Contents

Preface and acknowledgements x
Nomenclature xiii

1 Introduction 1

1.1 Challenges when predicting the service life of reinforced concrete structures 3
1.2 Progress in test methods for measuring chloride transport 3
1.3 Mathematical models for describing chloride transport 5
1.4 Prediction of the service life of structures in chloride-exposed environments 5
1.5 The structure of this book 6

2 Chloride transport in concrete 8

2.1 Introduction 8
2.2 Chloride concentrations 8
2.3 Chloride binding/interaction and binding capacity 9
  2.3.1 Linear chloride binding 10
  2.3.2 Non-linear chloride binding 10
  2.3.3 Chloride-binding capacity 11
2.4 Ion diffusion 12
  2.4.1 Diffusion function and Fick's first law 14
  2.4.2 Steady-state diffusion and dimensions of the diffusion coefficient 15
  2.4.3 Non-steady-state diffusion 18
2.5 Migration 19
  2.5.1 Migration function 19
  2.5.2 Steady-state migration 20
  2.5.3 Non-steady-state migration 21
2.6 Diffusion and migration 22
  2.6.1 Combined diffusion and migration 22
  2.6.2 Steady-state process of diffusion and migration 23
3 Test methods and their precision

3.1 Introduction 27
3.2 Conventional test methods 27
  3.2.1 Diffusion cell test 27
  3.2.2 Immersion and ponding tests 30
3.3 Accelerated test methods 32
  3.3.1 Rapid chloride permeability test (Coulomb test) 35
  3.3.2 Potential diffusion index test 36
  3.3.3 Steady-state migration test 37
  3.3.4 Non-steady-state migration test 38
  3.3.5 Resistivity test 41
3.4 Test methods for in situ applications 43
  3.4.1 Use of chloride concentration profiles in concrete 43
  3.4.2 Use of accelerated chloride migration tests 45
  3.4.3 Use of electrical resistance measurements 51
  3.4.4 Discussion of in situ methods 54
3.5 Inter-laboratory comparison 54
  3.5.1 Nordic inter-laboratory comparison 55
  3.5.2 European inter-laboratory comparison (CHLORTEST) 55
  3.5.3 International inter-laboratory comparison (RILEM) 58
3.6 Precision of the laboratory test methods 59
  3.6.1 Results of the Nordic inter-laboratory comparison 59
  3.6.2 Results of the European inter-laboratory comparison (CHLORTEST) 60
  3.6.3 Results of the international inter-laboratory comparison (RILEM) 62
  3.6.4 Summary of the precision results 63
3.7 Relationships between the results of the different test methods 66
  3.7.1 Effect of concrete age on the test results 66
  3.7.2 Relationship between the results of the diffusion and migration tests 67
  3.7.3 Relationship between the results of the resistivity and diffusion/migration tests 70
  3.7.4 Relationship between laboratory tests and in-field performance 72

4 Modelling of chloride ingress

4.1 Introduction 75
4.2 Principles of the ingress process 76
4.2.1 Concrete as an ingress medium 76
4.2.2 The concrete pore solution 76
4.2.3 The exposure conditions 77
4.2.4 The ingress process 77

4.3 'Fundamentals' of ingress models 78
4.3.1 Mass balance equations 78
4.3.2 Flux descriptions 79
4.3.3 Interaction/binding 80

4.4 Chloride-ingress models based on Fick's second law 83
4.4.1 Fick's second law 83
4.4.2 Error function complement (erfc) model with constant D and C_s 85
4.4.3 Error function complement (erfc) model with time-dependent D_a and constant C_s 87
4.4.4 ψ model with time-dependent D_a and C_s 97
4.4.5 Error function complement (erfc) model with time-dependent D_a and C_s 97
4.4.6 Numerical models with time-dependent D and C_s 101
4.4.7 Boundary conditions in models based on Fick's second law 102
4.4.8 Conclusions on models based on Fick's second law 106

