrete pore water (lowering its pH to 9) and thereby affecting the stability and continuity of the passive iron oxide film. Chloride ions in sufficient concentration can locally compromise the passivity of carbon-steel, prestressed, and post-tensioned steel reinforcement in concrete leading to pitting corrosion. Leaching of $\text{Ca}(\text{OH})_2$ (and NaOH and KOH) from concrete also lowers the pH, which can allow corrosion initiation of the steel reinforcement. Stray electrical currents, most commonly from electrified traction systems and interference

currents from cathodic protection systems can also breakdown the passive film, and cause corrosion of steel reinforced and prestressed concrete elements. Key issues relating to the mechanisms of corrosion of steel under these conditions are discussed. Fundamentals relating to the thermodynamics and kinetics of reinforcement corrosion are elucidated, together with the modelling of chloride and carbonation-induced corrosion initiation and propagation.

- It is essential that the mechanism(s) and extent of corrosion or concrete deterioration is known before appropriate remedial and/or protection measures can be developed for a reinforced concrete structure. Survey and diagnosis by onsite measurements as well as laboratory-based measurements are therefore important, and these are considered in Chapters 6 and 7.
- The methods that are employed to repair deteriorating reinforced concrete structures, or to protect reinforced concrete structures from deterioration depend on the nature and extent of deterioration occurring or likely to occur. In general repair techniques may be ‘mechanical’ or ‘electrochemical’, though often a combination of the two is necessary to ensure a long-lasting solution to the problem. Protection of the concrete is possible with coatings, penetrants, and membranes for example. Structural strengthening of concrete using fibre-reinforced polymers is also possible. Chapter 8 addresses repair and protection of concrete by mechanical methods. Cathodic protection (impressed current and galvanic) of reinforced concrete is examined in Chapter 9. Chapter 10 considers relevant aspects of electrochemical treatment methods available for reinforced concrete structures.
- Many of the problems that arise in the life of a reinforced concrete structure could be avoided if the appropriate precautions are taken at the design and construction stage. Chapter 11 looks at some options that can improve concrete durability such as concrete technology aspects, construction considerations, coatings and penetrants, coated and alternate reinforcement, and permanent corrosion monitoring.
- All engineering materials deteriorate with time, at rates dependent upon the type of material, the severity of the environment and the deterioration mechanisms involved. In engineering terms, the objective is to select the most cost-effective combination of materials to achieve the required design life. In doing so, it is critical to realise that the nature and rate of deterioration of materials is a function of their environment. Accordingly, the environment is a ‘load’ on a material as a force is a ‘load’ on a structural component. It is the synergistic combination of the structural load and environmental load which determines the performance of the structural component. Durability Planning is a system which formalises the process of achieving durability through appropriate design, construction, and maintenance. Chapter 12 closes the monograph by examining some key aspects of Durability Planning.

To Brian's wife Miriam, children James and Liz, and grandchildren Nicholas, Gretel, and William, this monograph is another contribution by your husband, dad, and grandfather to corrosion science and engineering.

To my wife Louise, and children Joshua, and Nicholas, I am indebted for your support and inspiration as well as that from my parents, brothers, educators, colleagues (current and previous but particularly in relation to this monograph Chelsea Derksen, Andrew Haberfield and Jack Katen) and mentors (most particularly Bruce Hinton, Brian Kinsella, Greg Moore, and Mark Byerley Sr).

Imagine the world without steel reinforced concrete structures and buildings. Imagine our primitive existence without the wonder and delight of steel reinforced concrete. Also, one cannot imagine such without the wonder and sheer delight of electrochemistry. Give that reinforced concrete element a hug next time rather than take it for granted.

Warren Green,
September 2020

Authors

Brian Cherry (deceased) was a Professor within the Department of Materials Science and Engineering at Monash University, Melbourne, Australia. He was the inaugural Associate Dean of Research at Monash University, and was also instrumental in the establishment of postgraduate degrees at Monash. Brian's legacy includes a stream of undergraduate students trained in corrosion, in addition to countless postgraduate students. These students have permeated academia and industry, nationally, and internationally, filling positions at large companies, consultancies, one-person companies, and everything in between.

Warren Green is a Director and a Principal Corrosion Engineer/Materials Scientist of Vinsi Partners, Sydney, Australia. He has experience in corrosion engineering and materials technology covering marine, civil, industrial, and building structures. Warren is also an Adjunct Associate Professor in the Institute for Frontier Materials at Deakin University, Melbourne, and a Visiting Adjunct Associate Professor within the Corrosion Centre of Curtin University, Perth, Western Australia.



Taylor & Francis

Taylor & Francis Group

<http://taylorandfrancis.com>

Steel-reinforced concrete characteristics

I.1 CONCRETE AND REINFORCED CONCRETE

Concrete is the most widely used material of construction in the world (and the second most used material by mankind after water) (Miller, 2018). Concrete is strong in compression but weak in tension and so much of the concrete is reinforced, usually with steel. The steel reinforcement can take the form of conventional carbon steel (black steel), prestressing steel, post-tensioned steel, and steel fibres, and its widespread utility is primarily due to the fact that it combines the best features of concrete and steel. The properties of these two materials may be compared below (Table 1.1).

The properties of the materials thus complement one another and so by combining them together a composite that has good tensile strength, shear strength, and compressive strength combined with durability and fire resistance can be formed. Typical properties of reinforcing steel and concrete might be (Table 1.2).

So that the strains at failure (if the stress strain curves were linear) are approximately 2×10^{-3} for the steel and 8×10^{-6} for the concrete. Consequently, when the steel is operating at or near its yield point the concrete must be cracked and so different forms of prestressing have been developed to ensure that the cracking is controlled to an appropriate level.

