DEVELOPMENT OF A TWO-COMPONENT DYNAMIC GROUTING SYSTEM FOR TAILSKIN INJECTED BACKFILLING OF THE ANNULAR GAP FOR SEGMENTAL CONCRETE LINING IN SHIELDED TUNNEL BORING MACHINES

by

Karin Bäppler
A thesis submitted to the Faculty and Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Doctor of Philosophy (Mining and Earth System Engineering).

Golden, Colorado

Date 9/6/2006

Signed: __________________________
Karin Bäppler

Approved: __________________________
Dr. Levent Ozdemir
Thesis Advisor

Golden, Colorado

Date 09/06/2006

____________________________
Dr. Tibor G. Rozgonyi
Professor and Head
Department of Mining Engineering
ABSTRACT

Tunnels that are excavated by means of tunnel boring machines (TBM) in soft ground and hard rock conditions are lined with reinforced concrete segments. The prefabricated elements are installed within the protection of the TBM shield tailskin. The advancing shield leaves an annular space between the excavated diameter of the surrounding ground to the outside, the outside diameter of the concrete segments to the inside and the tailskin seal to the front.

The overall height of the tailskin seal together with its support structure and the thickness of the tailskin plate determine the dimensions of the annular gap. The theoretical width of the annular gap with current seal manufacture dimensions lies between 85 and 180 mm with a joint working area of ± 20 to ± 40 mm.

In order to avoid or reduce ground settlement behind the shield, the annular gap must be backfilled immediately during tunnel excavation. For this purpose pressurized grouting material is injected into the annular gap. The objective of annular grouting is to maintain the original state of stresses in the surrounding ground during the excavation process. The lower the displacement in the ground, the smaller the soil movement and lower the surface settlements.

A more effective grouting system needs to be developed in order to improve the mechanical properties of the ground, especially when tunneling in heterogeneous and complex geological conditions.

This thesis was designed to address the following principal objectives:

- Analysis and evaluation of the grout wash out in the annular gap in permeable soils with prevalent groundwater inflow,
- Analysis and assessment of the ground convergence occurring in the annular gap
- Improvement of the overall grouting process to achieve proper and more effective backfilling of the annular gap.
The injected grout must develop sufficient shear strength to prevent both displacement and damage of individual segments when they are loaded by the TBM back-up gantries and buoyancy of the segment ring in the annular gap. The shear strength should reach values which correspond with the surrounding ground for optimal bedding of the installed tunnel lining.

In this thesis, the dynamic grouting method is first introduced and then this new method is validated by laboratory and field injection tests, optimum grouting materials and conditions. Existing grouting materials and methods are compared with the dynamic grouting method. The results of the grout injection tests which have been conducted in an effort to find the best grouting specifications with respect to gap width, grout materials and their mix or concentration are also presented and discussed. Finally, the development of the dynamic grouting system and its application in actual tunnel construction projects is considered.

The results of the laboratory and field testing performed in this thesis allow for an accurate assessment of grout backfill properties with regard to exposed soil conditions. It can be concluded from the investigations carried out within this research that a recipe and mixing ratio of two component backfill material for permeable loose soil conditions was devised. The early strength development of the annular backfill material shows that it would be advantageous to stabilize the bond between the excavated surface and the tunnel lining in order to prevent a displacement of the rings when they are stressed by TBM back-up loads. Further, the test results have shown that the technical and economic effectiveness of filling the annular gap with a dynamic, two component grouting system is greater than backfilling by traditional grouting methods.

Field measurements performed in a segmental concrete lined TBM tunnel with a ring convergence measuring system indicate that convergences in the annular gap can be kept to a minimum by using the developed two component grouting material. The results show that the ring shape and the injection of the annular gap with two component grout can be maintained stable during the measurement period.
Finally, recommendations of practical interest to achieve a better assessment of the annular gap backfill material for future tunnel drives with regards to specific soil and project conditions, as well as suggestions for future research in this area are given.
# TABLE OF CONTENTS

ABSTRACT ....................................................................................................................... v

LIST OF FIGURES ........................................................................................................... xv

LIST OF TABLES ............................................................................................................. xix

GLOSSARY ...................................................................................................................... xix

ABBREVIATIONS .......................................................................................................... xxi

SYMBOLS ....................................................................................................................... xxiii

ACKNOWLEDGEMENTS ................................................................................................. xxix

CHAPTER 1 INTRODUCTION ......................................................................................... 1

1.1 Scope of the thesis ................................................................................................. 4

1.2 Objectives of the thesis ....................................................................................... 5

1.3 Outline of the thesis ............................................................................................. 7

CHAPTER 2 PURPOSE AND REQUIREMENTS OF BACKFILLING OF THE ANNULAR GAP .................................................................................................................. 11

CHAPTER 3 STATE OF THE ART OF THE GROUTING PROCESS ................................. 13

3.1 Grouting of the annular gap through the segments ............................................. 13

3.1.1 Grouting through segments in soft ground ..................................................... 13

3.1.2 Grouting through the segments in hard rock ................................................ 15
3.2 Continuous grouting of the annular gap through the tailskin.................21
  3.2.1 Design of conventional grouting system through the tailskin..........21
  3.2.2 Functioning of the conventional grouting system through the tailskin.....22

CHAPTER 4 GROUTING OF THE ANNULAR GAP WITH SINGLE
COMPONENT GROUTS AND EFFECTS ON THE TUNNEL LINING.................27
  4.1 Pressure and loads ........................................................................27
  4.2 Bedding of the tunnel lining.............................................................32

CHAPTER 5 INTERACTION BETWEEN TAIL VOID GROUTING AND
TUNNELING INDUCED SETTLEMENTS......................................................35
  5.1 Settlement components during tunnel boring operation.....................35
  5.2 Settlements on the surface...............................................................42
  5.3 Settlements due to grouting process.................................................47

CHAPTER 6 GROUT CHARACTERISTICS AND SPECIFICATION
FOR GROUT EQUIPMENT........................................................................57
  6.1 Grout characteristics.........................................................................57
    6.1.1 Requirements for grouting material............................................57
    6.1.2 Composition of the state of the art of the grouting compound........59
    6.1.3 Retarding behavior of the grouting compound..............................61
  6.2 Specification for grout equipment......................................................62
    6.2.1 Grouting process.........................................................................63
    6.2.2 Grouting pressure.......................................................................64
    6.2.3 Quantity and capability of grouting compound............................65
    6.2.4 Grout equipment and grout transport........................................68
  6.3 Single component and two component grouts....................................72
CHAPTER 7 DEVELOPMENT OF DYNAMIC GROUTING SYSTEMS.............77

7.1 Definition of the parameters influencing the dynamic grouting system........80

7.2 Two component low pressure annular gap backfilling system..................82

7.2.1 Function principle and structure of the two component low pressure
backfilling system........................................................................83

7.2.2 First time application of two component grout in tunnel construction....87

7.2.3 Active Mortar Tests....................................................................92

7.2.3.1 Test equipment for active mortar tests with two
component backfill material............................................................93

7.2.3.2 Active Mortar Test with Condat products..........................95

7.2.3.3 Active Mortar Tests with products from Mapei.........................100

7.2.3.4 Results of active mortar tests with products from two
different suppliers..........................................................................103