4.5 Chloride-ingress models based on flux equations 106
4.5.1 General 106
4.5.2 Boundary conditions in physical models 107
4.5.3 Models based on Fick's first law, without convection 109
4.5.4 Models based on Fick's first law, with convection 114
4.5.5 Models based on the Nernst–Planck equation 115
4.5.6 Conclusions on models based on flux equations 118

5 Sensitivity analysis and tests of chloride-ingress models 120

5.1 Introduction 120
5.2 Probabilistic sensitivity analysis – examples 120
5.2.1 Methodology for sensitivity analysis 121
5.2.2 Application of the methodology in the error function complement (erfc) model 126
5.2.3 Application of the methodology in the LEO model 129
5.2.4 Application of the methodology in the MsDiff model 132
5.2.5 Conclusions 134

5.3 Long-term sensitivity of error function complement (erfc) models 135
5.3.1 Mathematical expressions 136
5.3.2 Sensitivity of various parameters in the prediction of chloride concentration 136
5.3.3 The effect of different parameters on the sensitivity 141
vi - Contents

5.3.4 Discussion 141
5.3.5 Combined uncertainty of models for predicting chloride concentration 142
5.3.6 Concluding remarks 143

5.4 First comparison of predictions from early exposure data 144
5.4.1 The test concrete 145
5.4.2 The test environments 146
5.4.3 The test results 146

5.5 Second comparison of predictions from early exposure data 149
5.5.1 Objectives and overview of work performed 149
5.5.2 Establishment of criteria for benchmarking 149
5.5.3 Selection of profiles and documentation prepared for benchmarking 151
5.5.4 Selection of models 153
5.5.5 Responses obtained 155
5.5.6 Comparison of results 155
5.5.7 Some examples of results 155
5.5.8 Analysis of all predictions 161
5.5.9 Final comments on the benchmarking evaluation of models 166

5.6 Validation against long-term exposure data 167
5.6.1 Data collected over 10 years of exposure in a marine environment 167
5.6.2 Data collected over 10 years of exposure in a road environment 177
5.6.3 Data from real structures 183

5.7 Conclusions 190
5.7.1 Conclusions on the sensitivity analysis of the models 190
5.7.2 Conclusions on the benchmarking models 192
5.7.3 Conclusions on the validation against long-term exposure data 192

6 Overall discussion and conclusions

6.1 Concretes in chloride environments 194
6.2 Summary of frequently used test methods 195
6.2.1 The immersion test (NT BUILD 443) 195
6.2.2 The rapid chloride permeability test (RCPT) 196
6.2.3 The rapid chloride migration (RCM) test (NT BUILD 492) 196
6.2.4 The steady-state migration test 197
6.2.5 The resistivity test 198
6.2.6 In situ test methods 198
6.3 Recommended test methods 199
6.4 Interpretation of the test results 199
   6.4.1 Results of the immersion test (NT BUILD 443) 199
   6.4.2 Results of the rapid chloride migration (RCM) test 200
   6.4.3 Results of the resistivity test 201
6.5 Conclusions on prediction models 202
6.6 Acceptance criteria 203
   6.6.1 How to set acceptance criteria 203
   6.6.2 Some examples 204
6.7 General remarks and recommendations for further progress 207

Appendix: test methods for determining the resistance of concrete to chloride ingress 210
A1 Introduction 210
A2 Terms and definitions 210
A3 Test specimens in general 211
A4 Immersion test 211
   A4.1 Principle 211
   A4.2 Reagents and equipment 212
   A4.3 Preparation of the test specimen 212
   A4.4 Test procedures 213
   A4.5 Expression of results 215
   A4.6 Test report 216
A5 Rapid chloride migration (RCM) test 217
   A5.1 Principle 217
   A5.2 Reagents and equipment 217
   A5.3 Preparation of the test specimen 219
   A5.4 Test procedures 220
   A5.5 Expression of results 223
   A5.6 Test report 224
A6 Resistivity test 224
   A6.1 Principle 224
   A6.2 Equipment 225
   A6.3 Preparation of the test specimen 225
   A6.4 Test procedures 226
   A6.5 Expression of results 226
   A6.7 Test report 227
A7 Precision data 227
A8 Modifications of the test procedures 228

Bibliography 229
Index 239