Table 1.1 Properties of steel and concrete

Property	Concrete	Steel
Strength in tension	Poor	Good
Strength in compression	Good	Buckling can occur
Strength in shear	Fair	Good
Durability	Good	Corrodes if unprotected
Fire resistance	Good	Poor, low strength at high temperatures

Table 1.2 Properties of steel and concrete

Property	Steel	Concrete
Tensile strength	400 MPa	2.5 MPa
Modulus	200×10^3 MPa	320×10^3 MPa

The properties of the materials also complement each other in that the properties of the steel can be modified by alloying and working to vary its strength and corrosion resistance, the properties of the concrete can be modified to facilitate the building of the structure by changing the ease with which it can be formed into the required shape and the penetrability of the final structure to aggressive agents that might attack the steel. In this chapter attention, will be focussed on the structure of concrete and the way in which its properties are controlled by its components, the cement, the aggregate, the mixing water, and admixtures.

1.2 THE STRUCTURE OF CONCRETE

Basically, concrete consists of mineral aggregate held together by a cement paste, so that if we consider a normal mix it will consist of cement, sand (fine aggregate), coarse aggregate and water (and often other admixtures) which are mixed together to form eventually a hard, strong material. The primary binding agent in concrete is cement. The water reacts with the cement to make a cement paste which then hardens and binds the aggregate together to make the solid concrete and the cured composition of the concrete may be represented by the proportions shown in Figure 1.1.

Its structure may be as shown in Figure 1.2.

1.3 CEMENTS AND THE CEMENTING ACTION

1.3.1 General

The aggregate is bound together by hydrated cement. The hydraulic binder of concrete commonly consists of Portland cement or of mixtures of Portland cement and one or more of fly ash, ground granulated iron blast furnace slag or silica fume.

Portland cement takes its name from a cement manufactured in England in the late eighteenth century which bears a similarity to stone quarried near Portland in Dorset, England. It is defined in ASTM C150 (2016) as 'hydraulic

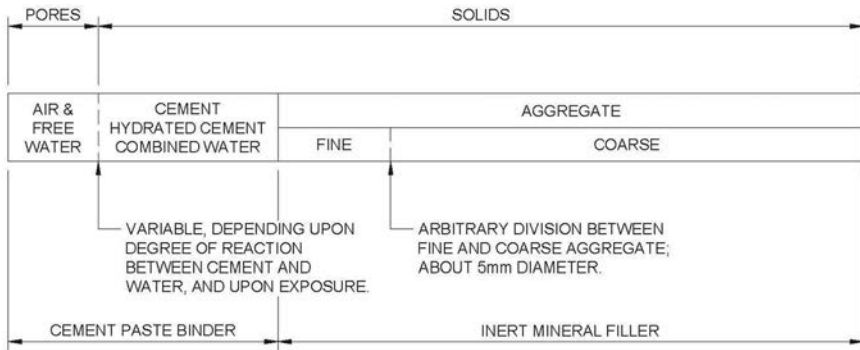


Figure 1.1 The components of a hardened concrete. (Courtesy of Troxell & Davies, 1956, p.4)

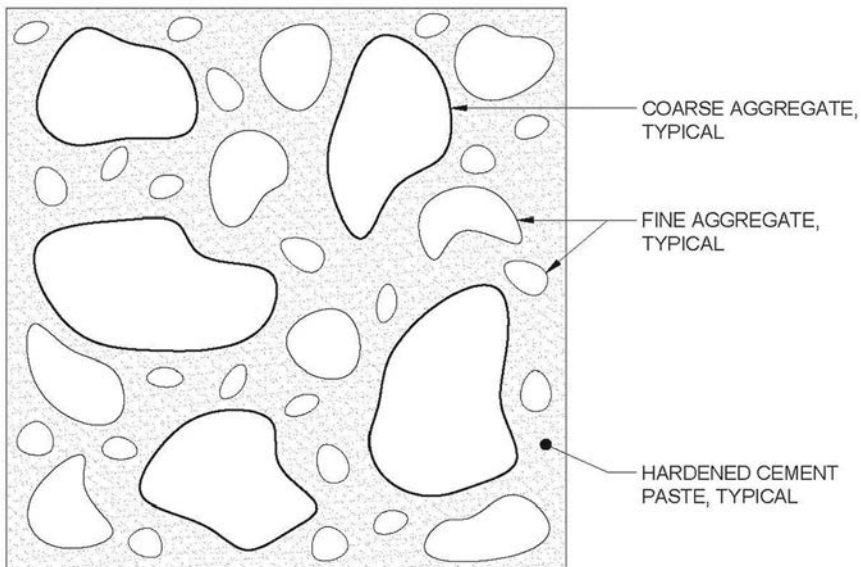
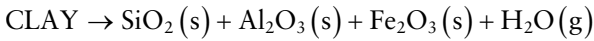
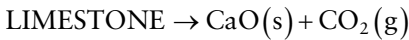


Figure 1.2 Diagrammatic representation of a concrete mix. (Courtesy of Troxell & Davies, 1956, p.63)

cement (cement that not only hardens by reacting with water but also forms a water-resistant product) produced by pulverising clinker which consists essentially of hydraulic calcium silicates, usually containing one, or more of the forms of calcium sulphate as an inter-ground addition’.

Mixtures of Portland cement with fly ash, ground granulated iron blast furnace slag or silica fume are referred to as blended cements and will be discussed later.

Portland cement, or ordinary Portland cement (OPC) or general purpose (GP) cement consists (nominally) of a mixture of oxides: CaO , SiO_2 , Al_2O_3 , Fe_2O_3 , MgO , Na_2O , and K_2O . These oxides are, however, combined together as a series of cement compounds, which are themselves combinations of the principle oxides. The manufacture of Portland cement involves the grinding of limestone or chalk and clay to a suitable degree of fineness, followed by mixing of appropriate proportions of the ground raw materials and then burning them in a large rotary kiln at a temperature around 1480°C . The kiln is inclined and the raw materials are fed into the upper end while the heat source is at the lower end. Hence, there is a temperature gradient along the kiln. Firstly, water is evaporated from the clay and CO_2 is evolved from the limestone, as follows:



The main reaction products, the CaO , SiO_2 , Al_2O_3 , and Fe_2O_3 in the kiln fuse together and form a glassy mass of which the main constituents are the cement compounds: tricalcium silicate ($3\text{CaO}.\text{SiO}_2$) often abbreviated to C_3S ; dicalcium silicate ($2\text{CaO}.\text{SiO}_2$) often abbreviated to C_2S ; tricalcium aluminate ($3\text{CaO}.\text{Al}_2\text{O}_3$) abbreviated to C_3A ; and tetracalcium aluminoferrite ($4\text{CaO}.\text{Al}_2\text{O}_3.\text{Fe}_2\text{O}_3$) abbreviated to C_4AF . Minor components include K_2O and Na_2O . The products are termed clinker at this stage and are cooled before grinding with about 5% gypsum (CaSO_4). Gypsum is added to regulate the setting time of cement. Different Portland cement types have different proportions and fineness of the final products.