7.2.4 Development steps of an optimum low pressure injector design
for B-component injection................................................................105

7.2.4.1 Step N° 1: Injector with four bore cross sections and
four packers..................................................................................107

7.2.4.2 Step N° 2: Injector with one bore cross section and one packer...108

7.2.4.3 Step N° 3: Injector with a steel casing......................................110

7.2.5 Definition of a two component mixing formula against grout
washout in the annular gap................................................................114

7.2.5.1 General criteria of two component backfilling material.............115

7.2.5.2 Testing methods and formulas for two component mix
(Condat products) for application in permeable soils....................117

7.2.5.2.1 Preliminary tests.................................................................118

7.2.5.2.2 Comparison of different formulas.......................................121
7.2.5.2.3 Requirements and testing results of two backfill mixes configured for the application in high permeable soils with presence of running water.................................................123

7.2.6 Examination of washout resistance of two component backfill material for annular gap grouting.................................................................136

7.2.6.1 Washout resistance test for two component backfill material, "running water" tests.................................................................136

7.2.6.1.1 Test set-up and test material.........................................................137

7.2.6.1.2 Test set-up and course of testing.......................................................140

7.2.6.1.3 General Result of the washout-resistance tests "running water" tests for two component backfill material.................................159

7.2.7 Two component backfilling material and influence on convergences in the annular gap..................................................................................161

7.3 Two component high pressure annular gap backfilling.................................................................171

7.3.1 Design and function of the high pressure backfill system.................................................................171

7.3.2 Experiences with the high pressure backfill system.................................................................174

7.4 Premix variant for annular gap backfilling......................................................................................175

7.4.1 Design and function of the premix variant......................................................................................175

7.4.2 Development steps of the premix variant......................................................................................176

CHAPTER 8 COMPARISON BETWEEN EXISTING SINGLE COMPONENT GROUTING SYSTEMS AND DYNAMIC GROUTING SYSTEMS ..............179

8.1 Calculation of injection volume, flow rate and power.................................................................179

8.1.1 Determination of flow rates using the two component low pressure system......................................................................................179

8.1.2 Determination of flow rates using the conventional grouting system with single component grout......................................................................................182

8.1.3 Calculation of the pipe friction loss and required pumping capacity of the two component low pressure system.................................................................184
APPENDIX E  Operational data  Naples Metro Line 1, Italy –
TBM 1 + TBM 2........................................................................................................CD in pocket

APPENDIX F  Operational Data  Circle Line 852, Singapore –
TBM 1 + TBM 2........................................................................................................CD in pocket

APPENDIX G  BRESchia_RCms_ACCURACY_ESTIMATION.XLS...CD in pocket
LIST OF FIGURES

Figure 1.1 Types of tunnel boring machines..................................................2
Figure 1.2 Shield tunnel linings and support...................................................3
Figure 1.3 Visualization of the thesis topics...................................................9
Figure 3.1 Primary and secondary grouting....................................................14
Figure 3.2 Backfilling with gravel.................................................................17
Figure 3.3 Tests with a flexible backfilling material with high potential of
deformation .....................................................................................................18
Figure 3.4 Schematic diagram of the two grouting methods, backfilling through
the segments and backfilling through the tailskin........................................20
Figure 3.5 Schematic of grout flow pattern in the annular gap. The grout is
injected through six equally distributed injection openings..........................24
Figure 3.6 Calculated pressure distribution at rear of TBM (3 injection openings
near crest). Pressures at 0 and 4.1 m behind TBM........................................25
Figure 3.7 Calculated pressure distribution at rear of TBM (6 injection openings
equally distributed). Pressures at 0 and 4.1 m behind TBM.........................25
Figure 4.1 Pressure distribution in the annular gap during grouting and parallel
pushing forward of the sealing......................................................................28
Figure 4.2 Twisting and tilting of the segment..................................................31
Figure 5.1 Settlement Categories......................................................................37
Figure 5.2 Grout Injection Parameters..............................................................39
Figure 5.3 Pressure Sensors.............................................................................41
Figure 5.4 Shape of settlement trough caused by the tunnel operation.
Description of the parameters .........................................................................43
Figure 5.5 Dependence on depth of the settlement cavity.................................46
Figure 5.6 Idealized pressure distribution at the shield shell after grouting of
the annular gap ..............................................................................................49
Figure 5.7 Acting load in the uplift loading case on tunnel lining, frame analyses...53

Figure 6.1 Effective grout consumption for the tunnel project Airport Light Rail Hamburg. (Theoretical volume per advancement: 4.8 m³.)...67

Figure 6.2 Schematic diagram of grouting.................................................................72

Figure 7.1 Overview of chapter 7............................................................................78

Figure 7.2 Consolidating grout around a tunnel lining and detail......................81

Figure 7.3 Schematic diagram of the low pressure two component grouting system..................................................................................................................85

Figure 7.4 Injection methods used for tests with ETAC and conventional backfilling of the annular gap at the Botlekspoortunnel.........................88

Figure 7.5 Arrangement of grout injection lines according to the ETAC design....90

Figure 7.6 Arrangement of grout injection lines according to the design of Herrenknecht AG..............................................................91

Figure 7.7 Scheme: test set up for active mortar tests .......................................93

Figure 7.8 Setting behavior of active mortar (two component grout) with products of Condat.........................................................................................96

Figure 7.9 Calibration tests, chamber pressure......................................................98

Figure 7.10 Result of mixing tests (inspection of mortar body)..........................98

Figure 7.11 Injector after 10 seconds delay between switching-off of accelerator and base mortar flow (Start-stop-testing).................................99

Figure 7.12 Setting behavior with different formulas of active mortar with products of Mapai SpA.................................................................101

Figure 7.13 Mixing test: Material immediately after opening the flange..............102

Figure 7.14 Schematic of shield tail with the position of the injector.................104

Figure 7.15 Conductor cross sections of the two component system with redundant design......................................................................................................105

Figure 7.16 Injector for component B with packers. (1. Silicone packers, 2. Injection openings)..............................................................107

Figure 7.17 Determination of the nozzle (with protecting cage) after usage........109

