Sprayed Concrete Lined Tunnels
An introduction

Alun Thomas

To adapt Oscar Wilde’s observation on socialism, the purpose of this book is not to present new ideas but rather to provide a comprehensive overview of the existing body of knowledge. The book presents a critical evaluation of the current state of the art in sprayed concrete lining of tunnels, with a focus on the technical aspects and practical applications.

It is essential to recognize the role of sprayed concrete in the construction, rehabilitation, and operation of tunnels. The book aims to provide a valuable resource for engineers, architects, and researchers interested in the field of sprayed concrete lining.

Sprayed concrete has become an integral part of tunnel construction, offering a versatile and cost-effective solution for various tunnel lining requirements.
# Contents

List of illustrations xi
Preface xvii
Acknowledgements xviii
List of abbreviations and symbols xx

1 What is a SCL tunnel? 1
   1.1 Sprayed concrete – the early days 3
   1.2 Why use sprayed concrete linings? 4
   1.3 Development of SCL tunnelling 5

2 Sprayed concrete 9
   2.1 Constituents and mix design 9
      2.1.1 Cement 11
      2.1.2 Water 12
      2.1.3 Sand and aggregate 12
      2.1.4 Accelerators 12
      2.1.5 Admixtures 13
      2.1.6 Microsilica 14
      2.1.7 Mix design 14
   2.2 Material properties and behaviour 14
      2.2.1 Strength in compression 15
      2.2.2 Strength in tension 22
      2.2.3 Strength in other modes of loading 26
      2.2.4 Stress-strain relationship in compression 28
      2.2.5 Stress-strain relationship in tension 35
      2.2.6 Shrinkage and temperature effects 37
      2.2.7 Creep 44
      2.2.8 Variation in properties with environmental conditions 47
      2.2.9 Durability and construction defects 49
3 Construction methods

3.1 Soft ground
  3.1.1 Method of excavation
  3.1.2 Support and excavation sequences
  3.1.3 Special cases

3.2 Blocky rock
  3.2.1 Method of excavation
  3.2.2 Support and excavation sequences
  3.2.3 Special cases

3.3 Hard rock
  3.3.1 Method of excavation
  3.3.2 Support and excavation sequences
  3.3.3 Special cases

3.4 Modern sprayed concrete
  3.4.1 Dry mix sprayed concrete
  3.4.2 Wet mix sprayed concrete
  3.4.3 Pumping
  3.4.4 Spraying

4 Design approaches

4.1 Observation vs prediction
  4.1.1 Risk-based designs
  4.1.2 General loading

4.2 Basic Principles
  4.2.1 Ground loads
  4.2.2 Excavation and support sequence
  4.2.3 Water
  4.2.4 Primary plus secondary lining – two pass lining
  4.2.5 Single shell lining – one pass lining

4.3 Design Tools
  4.3.1 Empirical tools
  4.3.2 Analytical tools
  4.3.3 Numerical modelling
  4.3.4 Physical tools

4.4 Code compliance
4.5 Continuity between design and construction

5 Modelling sprayed concrete

5.1 Linear elastic models
5.2 Hypothetical Modulus of Elasticity (HME) 113
5.3 Nonlinear stress-strain behaviour 115
  5.3.1 Nonlinear elastic models 115
  5.3.2 Plastic models 119
5.4 Tensile strength 123
  5.4.1 Unreinforced sprayed concrete 124
  5.4.2 Reinforced sprayed concrete 125
5.5 Shrinkage 125
5.6 Creep models 126
  5.6.1 Rheological models 127
  5.6.2 Generalised Kelvin model 128
  5.6.3 Burgers model 136
  5.6.4 Viscoelastic model 137
  5.6.5 Rate of flow model 138
  5.6.6 Other creep models 139
5.7 Ageing 142
  5.7.1 Thermo-chemo-mechanically coupled model 143
5.8 Construction sequence 146
5.9 Construction defects 151
5.10 Summary 153

6 Detailed design 157
6.1 Design for tunnels in soft ground 157
  6.1.1 Key behaviour of sprayed concrete 158
  6.1.2 Determining the loading on the sprayed concrete 158
  6.1.3 Lining design 158
6.2 Design for tunnels in blocky rock 160
  6.2.1 Key behaviour of sprayed concrete 160
  6.2.2 Determining the loading on the sprayed concrete 162
  6.2.3 Lining design 162
6.3 Design for tunnels in hard rock 163
  6.3.1 Lining design 164
6.4 Shafts 165
6.5 Junctions 166
  6.5.1 Key behaviour of sprayed concrete 166
  6.5.2 Determining the loading on the sprayed concrete 167
6.5.3 General arrangement and construction sequence 167
6.5.4 Lining design 169
6.6 Tunnels in close proximity 170
6.7 Portals 171
6.8 Special cases 172
   6.8.1 Seismic design 172
   6.8.2 Squeezing ground 174
   6.8.3 Swelling ground 174
   6.8.4 Creeping ground 175
   6.8.5 Rockburst 176
   6.8.6 Compressed air tunnelling 176
   6.8.7 Frozen ground and cold weather 177
   6.8.8 Hot ground and hot weather 178
   6.8.9 Fire resistance 178
6.9 Specifications 179
6.10 Detailing 181
   6.10.1 Steel reinforcement 181
   6.10.2 Structural continuity at joints 182
   6.10.3 Waterproofing at joints 183