The reactions of the Portland cement compounds with water result in the setting and hardening of cement paste so that it binds the aggregate together. The hydration reactions of the four principle components of Portland cement are as follows:

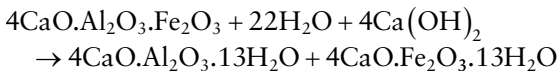
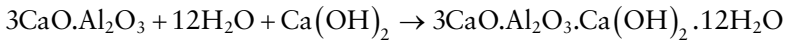
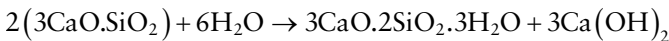


Table 1.3 Composition of a typical Portland cement

C_3S	C_2S	C_3A	C_4AF	K_2O, Na_2O etc
45%	27%	11%	10%	7%

A Portland cement may typically consist of a mixture of cement compounds with the approximate composition given in Table 1.3 and from the above equations it can be calculated that the amount of water required theoretically to hydrate the cement would be 38%.

In the process of hydration, however, the surfaces of the cement compounds dissolve in the water and then, as the hydrates are less soluble than the cement compounds, they precipitate out as a fine mesh of interlocking crystals which bind themselves and the aggregate together. This hydration process must take place on the surface of the cement particles and so the curing process thus involves the swelling of the particles of cement as they are hydrated leaving a core of unhydrated cement compounds. The volume of the hydrates is approximately 54% greater than that of the dry unhydrated cement compounds and so the particles swell trapping water between themselves, with the result that the cement paste has a porosity of ~28% with all the pores filled with water. The amount of water trapped in the pores can easily be calculated. The density of dry cement is 3.15 g/cm^3 and so the volume of 100 g of the cement is 31.8 ml, which swells on hydration to 48.9 mls. If the volume of water trapped in the pores is v_g then $v_g/(v_g + 48.9) = 0.28$ or $v_g = 19.0 \text{ ml}$. The amount of combined water in the cement paste can similarly be determined as the amount of non-evaporable water under given drying conditions and is put at 23% of the mass of the dry cement and so the total amount of water needed to hydrate 100 g of the cement is $(23 + 19 = 42) \text{ g}$. The gel pores gradually diminish in size as further hydration causes the particles to swell further but in the fully hydrated state the water contained within them contributes 19% of the mass of the gel. However, since the hydration of the cement compounds can only take place by the cement swelling into the water and since the water already trapped within the gel pores is immobilised and therefore unable to migrate to where it is required for hydration, a greater water/cement ratio is necessary than the theoretical 38% to ensure complete hydration. Complete hydration of the cement compounds, leaving the gel pores full of water, requires a minimum theoretical water/cement ratio (by weight) of 0.42.

The additional water available above that which is necessary for complete hydration means that the hydrated cement compounds are unable to completely fill the volume contained by the plastic concrete and so gives rise to the presence of capillary pores.

The gel pores are perhaps 1.5–2 nm in diameter.

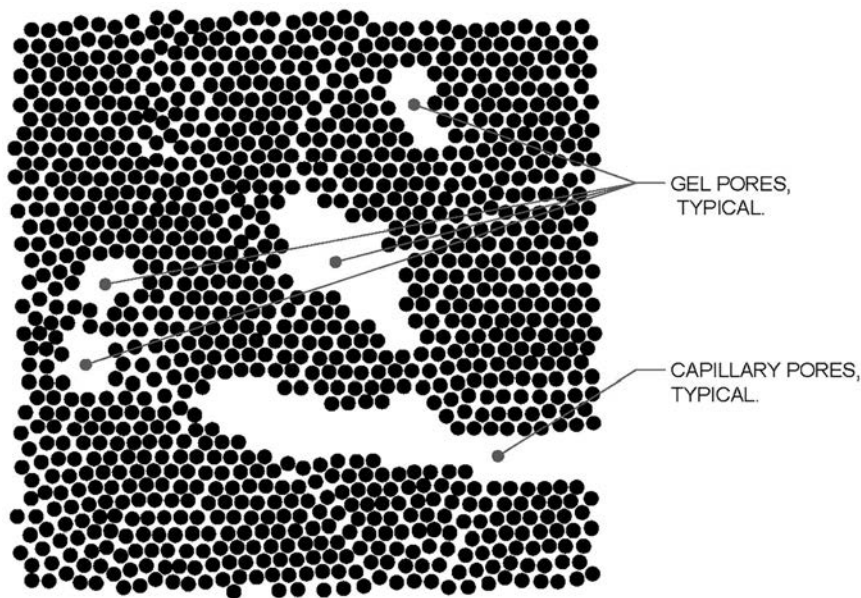


Figure 1.3 Structure of cement gel. (Courtesy of Neville, 1981, p.23)

The capillary pores are much bigger, possibly of the order of a micron or more and they may or may not be interconnected.

Interconnected pores are responsible for the penetrability of the concrete to air or water. As the hydration proceeds these pores diminish in size. The structure of the cement paste then has the appearance of Figure 1.3. Interconnected capillary pores are responsible for penetrability of concrete. Continued hydration may, however, produce a sufficient volume of material to produce blocks in the pores and turn them into discrete capillaries which do not provide a continuous path through the concrete. When the pores become segmented, the penetrability of the concrete is considerably reduced and its ability to inhibit access of aggressive agents that could accelerate corrosion of the reinforcement or degradation (e.g. chemical attack) of the cement paste is much enhanced. The time for this segmentation to take place is dependent upon the amount of water present initially, as can be seen in Table 1.4.