Figure 7.18 Optimized injector design (one bore and one packer)....................110
Figure 7.19 Schematic representation of the mechanism of a new injector type......111
Figure 7.20 Design 3 injector for B-component installed in Ø30 mm grout line
(EPB-Shield, Metro Line 1 Naples). ...........................................112
Figure 7.21 Factory-test to verify the function of the new injector design. ..........113
Figure 7.22 Layout of the design of the hardening test..................................120
Figure 7.23 Test set up for measuring the Fann viscosity of formulas
FHK 0464 A, FHK 0464 B ..................................................................125
Figure 7.24 Measurements of viscosity (Fann viscosity) ...................................126
Figure 7.25 Bleeding under atmospheric pressure, testing of component A..........127
Figure 7.26 Baroid filter press for the determination of bleeding under pressure....128
Figure 7.27 Bleeding under pressure, testing of formulas FHK 0464 A,
FHK 0464 B ..................................................................................129
Figure 7.28 Comparison of hardening times for both formulas with a mixing
ratio of 90:10 ..................................................................................131
Figure 7.29 Test equipment for determining the water washout: Device from
Condat with a turbidimeter ..................................................................132
Figure 7.30 Test results of water washout test with a device designed by Condat ....133
Figure 7.31 Test rig for two component injection tests.................................138
Figure 7.32 Grain size distribution curve “Gravel Alluvium”, project West Side
CSO Portland (Red curve corresponds to the used test soil) .....................138
Figure 7.33 Testing devices for the determination of properties of component A
suspension. .....................................................................................140
Figure 7.34 Test equipment for two components washout resistance tests..........142
Figure 7.35 Steel tube (left) and steel tube filled with permeable sand (right) ......143
Figure 7.36 Preliminary experimental run....................................................144
Figure 7.37 Functionality of injector type and rate of mixing of components ......145
Figure 7.38 Depressurized vessel, constant water flow, discharge valve closed ....147
Figure 7.39 Depressurized vessel, constant water flow, discharge valve closed ....148
Figure 7.40 Vessel not pressurized, constant water flow, discharge valve opened ....149
| Figure 7.41 | Pressurized vessel (4 bar), constant water flow, 4 bar at constriction-hose valve | 150 |
| Figure 7.42 | Pressurized vessel (4 bar), constant water flow, constriction-hose valve 4 bar | 152 |
| Figure 7.43 | Pressurized vessel (4 bar), constant water flow | 153 |
| Figure 7.44 | Water filled vessel and opening of constriction-hose valve | 154 |
| Figure 7.45 | Set-up with constriction-hose valve assembled on the top of the vessel | 155 |
| Figure 7.46 | Injector with rubber sealing ring | 155 |
| Figure 7.47 | New injector type and injection of two components into a pressurized vessel under constant water flow | 156 |
| Figure 7.48 | Hardened material that was kept in the vessel for about 2.5 days with a constant water flow at times | 157 |
| Figure 7.49 | Tough injector after mixing line got completely blocked | 160 |
| Figure 7.50 | Position of inclinometers and crown prism (courtesy of VMT) | 162 |
| Figure 7.51 | Example visualization of inclinometer readings | 164 |
| Figure 7.52 | Schematic diagram of the RCMS (courtesy of VMT) | 167 |
| Figure 7.53 | Visualization of absolute vertical displacements on a defined test section in Brescia from Ring 58 to Ring 75 | 169 |
| Figure 7.54 | Visualization of the inclinometer readings of the RCMS for Brescia referring to data set N° 1 to 279 | 170 |
| Figure 7.55 | Hydraulic unit, high pressure system | 172 |
| Figure 7.56 | High pressure injector | 173 |
| Figure 7.57 | Inward transfer – high pressure system | 174 |
| Figure 7.58 | Connection between grouting and flushing line | 175 |
| Figure 7.59 | Modified pipe system | 177 |
| Figure 8.1 | Grout injection line | 182 |
| Figure 9.1 | Application of the two component grouting system to current TBM projects (based on end of year 2005) | 193 |
| Figure 9.2 | Arrangement of the injection groups and lines for annular gap backfilling | 195 |
Figure 9.3 Flow in l/h for two component injection through lines 2, 3, 6 and 7 for rings 15 to 914 ................................................................. 196

Figure 9.4 Flow in l/h for two component injection through lines 2, 3, 6 and 7 for rings 10 to 879 ........................................................................... 198

Figure 9.5 Arrangement of the injection groups and lines for annular gap backfilling ........................................................................... 199

Figure 9.6 TBM N° 1: Flow in l/min for two component injection through lines 2, 3, 6 and 7 for rings 1 to 453 ......................................................... 200

Figure 9.7 TBM N° 2: Flow in l/min for two component injection through lines 2, 3, 6 and 7 for rings 5 to 500 ......................................................... 201

Figure 9.8 Arrangement of the injection lines for annular gap backfilling, grout lines 1 to 8 ........................................................................... 202

Figure 10.1 Physical properties of grouts in terms of hardening time................................. 207

Figure 10.2 Appropriate solutions with dynamic grouting material to meet the engineering requirements ................................................................. 209

Figure 11.1 Requirements for a suitable composition of backfill material ......................... 214

Figure 11.2 Requirements on grouting process during TBM operation .............................. 215
LIST OF TABLES

Table 6.1 Composition by percentage of the grouting mortar of various shield tunneling projects ................................................................. 59

Table 6.2 Plastic consistency for single component grouts ............................................ 73

Table 7.1 Development steps of an appropriate injector design for component B. 106

Table 7.2 Tests used to assess two component backfilling material (laboratory and/or field tests) .................................................................. 116

Table 7.3 Soil-mechanical parameters, project West Side CSO Portland ............... 117

Table 7.4 Development of viscosity with time ............................................................ 119

Table 7.5 Compositions of component A for backfill application in Portland in kilogram in direct comparison ........................................... 122

Table 7.6 Hardening times in seconds for the five formulas with varied proportions of component A and B ..................................................... 122

Table 7.7 Comparison of the density of component A dependent on the formula... 122

Table 7.8 Composition of component A for FHK 0464 A, FHK 0464 B .............. 123

Table 7.9 Density of two formulas FHK 0464 A, FHK 0464 B (component A) .... 125

Table 7.10 Comparison of the test results for the tests bleeding under atmospheric conditions and bleeding under pressure ...................... 130

Table 7.11 Test results of unconfined compressive strength test of cube specimens with two component mix ............................................. 134

Table 7.12 Comparison of two component mix characteristics for application in highly permeable soils with presence of running water ...................... 135

Table 7.13 Two component mixture adapted to permeable soils with running water ................................................................................. 139

Table 7.14 Résumé of mechanical properties of component A mix and cube strengths of the two component mix ............................................ 158

Table 7.15 Main components and characteristics of the RCMS ......................... 166

Table 8.1 Technical data, EPB-Shield Metro Line 1 Naples .................................. 182
Table 8.2  Technical data of the two component system ........................................ 184

Table 8.3  Technical data of the grouting system .................................................. 188

Table 8.4  Cost comparison for two component low pressure and single component grouting systems in tabular form .................................................. 192

Table 9.1  Average mixing ratio in two component injection lines 2, 3, 6 & 7 for EPB-Shield N° 1 ................................................................. 196

Table 9.2  Average mixing ratio in two component injection lines 2, 3, 6 & 7 for EPB-Shield N° 2 ................................................................. 197
GLOSSARY

**accelerator** - chemical admixture that increases the rate of a chemical reaction.

**admixture** - materials other than water, fine aggregate, or hydraulic cement used as an component in grout.

**aggregate** - granular mineral material such as sand, ground slag, or rock that is used as fine aggregate and mixed with water and cement to form a grout.

**annular space** – void between the external part of the tunnel lining and the excavated ground.

**articulation** – the point of connection between two elements which allows motion

**backfill grouting** – injection to fill the annular gap.

**base** - primary component in a grouting system.

**bentonite** - clay containing 75 percent or more of smectite characterized by its large volume increase on wetting.

**Bingham fluid** - (\( \tau_0 \neq 0, \mu \neq 0 \)) where \( \tau_0 \) is the yield stress (in Pa), \( \mu \) is the plastic viscosity in (Pa·s). A Bingham fluid is an incompressible visco-plastic yield stress fluid. It is characterized by the fact that when the stress is below the yield stress, the rate-of-strain is zero, and the fluid moves as a rigid solid. When the stress is above this yield value, the rate-of-strain is in a linear relationship with the stress and the fluid flows in a viscous manner.