7 Construction management 184
7.1 Quality control 184
   7.1.1 Pre-construction testing 184
   7.1.2 Testing during construction 185
7.2 Instrumentation and monitoring 189
   7.2.1 Instrumentation 189
   7.2.2 Trigger values 194
7.3 Designer’s Representative on site 196
7.4 Daily Review Meetings (DRM) 197

Appendices 201
Bibliography 223
Index 237
Illustrations

Figures

1.1 Long-section of a SCL tunnel in soft ground 1
1.2 Cross-section of a SCL tunnel in soft ground 2
1.3 Cross-section of a SCL tunnel in rock 3
1.4 Development of SCL tunnelling in the UK 7
2.1 Typical grading curve for sprayed concrete 10
2.2 Early-age strength gain depending on dosage of accelerator with ØBV J-curves for minimum strength 11
2.3 Stress-strain curves for sprayed concrete at difference ages 17
2.4 Normalised biaxial strength envelope for plain concrete from experimental data 18
2.5 Predictions of strength development vs age 22
2.6 Tension stiffening of reinforced concrete 23
2.7 Shadowing 25
2.8 Bond strength in shear to various substrates 27
2.9 Normalised octahedral stress envelope for sprayed concrete 29
2.10 Yield stress/peak stress ratio 30
2.11 Predictions of the development of elastic modulus with age 31
2.12 Variation of Poisson’s ratio with age 32
2.13 Peak compressive strain vs age 33
2.14 Ultimate compressive strain vs age 33
2.15 Compressive test on sprayed concrete 35
2.16 Uniaxial tensile tests on samples of mix IK013 at different ages 36
2.17 Water loss from concrete 40
2.18 Temperature profile in a sprayed concrete lining 42
2.19 Decomposition of strains according to the Rate of Flow Method 45
2.20 Composition of strains in a creep test 45
Illustrations

2.21 Creep test 48
2.22 Permeabilities of sprayed concrete vs categories according to Concrete Society Technical Report 31 (1988) 51
3.1 Excavation of a SCL tunnel in soft ground 55
3.2 Lining details 56
3.3 Excavation sequences in soft ground 57
3.4 Excavation of a SCL shaft 58
3.5 Reinforcement around a tunnel junction 59
3.6 Excavation of a SCL tunnel using a roadheader 61
3.7 Rock support classes 62
3.8 Hard rock tunnel boring machine 64
3.9 Excavation of a SCL tunnel using the drill and blast method 65
3.10 Dry mix process 67
3.11 Dry mix pump 68
3.12 Wet mix process 69
3.13 Wet mix pump 70
3.14 Dust levels for different types of sprayed concrete 71
3.15 Control of water ingress 72
3.16 Spraying defects 74
3.17 Effect on rebound and quality of the principal spraying parameters 75
3.18 Nozzle 76
4.1 Empiricism vs prediction in design 80
4.2 'Arching' of stresses around a hole in a stressed plate 82
4.3 Options for 'undrained' solution to achieve a dry tunnel 89
4.4 Drainage pipes 90
4.5 Depth to wavelength criterion for smoothness 91
4.6 Sheet membrane installation 92
4.7 Sprayed concrete surfaces covered by MS 345 with different maximum sizes of aggregate 93
4.8 Spray-on membrane installation 93
4.9 Formwork for cast concrete secondary lining 95
4.10 Water inflows into tunnels of various lining and ground permeabilities 99
4.11 Joint detail in sprayed concrete lining 100
4.12 Utilisation factors in a shallow SCL tunnel in soft ground 106
4.13 Results from numerical model of a shallow SCL tunnel in soft ground 107
5.1 Hoop axial force in crown vs distance from face for different sprayed concrete models 112
5.2 Hoop bending moment in crown vs distance from face for different sprayed concrete models 113
5.3 Back-analysis of a uniaxial compression test on sprayed concrete 117
5.4 Back-analysis of a triaxial compressive test on sprayed concrete
5.5 Yield surfaces in 3D stress space
5.6 Peak compressive strain vs age
5.7 Ultimate compressive strain vs age
5.8 Theoretical strain hardening curves
5.9 Shrinkage of sprayed concrete
5.10 Rheological models
5.11 Stress reduction due to creep, computed from strain gauge data
5.12 Specific creep strain of sprayed concrete, loaded at different ages
5.13 Shear stiffness (of spring in Kelvin rheological model), $G_k$ vs age
5.14 Viscosity of damper (in Kelvin rheological model), $\eta_k$ vs age
5.15 Relaxation time, $B$, vs age
5.16 Specific creep strain increment vs utilisation factor
5.17 Comparison between FLAC models and test data from Huber 1991
5.18 Decomposition of strains according to the Rate of Flow Method
5.19 Predicted specific creep values
5.20 The effect of creep on utilisation factors
5.21 Crown displacement vs distance from leading edge of top heading
5.22 Typical approximation of age-dependent stiffness in a numerical model
5.23 Hydration kinetics for shotcrete
5.24 Variation of stiffness and shrinkage with the degree of hydration
5.25 Longitudinal axial forces in the crown vs distance to face
5.26 Longitudinal bending moments in the crown vs distance to face
5.27 Utilisation factors in the crown at extrados vs distance from leading edge
5.28 Normalised hoop loads vs $(RCD/AR) \times (AL/R)$ corrected for tunnel radius and stiffness at ring closure at 9 m from the face
5.29 Locations of joints in mesh of the SCL tunnel modelled by Thomas (2003)
5.30 Utilisation factors in the crown vs distance from leading edge (for models with weak joints)
5.31 Transverse surface settlement profile at 18 m from the face
Illustrations