1.3.2 Heat of hydration

A Portland cement may typically consist of a mixture of cement compounds with the approximate composition given in Table 1.3. The heat of hydration varies considerably between the different cement compounds as given in Table 1.5.

Table 1.4 Approximate time required for capillaries to become segmented

Water/cement ratio	Time required for capillary segmentation
0.40	3 days
0.45	7 days
0.5	14 days
0.6	6 months
0.7	1 year
>0.7	impossible

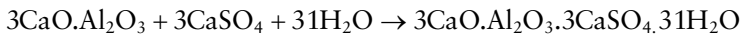
Source: Neville (1975, p.30)

Table 1.5 Heat of hydration of pure cement compounds

Compound	Heat of hydration J/g
C ₃ S	502
C ₂ S	260
C ₃ A	867
C ₄ AF	419

Source: Neville (1975, p.38)

The very high heat of hydration of tricalcium aluminate (C₃A) can give rise to the phenomenon of 'flash set'. When the cement and water are mixed together the first thing that can happen is that C₃A reacts quite quickly with the water. The heat of hydration is considerable and causes a considerable rise in temperature. This can cause accelerated hydration of the whole mix so that under these circumstances it can stiffen up within minutes. This is called flash set. In order to eliminate the flash set, gypsum (CaSO₄) is added to the mix. This reacts with the C₃A as follows to produce an insoluble compound, 3CaO.Al₂O₃.3CaSO₄.31H₂O, ettringite:



This is insoluble and eventually hydrates to the hydrated C₃A but because the C₃A reacts with the gypsum before its hydration reaction it can liberate enough heat to bring about flash set, the initial formation of the ettringite prevents the flash set.

1.3.3 Rate of strength development

The rate of development of strength varies considerably between the various cement compounds as can be seen in Figure 1.4. It was shown above that

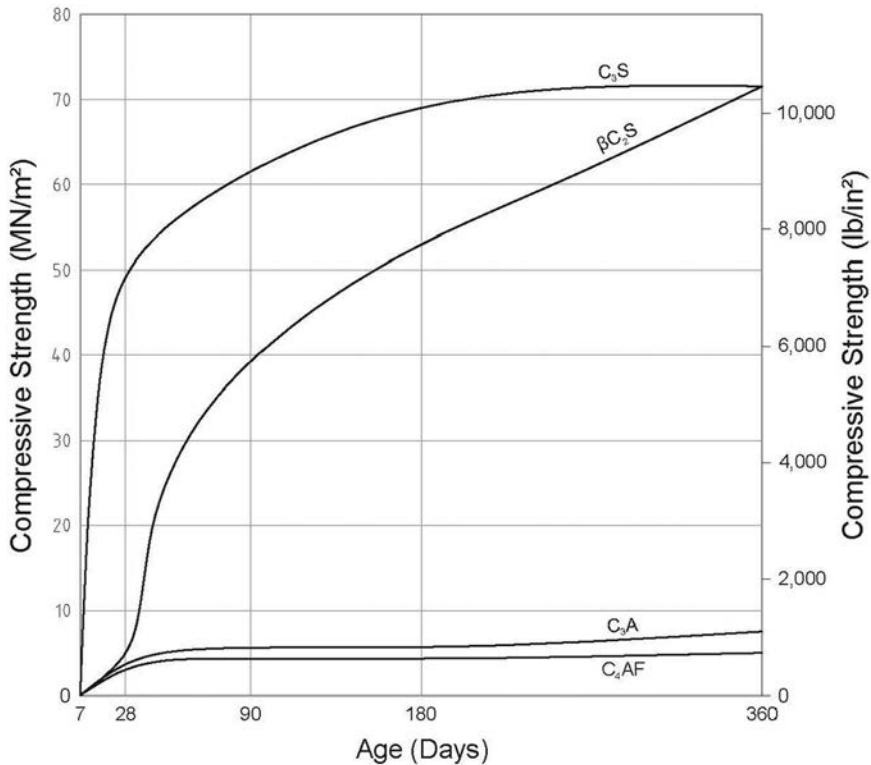
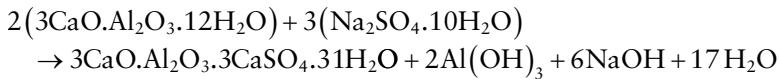


Figure 1.4 Rate of development of strength of different cement compounds. (Courtesy of Neville, 1975, p.42)

C₃A reacts with sulphate ions to produce ettringite. The same compound is formed by the reaction of the hydrated C₃A with sulphate ions:



As the volume of the ettringite which is formed is about three times the volume of the reactants and as this reaction takes place after the concrete has cured, such a process leads to cracking and spalling (fretting) of the concrete. For a concrete that is to be exposed to sulphate bearing waters it is therefore necessary to restrict the amount of C₃A in the Portland cement.

On the basis of these different cement reactions a number of specific Portland cements for specific situations have been developed. Typical Portland cement compound compositions of the various types of Portland cement are listed in Table 1.6.

Table 1.6 Typical compound compositions for Portland cements (%)

Compound	High early strength	Low heat	Ordinary	Sulphate resisting
C ₃ S	55	30	45	45
C ₂ S	17	46	27	35
C ₃ A	11	5	11	4
C ₄ AF	9	13	10	10
Miscellaneous	8	6	7	6

Source: Taylor (1967, p.8)

Table 1.7 Cement types in accordance with AS 3972 (2010) or NZS 3122 (2009)

Cement type	Applications
General purpose	
Type GP	All types of construction
General purpose	
Type GB	All types of construction; curing and strength development differ from Type GP
General purpose blended	
Special purpose	
Type HE	Early strength requirements, e.g. cold weather and formwork removal
High early strength	
Type LH	Low temperature requirements, e.g. hot weather and mass concreting
Low heat	
Type SR	High resistance to sulphates, e.g. aggressive soils
Sulphate resistant	
Type SL	Controlled shrinkage applications
Shrinkage limited	

Table 1.7 shows a classification of binder systems as specified by Australian Standard AS 3972 (2010).