**Earth Pressure balance method (EPB)** – closed shield method with active face support by the pressurized soil.

**fines** - soils or granular material with a nominal size smaller than 0.075 μm.

**gel** - condition in which a liquid grout begins to develop strength.

**gel time** - time interval elapsed between the mixing of a fluid grout and the formation of a gel.
**grout** - substance that has sufficient fluidity to be injected or pumped into a porous body or into cracks and is intended to harden in place (see grout, cementitious; grout chemical, etc.).

**grout, cementitious** - mixture of cementitious material and water, with or without aggregate, proportioned to produce a pourable consistency without segregation of the constituents; also a mixture of other composition but of similar consistency.

**grout, chemical** - solution injected into a porous body or a crack that reacts in place to form a gel or solid.

**grouting** - process of filling with grout. (See also grout.)

**hardener** - component in an epoxy or resin grout that causes the base material to cure to a solid.

**Injector** - equivalent to nozzle design.

**Newtonian fluid** - fluid that shows a constant velocity under different rates of shear. \( \tau_0 = 0, \mu \neq 0 \) where \( \tau_0 \) is the yield stress (in Pa), \( \mu \) is the plastic viscosity in (Pa·s).

**penetrability** - property of a grout that describes its ability to fill up a porous mass.

**permeability** - property of a porous material that indicates the rate at which a liquid can flow through the pore spaces.

**plasticizer** - chemical additive that can be added to concrete mixtures to soften the mix before it hardens, increasing its workability, and is usually not intended to affect the properties of the final product after it hardens.

**retarder** - grout component that slows the rate at which chemical reactions occur in the grout.

**seepage** - movement of a small volume of fluid through fissured rock or soil.

**segment** - precast elements set up to form the tunnel lining. (They may be of concrete, steel, cast iron or ductile cast iron).

**shield** - a circular-shaped cylindrical pipe made by a metallic structure to protect the working area.
**slurry** - viscous suspension of mineral and/or polymeric products.

**Slurry shield** – closed shield TBM with active face support by the pressurized slurry.

**tail seal** – flexible device to prevent water or grout ingress between the lining and the shield machine.

**tunnel boring machine (TBM)** – machines designed to create/bore tunnels. They perform several functions, from the excavation only to the application of the tunnel lining.

**time of setting** - time interval between grout mixing and gelation.

**unconfined compressive strength** - stress (load per unit area) at failure of a cylindrical specimen subjected to axial loading without lateral or confining stress.

**uplift** - vertical displacement of a formation due to grout injection.

**viscosity** - internal resistance of a liquid to flow.

**yield point** – is defined in engineering and material science as the stress at which a material begins to plastically deform.
ABBREVIATIONS

AG  public limited company
approx.  approximately
ASTM  American Society for Testing and Materials
CEM II/B-LL 32.5 R Portland Limestone Cement with an early compressive strength
of ≥ 10 N/mm² after 2 days and a standard compressive strength
after 28 days of ≥ 32.5 N/mm² and ≤ 52.5 N/mm²
CSO  Combined Sewer Outflow
CTRL  City Tunnel Rail Link
DIN  Deutsches Institut für Normung e.V. (German Institute for
Standardization)
DN  nominal diameter
EFNARC  European federation dedicated to specialist construction
chemicals and concrete systems
EN  European Norm
EPB  Earth Pressure Balance Shield
ETAC  thixotropic-gel grouting method (called ETAC or TAC
developed by the TAC Corporation and by the Geo Reserarch
Institute of Osaka)
FEM  finite element method
FHK  formula Herrenknecht
GmbH  Limited company (Ltd.)
GOK  Geländeoberkante (surface of land)
GW  ground water
ID  Internal diameter
LRT  Light Rail Tunnel
max.  maximum