5.32 Results from numerical model of a shallow SCL tunnel in soft ground 154
6.1 Example proportions of a SCL tunnel in soft ground 159
6.2 Lining thicknesses for SCL tunnels in soft ground 160
6.3 Stability chart for plain sprayed concrete 161
6.4 Q-system support chart 164
6.5 Reinforcement around junctions 168
6.6 Construction sequences for junctions 168
6.7 Stress distribution around a hole in an elastic medium under applied stresses Pz and K-Pz 170
6.8 3D numerical model of a tunnel junction 171
6.9 Cross-section through movement joint 173
6.10 Weather proofing in icy conditions 177
6.11 Early-age strength criteria 180
6.12 Connecting reinforcing bars at a footing joint 181
6.13 KWIK-A-STRIP at a joint in the lining 182
7.1 Laser-guided profile control 188
7.2 Monitoring regime for a shallow urban tunnel 190
7.3 Trigger values 194
7.4 Derivation of trigger values 195
7.5 Information flow at the Daily Review Meeting 197
7.6 Excavation and Support Sheet 198

Tables

2.1 Typical mix design 10
2.2 Acceptable setting times for accelerated cements 13
2.3 Typical properties of sprayed and cast concrete 15
2.4 Composition of porosity 16
2.5 Typical properties of structural fibres for sprayed concrete 24
2.6 Strength in other modes of loading 27
2.7 Maximum temperature rises in sprayed concrete linings 42
3.1 Types of ground 53
3.2 Key mechanisms of behaviour in soft ground 54
3.3 Key mechanisms of behaviour in blocky rock 60
3.4 Key mechanisms of behaviour in hard rock 64
3.5 Recommended minimum age for sprayed concrete to be subjected to blasting 66
3.6 Compressive strengths of modern mixes 69
3.7 Normalised cost comparisons between dry and wet mix sprayed concrete 71
3.8 Finished surfaces of sprayed concrete 77
4.1 Sample long-term ground loads and relaxation factors for shallow tunnels 84
4.2 Analytical solutions for estimating ground loads 85
4.3 Design approaches for waterproofing 87
4.4 An example of criteria for smoothness of SCL tunnels 91
4.5 Typical design requirements for permanent sprayed concrete linings 96
4.6 Design approaches for 'grey rock' – degraded sprayed concrete 97
4.7 Examples of single shell SCL tunnels 98
5.1 Common design parameters for sprayed concrete 110
5.2 Values of Hypothetical Modulus of Elasticity 114
5.3 Specific creep strain increment, $\Delta e_{xx,3}$, in $/-$MPa 131
5.4 Relaxation time, $B$, in hours 131
6.1 Common specifications 180
7.1 Pre-construction tests (EN 14487 2005) 185
7.2 Control of sprayed concrete properties (EN 14487 2005) 186
7.3 Test methods for sprayed concrete 187
7.4 Instruments for monitoring ground behaviour 190
7.5 Instruments for monitoring lining performance 190
7.6 Hierarchy for monitoring 195
7.7 Frequency of monitoring 196