1.4 SUPPLEMENTARY CEMENTITIOUS MATERIALS – BLENDED CEMENTS

1.4.1 General

Concrete mix design/selection can involve the specification of the relative amounts of cement, coarse aggregate, fine aggregate, and water, and has four major objectives which apply to nearly all structures. The wet freshly mixed concrete must be sufficiently workable that it can be placed in position, and this often involves the ability to penetrate the small gaps between reinforcing bars. The cured concrete must have a required strength. The cured concrete must crack where it is permissible and for the cracks to be of a surface width sufficient to not compromise durability. The cured

concrete must be sufficiently impenetrable (impermeable) to the ingress of aggressive agents that its durability is assured. These qualities of the concrete mix, in their different ways, are affected by the concrete mix design/selection and also by the conditions under which it is placed in position, by the curing conditions, and by additions that may be incorporated into the mix to modify its properties. Particularly effective in the modification of the concrete properties are the so called 'Supplementary Cementitious Materials' (SCMs).

During the manufacture of Portland cement, the oxides of calcium, aluminium, silicon, iron etc. are fused together to form the cement compounds and cooled sufficiently quickly that they form an amorphous glass which is ground up to form cement. There are a number of other major industrial processes that produce metallic oxides at a very high temperature and which because of a very high rate of cooling form glassy non-crystalline compounds in a similar fashion to a Portland cement. Coal fired electricity generation of pulverised-fuel black coal in which the molten residues of the burning process are recovered from the exhaust gases by electrostatic precipitation to yield classified fly ash (FA). The blast furnace production of iron produces a slag which, if subjected to rapid cooling, can be ground up to provide ground granulated iron blast furnace slag (BFS). Silicon and ferro-silicon alloys are produced in electric furnaces where SiO_2 is reduced by carbon at very high temperatures. SiO_2 vapours condense in the form of very tiny spheres ($\sim 0.1\mu$) of amorphous silica, silica fume (SF). SF is also known as 'condensed silica fume' and 'microsilica'.

These materials may be blended with Portland cement to improve its qualities or simply to benefit the environment and are termed SCMs. They are generally divided into two classes; pozzolanic and hydraulic. Pozzolanic SCMs (the name comes from the Italian village of Pozzuoli near Naples where vast amounts of Volcanic ash from Mt. Vesuvius were used for the manufacture of a primitive cement) such as SF, or Class F FA SCMs are low in CaO and are not themselves cementitious, but when they react with a solution of Ca(OH)_2 formed by the hydration of Portland cement, they dissolve, and form a cementitious compound. Hydraulic SCMs such as Class C FA or BFS, contain sufficient CaO that when mixed with water, they form a cementitious compound. The characteristic of these materials is that they have a very fine particle size; FA of the order of 1μ – 10μ , SF of the order of 0.1μ and that they react quite slowly. Because of this, blended cements can develop superior qualities in the concrete in which they are used.

1.4.2 Fly ash

FA for use in cement in Australia, for example, needs to comply with AS 3582.1 (Standards Australia, 2016a). The fly ash content of a FA blended cement based concrete varies but is commonly in the range 20–35%. For example, some Road Authorities in Australia stipulate in their structural

concrete specifications a minimum 25% FA content (Roads & Maritime Services, 2019; VicRoads, 2020) so as to achieve increased durability.

1.4.3 Slag

Ground granulated iron BFS for use in cement in Australia, for example, needs to comply with AS 3582.2 (Standards Australia, 2016b). The slag content of a BFS blended cement based concrete varies but is commonly in the range 50–70%. For example, some Road Authorities in Australia stipulate in their structural concrete specifications a minimum 50–65% BFS content (Roads & Maritime Services, 2019; VicRoads, 2020) so as to achieve increased durability.

1.4.4 Silica fume

Amorphous silica for use in Australia as a cementitious material in concrete, mortar, and related applications, for example, needs to comply with AS 3582.3 (Standards Australia, 2016c). The SF content of a blended cement based concrete typically varies between 5–15%. For example, some Road Authorities in Australia stipulate in their structural concrete specifications a 10% SF proportion (VicRoads, 2020).

1.4.5 Triple blends

Triple blend cement based concretes are also used for increased durability. For example, in Australia VicRoads in their ‘Structural Concrete Specification 610’ (2020) stipulate that in a triple blend concrete mix, the Portland cement shall be a minimum of 60% and the individual contribution of slag, FA or Amorphous Silica shall be a maximum of 40%, 25% or 10% respectively.

For marine durability, triple blend cement based concretes such as 52% SL cement, 25% FA and 23% slag have been used (Green et al., 2009) in Australia, for example.

1.5 AGGREGATES

1.5.1 General

Since aggregate forms perhaps three quarters of the volume of the cured concrete, its properties play a major role in determining the durability and structural performance of the concrete. Aggregate is normally arbitrarily divided into ‘fine’ and ‘coarse’ aggregate. Fine aggregates or sand pass a 5 mm mesh sieve, while coarse aggregates do not usually exceed a nominal size of 50 mm. Naturally occurring coarse aggregate may consist of crushed rocks such as basalt, granite, quartzite, diorite, limestone, or dolomitic limestones. Other aggregates include BFS, scoria, expanded shale, and foamed

slag. Lightweight and ultra-lightweight aggregates are available. Manufactured aggregates also and crushed concrete is used as an aggregate. The requirements of aggregates for use in concrete in Australia, for example, are specified in AS 2758.1 (2014a).

The durability, strength, shrinkage, wear resistance, and other mechanical properties of concrete will be influenced by aggregate characteristics such as particle size, shape, and surface texture, hardness, strength, elastic modulus, porosity, contamination, and chemical reactivity with the cement paste. Aggregates do not normally influence the chemistry of cement unless they participate in alkali-aggregate reactions (AAR), as will be elaborated later. Therefore, the chemistry of concrete is usually the chemistry of cement. Use of chloride contaminated aggregates such as sea sand or other materials from saline origins can have dire consequences with respect to reinforcement corrosion, as will be elaborated later. Organic matter may interfere with the hydration of the cement and reduce the final strength of the concrete. Clay and other fine material should be avoided wherever possible as it may coat the aggregate, be chemically reactive, and/or form soft inclusions in the concrete. It may also increase the water demand of the concrete.