xxiii
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mix</td>
<td>Mixshield</td>
</tr>
<tr>
<td>No.</td>
<td>number</td>
</tr>
<tr>
<td>PLC</td>
<td>programmable logical computer</td>
</tr>
<tr>
<td>RCMS</td>
<td>Ring Convergence Measurement System</td>
</tr>
<tr>
<td>R&amp;D</td>
<td>Research and development</td>
</tr>
<tr>
<td>Re</td>
<td>Reynold's number</td>
</tr>
<tr>
<td>rpm</td>
<td>revolutions per minute</td>
</tr>
<tr>
<td>SLS-T</td>
<td>Steuerleitsystem im Tunnelbau (Tunnel Guidance System)</td>
</tr>
<tr>
<td>SMART</td>
<td>Storm water Management And Road Tunnel</td>
</tr>
<tr>
<td>TBM</td>
<td>tunnel boring machine</td>
</tr>
<tr>
<td>UCS</td>
<td>unconfined compression strength</td>
</tr>
<tr>
<td>US</td>
<td>United States</td>
</tr>
<tr>
<td>VICAT</td>
<td>Cement manufacturer, “Louis Vicat” the inventor of artificial cement in 1817</td>
</tr>
<tr>
<td>VMT</td>
<td>Gesellschaft für Vermessungstechnik (company for survey technology)</td>
</tr>
<tr>
<td>Vol.-%</td>
<td>percent by volume</td>
</tr>
<tr>
<td>VTR</td>
<td>Vortriebsrichtung (direction of tunnel advance)</td>
</tr>
<tr>
<td>2-C</td>
<td>two component(s)</td>
</tr>
<tr>
<td>Symbol</td>
<td>Definition</td>
</tr>
<tr>
<td>--------</td>
<td>------------</td>
</tr>
<tr>
<td>A</td>
<td>cross section</td>
</tr>
<tr>
<td>A_M</td>
<td>cross section of the oval injection line</td>
</tr>
<tr>
<td>A_1</td>
<td>pump 1</td>
</tr>
<tr>
<td>A_2</td>
<td>pump 2</td>
</tr>
<tr>
<td>A_3</td>
<td>pump 3</td>
</tr>
<tr>
<td>A_4</td>
<td>pump 4</td>
</tr>
<tr>
<td>α</td>
<td>angle</td>
</tr>
<tr>
<td>b</td>
<td>half segmental width</td>
</tr>
<tr>
<td>B</td>
<td>segment length/ width of injection line</td>
</tr>
<tr>
<td>b_1'</td>
<td>effective width after Houska</td>
</tr>
<tr>
<td>bar</td>
<td>bar (1 bar = 10^5 Pascal)</td>
</tr>
<tr>
<td>β</td>
<td>critical angle</td>
</tr>
<tr>
<td>c</td>
<td>undrained cohesion</td>
</tr>
<tr>
<td>C</td>
<td>Centigrade</td>
</tr>
<tr>
<td>cm</td>
<td>centimeter</td>
</tr>
<tr>
<td>cp</td>
<td>centipoise (a unit of viscosity, 1 centipoise = 1 millipascal-second)</td>
</tr>
<tr>
<td>d</td>
<td>segment thickness/ diameter</td>
</tr>
<tr>
<td>D</td>
<td>tunnel diameter, excavation diameter</td>
</tr>
<tr>
<td>d_hydr.</td>
<td>hydraulic equivalent diameter</td>
</tr>
<tr>
<td>D_A</td>
<td>outside diameter segment ring</td>
</tr>
<tr>
<td>D_R</td>
<td>diameter cutting wheel</td>
</tr>
<tr>
<td>D_1</td>
<td>outside diameter of the segment ring/ outside diameter hose (for component A)</td>
</tr>
<tr>
<td>D_2</td>
<td>diameter of the shield cutting edge/ outer diameter hose (for component B)</td>
</tr>
<tr>
<td>Symbol</td>
<td>Definition</td>
</tr>
<tr>
<td>--------</td>
<td>------------</td>
</tr>
<tr>
<td>D_3</td>
<td>inside diameter hose (for component B)</td>
</tr>
<tr>
<td>( \varnothing )</td>
<td>diameter</td>
</tr>
<tr>
<td>( \eta_A )</td>
<td>assumed viscosity component A</td>
</tr>
<tr>
<td>( \eta_B )</td>
<td>assumed viscosity accelerator</td>
</tr>
<tr>
<td>( \eta_M )</td>
<td>dynamic viscosity</td>
</tr>
<tr>
<td>F</td>
<td>force</td>
</tr>
<tr>
<td>F_{up}</td>
<td>upward directed load</td>
</tr>
<tr>
<td>g</td>
<td>acceleration of gravity/ grade</td>
</tr>
<tr>
<td>G</td>
<td>dead weight</td>
</tr>
<tr>
<td>( \gamma )</td>
<td>dead weight of the lining/ shear rate</td>
</tr>
<tr>
<td>( \gamma_{eq} )</td>
<td>equivalent specific weight of the grout pressure</td>
</tr>
<tr>
<td>( \gamma_w )</td>
<td>dead weight of unsaturated soil</td>
</tr>
<tr>
<td>( \phi )</td>
<td>angle</td>
</tr>
<tr>
<td>h</td>
<td>hour</td>
</tr>
<tr>
<td>H</td>
<td>height of cover/ height of injection line</td>
</tr>
<tr>
<td>i</td>
<td>distance of point of inflection</td>
</tr>
<tr>
<td>k</td>
<td>buoyancy force/ horizontal coefficient of earth pressure at rest</td>
</tr>
<tr>
<td>k_0</td>
<td>horizontal effective earth pressure</td>
</tr>
<tr>
<td>kg</td>
<td>kilogram</td>
</tr>
<tr>
<td>kg/cm^2</td>
<td>kilogram per square centimeter</td>
</tr>
<tr>
<td>KN/m^2</td>
<td>kilonewton per square meter</td>
</tr>
<tr>
<td>KN/m^3</td>
<td>kilonewton per cubic meter</td>
</tr>
<tr>
<td>kPa</td>
<td>kilopascal</td>
</tr>
<tr>
<td>l</td>
<td>liter</td>
</tr>
<tr>
<td>L</td>
<td>length of grout line/ total length of injection line</td>
</tr>
<tr>
<td>L_T</td>
<td>segment length</td>
</tr>
<tr>
<td>l/min</td>
<td>liter per minute</td>
</tr>
<tr>
<td>m</td>
<td>meter</td>
</tr>
<tr>
<td>m^3</td>
<td>cubic meter</td>
</tr>
<tr>
<td>m^3/h</td>
<td>cubic meter per hour</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>---------------------------------------</td>
</tr>
<tr>
<td>min</td>
<td>minute</td>
</tr>
<tr>
<td>ml</td>
<td>milliliter</td>
</tr>
<tr>
<td>mm</td>
<td>millimeter</td>
</tr>
<tr>
<td>Mm</td>
<td>millimeter</td>
</tr>
<tr>
<td>mm²</td>
<td>square millimeter</td>
</tr>
<tr>
<td>mm/min</td>
<td>millimeter per minute</td>
</tr>
<tr>
<td>MPa</td>
<td>megapascal</td>
</tr>
<tr>
<td>m/s</td>
<td>meter per second</td>
</tr>
<tr>
<td>m/s</td>
<td>meter per second</td>
</tr>
<tr>
<td>μ</td>
<td>viscosity</td>
</tr>
<tr>
<td>μm</td>
<td>micron</td>
</tr>
<tr>
<td>μSM</td>
<td>maximum advancement speed</td>
</tr>
<tr>
<td>μ₁</td>
<td>extra grout consumption</td>
</tr>
<tr>
<td>μ₂</td>
<td>mortar compaction under injection</td>
</tr>
<tr>
<td>μ₃</td>
<td>coefficient for the filling of the</td>
</tr>
<tr>
<td></td>
<td>cylinder depending on the</td>
</tr>
<tr>
<td></td>
<td>consistency of the grout</td>
</tr>
<tr>
<td>μ₄</td>
<td>ratio of the stroke time of the</td>
</tr>
<tr>
<td></td>
<td>transport cylinder to the</td>
</tr>
<tr>
<td></td>
<td>switch-over time of the rotor</td>
</tr>
<tr>
<td>n</td>
<td>rotation speed</td>
</tr>
<tr>
<td>N</td>
<td>number of injection lines</td>
</tr>
<tr>
<td>N/mm²</td>
<td>Newton per square millimeter</td>
</tr>
<tr>
<td>ν</td>
<td>flow rate/kinematic viscosity</td>
</tr>
<tr>
<td>νₐ</td>
<td>specific ground loss</td>
</tr>
<tr>
<td>νₘ</td>
<td>kinematic viscosity</td>
</tr>
<tr>
<td>Δp</td>
<td>friction loss in pipe</td>
</tr>
<tr>
<td>Pa</td>
<td>pascal</td>
</tr>
<tr>
<td>Pas</td>
<td>pascal second</td>
</tr>
<tr>
<td>pₐ</td>
<td>pressure in injection line A</td>
</tr>
<tr>
<td>pₐ₈</td>
<td>pressure in accelerator line</td>
</tr>
</tbody>
</table>
\( P_{th} \)
- pumping capacity

\( p_U \)
- pressure in the grouting line

\( \phi \)
- inner angle of friction of the soil

\( \rho \)
- \( \text{Phi} = 3.14 \)

\( \% \)
- percent

\( q \)
- load

\( Q \)
- required pump performance

\( r \)
- radius of lining

\( R \)
- radius

\( \text{Re} \)
- Reynolds's number

\( r_l \)
- inside diameter of tunnel lining

\( \rho \)
- density

\( \rho_A \)
- density component A

\( \rho_B \)
- density component B

\( \rho_g \)
- density of grout

\( \rho_M \)
- assumed grout density

\( \rho_t \)
- average density of the tunnel (lining and air)

\( s \)
- width of tail void/ second

\( s(x) \)
- settlement

\( s_{max} \)
- maximum settlement

\( \text{sec} \)
- second

\( \sigma_{\text{grout,radial,vertical}} \)
- vertical component of the radial grout loading

\( \sigma_{\text{grout,tan,vertical}} \)
- vertical component of the tangential loading

\( \sigma_{\text{tot}} \)
- total vertical tension

\( t \)
- overburden above crown/ injection time

\( T \)
- injection time

\( \tau \)
- shear stress

\( \tau_y \)
- shear force of the grout

\( \tau_{\text{yield}} \)
- maximum plastic yield stress
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>flow rate</td>
</tr>
<tr>
<td>V</td>
<td>volume/ advancement speed/ volt</td>
</tr>
<tr>
<td>( V_{\text{Komp. A}} )</td>
<td>volume of injection material component A per injection line</td>
</tr>
<tr>
<td>( V_{\text{Komp. B}} )</td>
<td>volume of injection material component B per injection line</td>
</tr>
<tr>
<td>( V_L )</td>
<td>volume of grouting material per injection line</td>
</tr>
<tr>
<td>( V_M )</td>
<td>non-compacted amount of grout</td>
</tr>
<tr>
<td>( V_{RS} )</td>
<td>theoretical grout volume</td>
</tr>
<tr>
<td>( \dot{V}_{\text{Komp. A}} )</td>
<td>volume flow component A</td>
</tr>
<tr>
<td>( \dot{V}_{\text{Komp. B}} )</td>
<td>volume flow component B</td>
</tr>
<tr>
<td>x</td>
<td>distance perpendicular to tunnel axis/ control variable rectangular to the tunnel axis</td>
</tr>
<tr>
<td>?</td>
<td>loss coefficient</td>
</tr>
<tr>
<td>( z_0 )</td>
<td>depth of tunnel axis (t + D/2)</td>
</tr>
</tbody>
</table>
ACKNOWLEDGEMENTS

The thesis was written in addition to my activity as a civil engineer at Herrenknecht AG in Germany in the field of Sales, Geotechnics and R & D.

The writing of such a work is not possible without the support of a number of organizations and individuals. Therefore I would like to acknowledge and express my special gratitude to the following persons:

Dr. Levent Ozdemir for his support as my thesis advisor and Dr. Tibor Rozgonyi for their encouragement and guidance throughout the entire period.

Dr.-Ing. E.h. Martin Herrenknecht (Chairman of the Board of Management of Herrenknecht AG) and Dipl.-Ing. (FH) Gebhard Lehmann (Vice-Chairman of the Board of Management of Herrenknecht AG) for the financial support and encouragement, in particular the opportunity to be able to write this thesis parallel to my work.

Dipl.-Ing. (FH) Werner Burger, Manager Design Division of Herrenknecht AG, for the ideas and informations.

I am much obliged to Dipl.-Ing. Manfred Messing, managing director from VMT GmbH, and his team for the supply of the ring convergence measuring system (RCMS) and Jean-Marc Basset from Condat Lubricants in France for his support by arranging to have the testing materials and components at my disposal.

I thank Dr. Graham Mustoe and Dr. Gene Woolsey as members of the doctoral advisory committee for their assistance and directions and Shannon Man from the Mining and Engineering department of CSM for her organizational support.

Special thanks to Dr. Franz Friedrich Brost, consultant and former head of the Logistics & Production section at IECS of the University of Strasbourg III, for the methodological annotations and corrections during the completion of this thesis.

I am most grateful to my sister Dipl.-Volkswirt Ellen Bäppler who took over the task of veryfing and formatting the present thesis.
Also, many thanks to Jim Broomfield (M I Mech E, C Eng), Sales Manager Middle East and India of Herrenknecht AG, for reading the final version of the document.

Last, but not least, I would like to express my gratitude to my parents Hannelore and Wirtsch.-Ing. Karl-Dieter Bäppler and my sister Dipl.-Volkswirt Ines Klaus for their strong support.
CHAPTER 1
INTRODUCTION

The general increase in growth is a result of a worldwide growing need for an efficient infrastructure in the areas of transport, supply and disposal services. Without such infrastructure, cities, states and even countries cannot move towards the future. Infrastructure must be created to secure water supplies, energy and data.

Topographical conditions in large cities and towns encourage tunneling solutions, particularly by mechanised methods. Today 45 percent of all large diameter tunnels are driven by mechanized methods. Compared to conventional open trench tunnel construction methods, underground tunnel construction has almost negligible impact on life and commerce above ground.

Depending on the prevailing ground conditions and project specific requirements, different types of tunnel boring machines (TBMs) can be utilized for the construction of infrastructure or utility tunnels. They can generally be subdivided into following machine types:

- Earth Pressure Balance Shields (EPB),
- Mixshields (Hydroshields and slurry supported TBMs that can be converted inside the tunnel from one operation mode to the other in heterogeneous ground conditions),
- Hard Rock TBMs.

The EPB-Shields, Mixshields and Slurry Shields are soft ground TBMs that are generally used in ground conditions below the groundwater table.

The typical operative range for EPB-Shields are cohesive soil conditions. They can also be used in more coarse grained geology together with suitable conditioning materials such as foam or polymer, thereby extending their range of application.
The typical operative range for Slurry Shields, Hydroshields or Mixshields, so to speak TBMs with slurry supported tunnel face, are loose soil conditions like sands and gravels. These types of soft ground TBMs can also be used in mixed face conditions and in cohesive soils like silts and clays. However, in cohesive conditions a high effort for separation of the excavated material has to be taken into account with these TBMs.

Hard rock TBMs can be further categorized as either Gripper TBMs or Shielded Hard Rock TBMs. The Gripper TBMs are used in solid or massive rock conditions. The tunnel support consists of anchors, steel arches, wire mesh and shotcrete. The Shielded hard rock TBMs are used in weaker rock conditions where the tunnel support consists generally of reinforced pre cast concrete segments similar to those used with soft ground TBMs such as EPB-Shields and Mixshields.

The focus of this thesis is grouting of the annular gap with dynamic two component grouting material in Shielded Tunnel Boring Machines (EPB-Shields, Slurry Shields & Mixshields, Shielded Hard Rock TBMs).

The main principle of the shield is a cylindrical steel structure that will be moved forward along the planned tunnel axis parallel with the excavation. The steel
structure supports the excavated void until the preliminary or final tunnel support is built at the end position of the steel structure. Thereby the shield has to withstand the pressure of the surrounding geology and, if present, to keep away prevailing groundwater.

In soft ground shield tunneling the excavated void will generally be supported by a segmental tunnel lining consisting of reinforced pre cast concrete segments. Here a number of different forms, materials, arrangements, sealing systems and ring building methods exist. Further other lining systems are possible and are already in use (Figure 1.2).

Figure 1.2 Shield tunnel linings and support (Maidl et al. 1995, p. 6)

Because the tunnel support (lining) is mostly built within the protection of the shield, a gap is created whilst the shield advances because the outside diameter of the tunnel lining is necessarily smaller than the diameter of the shield. This gap needs to be filled to minimize loosening of the ground and subsequent surface settlement. Thus an appropriate grouting method must be employed to fill this gap and the shield be equipped accordingly.
An adequate support of the whole annular gap ring area is achieved by filling with a free-flowing pressure controlled material. The injection material should not be too liquid to avoid the flow into the excavation chamber. On the other hand it has to be sufficiently free-flowing to completely fill the gap, which is constantly changing as the shield advances (Maidl et al. 1995, p. 38).

1.1 Scope of the thesis

Tunnels that are excavated in soft ground and hard rock conditions by means of shielded tunnel boring machines are lined with reinforced concrete segments. The prefabricated elements are installed within the protection of the shield tail. The advancing shield leaves an annulus, the annular gap, between the surrounding ground to the outside and the concrete segments to the inside. The gap is closed by the tailskin seal to the front. The separation of the TBM and the annular space is realized via the shield tailskin seals. They have to withstand the prevailing soil and water pressures that in turn determine the grouting pressure. The tailskin seals can be either rubber systems or steel brush systems.