1.5.2 The design of a concrete mix

Important qualities of concrete are workability, density, strength, and durability. In a hardened concrete, the cement gel that holds the particles together fills the space between the aggregate particles. The total amount of this space and hence, the amount of cement gel required to fill the space, is determined by the shape and size, or more particularly, the distribution of sizes of the aggregate particles. Since the relative amounts of aggregate and cement gel in the hardened concrete will also control the amount of water in the original mix, the particle size distribution, or grading is also a major factor in determining the workability of the concrete and hence, is of particular importance in the design of a concrete mix.

‘Workability’ is not a rigorously defined term but is used to describe the ease with which the concrete can be placed in position. Of particular importance is the ability of the concrete to form a coherent mass in between reinforcing bars without leaving holes or cracks which may subsequently be a site for the initiation of failure. The workability is primarily controlled by the size of the aggregate and the water content. The maximum size of the aggregate will be controlled by the structure into which the concrete will be placed. Large well-graded aggregates have fewer and smaller voids than smaller sizes, but the aggregate must be small enough to fit easily between the reinforcing bars if gaps in the concrete are to be avoided. It must also be small enough to fit easily into the formwork. A commonly accepted measure of the ability of the concrete to adapt itself to the shape into which it is to be poured is given by the ‘slump’ test. In this test described in Australian Standard 1012.3.1 (2014b) for example, a cone is filled with concrete, compacted in a

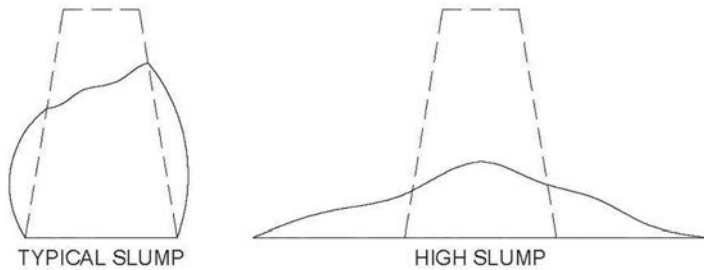


Figure 1.5 The slump test. (Courtesy of Standards Australia, 2014b)

standard manner and then the cone is inverted on to a flat surface. When the cone is removed the mass of concrete slumps as can be seen in Figure 1.5 and the vertical subsidence of the concrete is defined as the slump.

The slump is primarily controlled by the shape of the aggregate and the amount of water with which it is mixed. The slump that is required of a concrete will depend upon the conditions of the placement, but the American Concrete Institute (ACI) Manual of Concrete Practice – Section 211.1 (ACI 211.1-91, Reapproved 2009) gives the following general guidelines, Table 1.8.

An approximate relationship between the size of the aggregate and the water content is given in the ACI Manual and it can be seen, refer Table 1.9, that the larger the aggregate size, the less water is required to achieve the same slump.

The strength of the concrete is primarily controlled by the water/cement ratio (water/binder ratio). The ACI Manual gives the following table (Table 1.10) and so from the known water content and the water/cement ratio (water/binder ratio) the mass of cement (binder) required to achieve a given strength can be calculated.

Table 1.8 Example concrete slumps for various types of construction

TABLE A1.5.3.1 – RECOMMENDED SLUMPS FOR VARIOUS TYPES OF CONSTRUCTION (SI)

Type of construction	Slump, mm	
	Maximum*	Minimum
Reinforced foundation walls and footings	75	25
Plain footing, caissons, and substructure walls	75	25
Beams and reinforced walls	100	25
Building columns	100	25
Pavements and slabs	75	25
Mass concrete	75	25

Source: (ACI 211.1-91, Reapproved 2009)

* May be increased 25 mm for methods of consolidation other than vibration

Table 1.9 Water contents based on aggregate size

APPROXIMATE MIXING WATER AND AIR CONTENT REQUIREMENTS FOR DIFFERENT SLUMPS AND NOMINAL MAXIMUM SIZES OF AGGREGATES (SI)

Water, kg/m ³ of concrete for indicated nominal maximum sizes of aggregate Slump, mm	9.5	12.5	19	25	37.5	50	75	150
Non-air-entrained concrete								
25 to 50	207	199	190	179	166	154	130	113
75 to 100	228	216	205	193	181	169	145	124
150 to 175	243	228	216	202	190	178	160	–
Approximate amount of entrapped air in non-air-entrained concrete, percent	3	2.5	2	1.5		0.5	0.3	0.2

Source: (ACI 211.1-91, Reapproved 2009)

Table 1.10 Strength and water/cement ratio

RELATIONSHIPS BETWEEN WATER/CEMENT RATIO AND COMPRESSIVE STRENGTH OF CONCRETE (SI)

Compressive strength at 28 days, MPa	Water/cement ratio, by mass	
	Non-air-entrained concrete	Air-entrained concrete
40	0.42	
35	0.47	0.39
30	0.54	0.45
25	0.61	0.52
20	0.69	0.60
15	0.79	0.70

Values are estimated average strengths for concrete containing not more than 2% air for non-air-entrained concrete and 6% total air content for air-entrained concrete.

For a constant water/cement ratio, the strength of concrete is reduced as the air content is increased. (ACI 211.1-91, Reapproved 2009)

The ability of the aggregate to fill the available space will depend upon its size and the coarseness (fineness ratio) of the fine aggregate. The grading of an aggregate is normally determined by sieving. That is, the aggregate is passed through a series of sieves with decreasing openings between the wires of the sieves. Recommended gradings for fine aggregate are given in AS 2758.1 (1998a) for example, see Table 1.11.

The volume of coarse aggregate that can be contained within unit volume of concrete is given in Table A1.5.3.6 of the ACI Manual of Concrete Practice (ACI 211.1-91, Reapproved 2009), refer Table 1.12 below. Given the density of the coarse aggregate the mass can be calculated.

Table 1.11 The grading of fine aggregates

FINE AGGREGATE-RECOMMENDED GRADINGS

Sieve aperture mm	Mass of sample passing, per cent	
	Natural fine aggregate	Manufactured fine aggregate
9.50	100	100
4.75	90 to 100	90 to 100
2.36	60 to 100	60 to 100
1.18	30 to 100	30 to 100
0.6	15 to 100	15 to 80
0.3	5 to 50	5 to 40
0.15	0 to 20	0 to 25
0.075*	0 to 5	0 to 20

Source: Standards Australia (2014a)

* Consideration may be given to the use of a manufactured fine aggregate with greater than 20% passing the 0.075 mm size, provided it is used in combination with another fine aggregate where the total percentage passing 0.075 mm of the fine aggregate blend does not exceed 15% and provided the fine aggregate components meet the deviation limits in all respects.

Table 1.12 Volume of concrete occupied by coarse aggregate

VOLUME OF COARSE AGGREGATE PER UNIT OF VOLUME OF CONCRETE (SI)

Nominal maximum size of aggregate, mm	Volume of dry-rodded coarse aggregate* per unit volume of concrete for different fineness moduli† of fine aggregate			
	2.40	2.60	2.80	3.00
9.5	0.50	0.48	0.46	0.44
12.5	0.59	0.57	0.55	0.53
19	0.66	0.64	0.62	0.60
25	0.71	0.69	0.67	0.65
37.5	0.75	0.73	0.71	0.69
50	0.78	0.76	0.74	0.72
75	0.82	0.80	0.78	0.76
150	0.87	0.85	0.83	0.81

Source: (ACI 211.1-91, Reapproved 2009)

* Volumes are based on aggregates in dry-rodded conditions as described in ASTM C 29.

These volumes are selected from empirical relationships to produce concrete with a degree of workability suitable for usual reinforced construction. For less workable concrete such as required for concrete pavement construction they may be increased about 10%. For more workable concrete, such as may sometimes be required when placement is to be by pumping, they may be reduced up to 10%.

† See ASTM Method 136 for calculation of fineness modulus.

1.5.3 Estimation of fine aggregate content and mechanical properties

Knowing the density of all the other components, the amount of fine aggregate required to make up the mix can be calculated and a trial mix prepared. From the results obtained with the trial mix the necessary adjustments can be made to ensure that the final mix meets the desired specifications.

1.6 MIXING AND CURING WATER

The fourth component of the recipe for concrete is the mixing water. The relative amounts of water and cement (binder) are in fact the major determinants of the strength, the durability, and the workability of the concrete and so will form the subject of this next section.

The use of unsuitable water for mixing and/or curing concrete may result in reinforcement corrosion as well as other problems with strength, setting, and staining. Sea water introduces chlorides into concrete which may cause corrosion of reinforcement and also reduce long term strength. Brackish water also contains chlorides in high concentration. Water contaminated with organic matter may result in retardation of setting, staining, and strength reduction. High concentrations of sodium and potassium in mixing water increases the risk of alkali-aggregate reaction and high iron concentrations in curing water result in brown stains on the concrete surface. Curing water should be free of high concentrations of other aggressive agents such as sulphates, magnesium salts, and carbonic acid.

AS 1379 (2007a), for example, notes that water is deemed acceptable if:

- Service records show it is not injurious to strength and durability of concrete or embedded items.
- If service records show that when using the proposed water, the strength is at least 90% of the control sample strength at the corresponding age.
- If service records show that the initial set is between -60 to +90 minutes of the control sample time.
- Impurities limits are in accordance with Table 2.2 of the standard i.e.: Sugar <100 mg/L; Oil and grease <50 mg/L; and, pH >5.0.
- Total dissolved solids, chloride content, sulphate content, and sodium equivalent is tested and recorded.

The AS 1379 (2007a) requirement for the acid-soluble chloride content of hardened concrete, for example, is <0.8 kg/m³. Roads & Maritime Services (RMS) NSW (2019) in Australia, on the other hand set a requirement of <0.3 kg/m³ in their 'B80 Concrete Work for Bridges Specification' for both

reinforced and prestressed concrete for example. VicRoads (Victorian Road Authority) in Australia in their 'Specification 610 Structural Concrete' (2020) set a requirement for the maximum acid-soluble chloride ion content of concrete as placed, expressed as a % of the total mass of cementitious material in the concrete mix of 0.1% for prestressed concrete (equivalent to $\sim 0.4 \text{ kg/m}^3$) and 0.15% for reinforced concrete (equivalent to $\sim 0.5 \text{ kg/m}^3$).

The acid-soluble sulphate-ion content of the hardened concrete, reported as SO_3 , requirement in AS 1379 (2007a) is $<50 \text{ g/kg}$ of cement. The requirement in the RMS 'B80 Concrete Work for Bridges Specification' (2019) is 3.0% as acid-soluble SO_3 to cement for heat accelerated cured concrete or 5.0% otherwise. VicRoads 'Specification 610 Structural Concrete' (2020) is 4% as acid-soluble SO_3 to the total cementitious material for steam and heat accelerated cured concrete or 5% otherwise.

1.7 ADMIXTURES

The properties, and in particular the curing properties of a concrete as well as being controllable by the selection of the cement and aggregate, can be modified by the addition of 'admixtures', that is chemicals that added in small quantities to the mix can change the characteristics of the cure.

Admixtures are materials incorporated in the concrete mix to alter the properties of fresh or hardened concrete. The most common admixtures are accelerators, set retardants, water reducing agents (plasticisers), superplasticisers, air entraining agents, and waterproofing agents. The extensive list of admixtures detailed in AS 1478.1 (2000), for example, is shown in Table 1.13.