The steel brush seals have the advantage of sealing a gap on the longitudinal joints even if the individual segments of a ring are a bit staggered against each other. With a stiff rubber seal in comparison a residual gap remains which allows the pressurized grout to escape. In the case of steel brush seals, the chambers between the rows of brushes are filled with tail seal grease to prevent the grouting material penetrating the brushes thus reducing their elasticity. The grease is thus maintained at a certain pressure (Babendererde 1999, p. 49).

The overall height of the tailskin seal together with its support structure and the thickness of the shield tailskin plate and the overcut determines the width of the annular gap. The theoretical width of the annular gap as regards current seal technology varies between 85 and 180mm with a joint working area of ± 20 to ± 40mm.
The annular gap can also increase due to the factors such as conical form of the shield skin, ground displacement in curves and over cut, if the ground does not immediately fill the newly created voids (Maidl et al. 1995, p. 39).

Complete backfilling of the annular gap is an essential requirement of shield tunneling technology because it has direct influence on operational safety for the shift personal as well as on the soil or rock structure. In case of improper backfill of the annular gap, surface settlement will most likely be induced.

In order to avoid or rather reduce surface settlement behind the shield, the annular gap has to be backfilled immediately during tunnel excavation. For this purpose pressurized grouting material is injected. The requirement of the annular grouting is to support the original state of stresses in the surrounding ground during the excavation process. The natural state of stress of the ground can thus largely be maintained. Less displacement in the ground also causes less soil movement and thus less surface settlements.

1.2 Objectives of the thesis

An effective grouting system needs to be developed in order to improve the mechanical properties of the ground especially regarding tunneling in heterogeneous and complex geological conditions. For this, among other things, the composition of the annular gap backfilling material plays an important role.

The readily mixed backfill material should demonstrate smooth flow properties during injection and a quick setting time after injection. This is not always achieved with conventional single component grouting materials, since on the one hand delays in the TBM advance usually leads to setting of the grout in the injection lines resulting in extensive cleaning procedures which are quite time consuming.

Because on the other hand, cycle times for a ring can come down to an hour or less, the traditional annular gap grouts generally remain fully fluid for several hours. This with high production rates give rise to buoyancy of several rings due to the grout
remaining in its fluid state and can result in severe ring damage during the excavation process. Therefore, control of the consistency and the stiffening behavior of the grout are of special importance for the development of a dynamic two component grouting system with regard to the geological and hydrological conditions as well as additional current marginal conditions.

The backfill material needs to have smooth flowing properties for injection even after having remained in the supply (or injection) pipes for longer periods of time, especially during delays to TBM advance, in order to reduce cleaning of the supply pipes to a minimum (Maidl et al. 1995, p. 186).

In ground conditions with partially highly permeable soils and existing groundwater flow the conventional grouting material is prone to be segregated or even washed out of the annular gap. When this occurs, the tunnel tube is then not bedded properly in the surrounding soils, giving rise to buoyancy of the tunnel tube and/or surface settlement.

This topic will be closer examined within the context of the composition of the two component backfill material within this thesis.

The thesis has the following objectives:

- To discuss the grout wash out in the annular gap in permeable soils with existing groundwater flow.
- To discuss convergence in the annular space.
- To discuss the grouting process with regard to a proper backfilling of the annular gap.

After the ring leaves the shield tailskin, it is stressed by the grouting pressure, earth and water pressures. The loads exerted on the tunnel lining ring at this point of the construction process are the highest experienced both during tunnel construction and normal operation during the lifetime of the tunnel.

After leaving the tailskin, the segment rings are placed in the still soft backfill material and are additionally stressed from the inside by the concentrated loads of the wheel sets of the first TBM back-up trailers. Thus it is a requirement that the injected grout must develop sufficient shear strength to prevent on the one hand the
displacement or damage of individual segments when they are loaded by the back-up trailers and on the other hand to prevent buoyancy of the segment ring in the annular gap. The shear strength of the developed two component backfill material should reach values that correspond to the surrounding ground for optimal bedding of the installed tunnel lining.

1.3 Outline of the thesis

After a general introduction of existing tunnel boring machines and their application to geological conditions, either with or without groundwater, and their application to project specific conditions, the scope and the objectives of the thesis are presented (Chapter 1).

Then background information will be given about the state of the art grouting process including the purpose and requirements for the annular gap grouting with special attention to process engineering properties of the grouting material and the grouting process (Chapters 2 & 3).

The effects of grouting of the annular gap around the tunnel lining will be discussed as well as the effects on geology referring to the interaction of tail void grouting and tunneling induced settlements (Chapters 4 & 5).

The composition of the grouting material and its adjustment on the specific project requirements or geology including the specification of grouting equipment, are the basis for fulfilling the tunnel requirements such as the avoidance of settlement risks, the need for water-tightness and durability of the tunnel. This topic is dealt with in chapter 6 (Chapter 6).

The principal part of this thesis is the introduction of the dynamic grouting method where the superiority of this method will be confirmed by own developed and designed injection tests, by the use of specially defined optimum grouting material to the project specific requirements and by the grouting conditions. In this context first
the existing and state of the art single grouting system will be compared with the newly developed dynamic two component grouting method (Chapter 7).

Many cases of injection tests have been carried out within the thesis in order to evaluate the optimum combinations of grout specification, gap width, grout material and its concentration.

Finally, development of the dynamic grouting system and its application to actual construction will be discussed with the objective of presenting the most suitable and economical grouting system to avoid grout washout in the tail void in permeable soils, as well as have an optimal backfilling compound to fulfill the demands of a proper connection between the excavated void and the tunnel lining (Chapters 8 & 9).

In conclusion, the thesis will discuss the test results, with comments on best practice and the future outlook of TBM annular void grouting (Chapters 10 & 11).
Figure 1.3. Visualization of the thesis topics

- Geology and project specific requirements
  - Hard Rock TBM
  - Shielded TBM
  - Shielded hard rock TBM (with segmental lining support)
    - Backfilling of the annular gap with pea gravel
  - Shielded TBM (with segmental lining support)
    - Grouting of the annular gap with mortar
      - Purpose & Requirements
      - State of the art annular gap backfilling process
  - Shielded TBM (with segmental lining support)
    - Grouting through the segments
      - Effect on tunnel lining
    - Grouting through the tailskin
      - Effect on geology (Interactions between grouting and settlement)
      - Grout characteristics & grouting equipment
        - Single component grouts
        - Two component grouts
        - Development of dynamic grouting material
        - Dynamic grouting systems
          - Low Pressure variant: Design & Function
            - Development & Definition of an optimum 2-C mixing formula for highly permeable soils and against grout washout
            - Development of a test set up to test washout resistance of defined 2-C backfill mix
          - High Pressure variant: Design & Function
            - Premix variant: Design & Function
              - Comparison with existing grouting system
              - Application to actual construction
                - Discussion of test results
                - Conclusions & recommendations
CHAPTER 2
PURPOSE AND REQUIREMENTS OF BACKFILLING
OF THE ANNULAR GAP

The purpose of annular gap backfilling is primarily the minimization of settlement at the surface and the stabilization of the segment ring. This can be supported by

- A secure backfilling process that prevents material / soils entering the annular space.
- The stabilization of the bedding of the lining against sinking or buoyancy.
- Proper connection between the segmental lining and the ground (rock or soil) to
  • reduce the danger of axial compression during TBM operation
  • to seal the segments and shield tail seal against groundwater inflow (water-tightness – generally guaranteed by the use of gaskets in combination with annular gap grouting).