Table 1.13 Admixtures for concrete

<i>Admixture</i>	<i>Type symbol</i>
Air entraining	AEA
Water reducing	WR
Set retarding	Re
Set accelerating	Ac
Water reducing and set retarding	WRRRe
Water reducing and set accelerating	WRAC
High range water reducing	HWR
High range water reducing and set retarding	HWRRe
Medium-range WR, normal setting	MWR
Special purpose, normal setting	SN
Special purpose accelerating	SAC
Special purpose retarding	SRe

Source: Standards Australia (2000)

1.7.1 Air entraining admixtures

Air entraining agents are used to form an array of very small air bubbles in the concrete. This provides resistance to frost attack and improved workability. The strength is reduced. Air entraining additives usually consist of surface-active agents such as the soluble salts of sulphated or sulphonated petroleum hydrocarbons. Air entraining agents can also include animal and vegetable fats and oils, wood resins, and wetting agents such as alkali salts of sulphated and sulphonated hydrocarbons. The entrainment of air does not adversely affect the penetrability (permeability) of concrete because the entrained air has the form of discrete bubbles which are not interconnected.

1.7.2 Set retarding admixtures

The function of set retarding admixtures is to delay the onset of curing so that concrete placement is possible in hot weather when the speed of curing might otherwise cause problems. They are also used to delay curing when it is desired to obtain an architectural finish on the surface by working on the surface after the formwork has been struck. Typically set retarding admixtures consist of starches, soluble borates, and phosphates, and the like. In practice set retarding admixtures that are also water reducing agents are more commonly used.

1.7.3 Set accelerating admixtures

Accelerators are used to accelerate the development of early strength, with the aim of speeding up work and increasing productivity. They are predominantly used when concrete must be placed at low temperatures. Common set-accelerators are highly ionised inorganic salts such as sodium carbonate, potassium carbonate, sodium aluminate, and ferric salts. Organic compounds such as triethanolamine are also used as are hydroxycarboxylic acid salts.

The most common accelerator used is calcium chloride which acts by increasing the rate of hydration of C_3S or C_2S by increasing the volume of the hydration products. It may retard hydration of C_3A . At a dosage rate of less than 1% it acts as a retarder, but at higher concentrations it accelerates the cure and at a dosage of 3% may even induce 'flash set'. Its use in reinforced concrete is now negligible because the chloride ion has a very deleterious effect on corrosion of any reinforcement and its use has been declared illegal in nearly all countries for this reason.

Other accelerators may be based on calcium formate though they are more expensive and less effective.

1.7.4 Water reducing and set retarding admixtures

These admixtures permit concrete to be made using a lower amount of water (and hence reducing the penetrability) while retaining the same

workability as a mix containing more water. Thus, higher strength concretes can be produced by using a water reducing agent together with a reduced water/cement (water/binder) ratio. In unmodified form, such admixtures also retard the set and so in the interests of faster work on the construction site are more often used in conjunction with an accelerator. Set retarding admixtures or retarders are also used in high temperature situations to increase the setting time of the fresh concrete.

Calcium lignosulphonate (a by-product of the wood pulp industry) is widely used as a water reducing and set retarding admixture. Other examples of set retarders are lignosulphonic acids, carbohydrate derivatives, soluble zinc salts, and soluble borates.

The organic retarders appear to function by adsorbing on the active sites on the C_3S and inhibiting its hydration.

The inorganic retarders may function by precipitating a thin layer of compound on the grains of cement and similarly inhibit the hydration reaction.

1.7.5 Water reducing and set accelerating admixtures

These are set retarding admixtures (calcium lignosulphonates) to which has been added a set accelerator such as the salt of a hydroxycarboxylic acid or triethanolamine. Such admixtures permit a reduction in the water content while maintaining the same workability without a sacrifice of setting time.

1.7.6 High range water reducing admixtures

Superplasticisers (high range water reducing admixtures) are used to produce flowing concrete, which is easy to place, particularly in inaccessible areas. In addition, low water/cement (water/binder) ratio, high-strength concrete at workable consistency can be achieved by the use of superplasticisers. Examples of superplasticisers are sulphonated melamine formaldehyde condensates and sulphonated naphthalene formaldehyde condensates. Superplasticisers are anionic and give a negative charge to cement particles, thus making them self-repelling.

Hyperplasticisers are now also available to be produce highly flowable, self-levelling concrete.

1.7.7 Waterproofing agents

Waterproofing agents are used to reduce the water absorption of concrete. They consist of pore filling materials or water repellents that may or may not be chemically active. Active chemical pore fillers include alkaline silicates, aluminium, and zinc sulphates, and aluminium and calcium chlorides. These materials may accelerate setting time either alone or in conjunction with other compounds. Inactive pore fillers include finely ground chalk, talc and Fuller's earth. They are sometimes used with calcium and aluminium

soaps and improve workability. Active water repellents are soda and potash soaps which are sometimes used in conjunction with lime, alkaline silicates, or calcium chloride. Inert water repellents include vegetable oils, fats, waxes, calcium soaps, and bitumen.

1.7.8 Other

There is a wide range of other admixtures and additives that may be added to concrete to have possible effects such as inhibiting corrosion (see Inhibitors at Section 8.7), to decrease penetrability (permeability), to increase resistivity, and enhance durability.

The possible effects of any admixtures and additives should be carefully examined from a scientific and engineering point of view not just in terms of durability but also in terms of possible future maintenance actions for the reinforced concrete element. Some admixtures and additives may for example adversely affect the performance of future protection and repair methods.

1.8 STEEL REINFORCEMENT

1.8.1 Background

As was indicated earlier in this chapter, concrete is strong under compression but has weak tensile and shear strength. Reinforcing including steel reinforcement is incorporated into concrete to increase the tensile and shear strength of the reinforced concrete element. Steel and concrete also have similar coefficients of thermal expansion.

Rebar (short for reinforcing bar), collectively known as reinforcing steel, reinforcement steel, or steel reinforcement, is a steel bar, or mesh of steel wires.

There is also other steel reinforcement including: Galvanised steel reinforcement, Stainless steel reinforcement and Metallic-clad steel reinforcement for use in reinforced concrete construction and each of these is discussed at Chapter 11.

Reinforced concrete construction using other alternate reinforcement such as fibre-reinforced polymer (FRP) reinforcement is also possible (and is discussed at Chapter 11).

1.8.2 Conventional steel reinforcement

The most common type of conventional rebar is carbon steel. Conventional steel reinforcement for use in concrete in Australia and New Zealand is subject to the requirements of AS/NZS 4671 (2019).