The purpose of the annular gap filling should be guaranteed continuously during shield operation. Therefore it is necessary that TBM advance speed, capacity of the grouting unit and the properties of the grouting component are coordinated.

The maximum grout pressure in the annular gap must be regulated to prevent damage to the shield tail seal, excess pressure on the segments and flow of the grouting material along the shield shell towards the tunnel face.

The consistency of the grouting component should be adjusted thus that the annular gap is filled properly to ensure an efficient bedding between the lining and the ground. It is also essential to adjust the setting behavior of the grout in such a way that the rigidity behind the shield shell is adequate to support the loads of the segment tube as well as stabilize its position in order to minimize surrounding ground deformations.
Requirements of the annular gap grouting must consider two conditions, namely engineering and supply requirements.

**Engineering requirements**

The grout is a composite material between the surrounding ground (rock or soil) and the structure (precast segments). The grout has to fulfill the following engineering demands:

- To prevent buoyancy and heave
- To prevent surface settlement
- To prevent misalignment of the segmental lining
- To bed the soil and segments into a single component.

The grout will be pumped into position either through the tailskin or through holes in the segmental lining itself. The grout needs to provide early support in the build area (EFNARC 2005, p. 17).

**Supply requirements**

The supply requirements cover the logistics of mixing, transporting and placing of the grout and are dependant upon the nature of the backfilling compound. The grout should fulfill following supply or logistical requirements:

- It should be pumpable to the point of placing without segregation or bleeding, independent of the time or distance necessary for the process.
- The working properties should be maintained for an unspecified period (up to 24 to 48 hours) in case of difficulties with the logistics.
- After being placed the material should
  - stiffen quickly to provide fast and secure support to segments
  - achieve an early strength to reduce subsidence or
  - prevent water washout.

(EFNARC 2005, p. 17).
CHAPTER 3
STATE OF THE ART OF THE GROUTING PROCESS

Grouting of the annular gap has a big influence on the load bearing performance of the tunnel tube. Two basic grouting methods can be identified, namely:

- Continuous grouting of the annular gap through the tailskin of the TBM and
- Grouting through injection ports in the segments.

For both of these grouting methods, one or more admixtures for the composition of the backfill grout can be used to provide a better control over the grout properties (EFNARC 2005, p. 17).

3.1 Grouting of the annular gap through the segments

Grouting of the annular gap through the segments takes place relatively late, so that in loose rock a caving in of material to the annular gap normally cannot be prevented. Thus the grouting is not always uniform and a pressure build-up in the backfill material cannot be adequately controlled. In hard rock, the secondary grouting through the segment or pea gravel injection with following mortar injection is state of the art. It is essential for the limitation of deformations and the load bearing performance of the built segment ring to have fast stabilization of the grouting material.

3.1.1 Grouting through segments in soft ground

Design and function of backfilling the annular gap through the segments in soft ground is as described below.
Design of grouting through the segments

With this variant of grouting system, the mortar is injected through ports or openings in the segments. The material injection into the annular gap will be realized in a radial direction. For this the segments are designed with openings in which sockets (sacrificial plastic non return valves) are placed. The socket is conical at the extrados of the segment. The top of the socket is slit at four spots in longitudinal direction. During ring building these sockets are kept closed.

When grouting through the segments, a distinction must be made between primary and secondary grouting. The effect of the primary grouting is to facilitate the bedding of the segments in order to minimize settlement during tunneling. If primary grouting is carried out carelessly this can lead to difficulties when building the next ring.

In tunnels with a circular cross section, insufficient bedding becomes apparent in a flattening of the tunnel crown.

Figure 3.1  Primary and secondary grouting (Maidl et al. 1995, p. 181, Fig. 7-6)
Task of secondary grouting through the segments is to fill the remaining cavities around the tunnel which resulted for example from the settling of the primary grout. The dimension of the settling is approximately 1 cm for each meter of shield diameter. Thus the secondary grouting can be limited in most cases to the tunnel crown.

Because of reasons of space, the secondary grouting is normally only carried out at the end of the TBM back-up system, approx 40 to 100 meters behind the shield. High pressure secondary grouting also helps to recompact the surrounding ground (Maidl et al. 1995, p. 182).

Procedure of grouting through the segments

Grouting through the segments cannot be carried out until the grout port has cleared the tailskin seals. As a result unstable ground is likely to collapse onto the lining before grouting can be carried out (Shirlaw et al. 2004, pp. 1-8).

Before the grouting process starts, each socket has to be connected with a hose which delivers the injection material. When the pump is switched on, the pressure in the hose and thus in the sockets rises, forcing the flaps of the non return valve to open outwards and permit the flow of grouting material into the annular gap between segment extrados and ground. At the end of the grouting process the pumps will be switched off and the pressure in the lines will drop causing the socket or non return valve to close. The hose is then removed and the sockets remain in the segments.

3.1.2 Grouting through the segments in hard rock

The use of segments is essential in hard rock tunneling where the use of grippers against the open excavated tunnel wall is unable to provide an adequate thrust reaction in the surrounding rock due to low rock strength. In such cases the thrust force for TBM advance has to be transmitted via the tunnel lining, functioning as an abutment in longitudinal direction of the tunnel. Thus, the lining must be
capable to withstand the total TBM thrust that cannot be guaranteed by a shotcrete shell or in-situ concrete shell (Maidl et al. 1995, p.273).

The annular gap, which is the space between the extrados of the segment ring and the soil, will be filled by injection with a suitable medium through appropriate openings in either the segments themselves or through the tailskin. Thus a loosening of the rock will be restricted and a continuous introduction of external stresses resulting from rock thrust in the tunnel lining will be enabled, providing the bedding which is necessary for the stability of the tunnel lining.

Reinforced concrete segments are used almost exclusively today (Maidl et al. 2001, p. 273). They have replaced to the greatest possible extent the steel or cast iron segments for economical reasons. Besides the soft ground tunnelling, the reinforced concrete segments form also the tunnel lining for shielded hard rock tunnelling.

Shielded hard rock TBMs are open-faced shields without a closed pressure compensation system at the tunnel face to counteract or balance earth and groundwater pressure. If the natural stability of the tunnel face is not sufficient, stability will be achieved mechanically. In conditions above the groundwater level or with little seepage water the annular gap is usually backfilled with fine-grained and narrow-graded gravel. Alternatively, in conditions with low stability and within ranges where groundwater is present, the annular gap is backfilled with mortar.

**Backfilling with gravel**

During advancement of a TBM in hard rock the annular gap will generally be backfilled with a fine-grained and narrow-graded gravel.

The annular gap backfilling should take place as soon as possible after the ring was built. For this openings in the segments should be foreseen to fix the grout lines.

In hard rock, injection of pea gravel into the annular gap followed by secondary grouting is state of the art. In this connection the pea gravel (8-12mm diameter) will be blown into the annular gap through openings in the segments as closely as possible behind the TBM.
It has been demonstrated that both pea gravel with rounded edges and crushed material distributes well in the annular gap. However, uniformity of the material is essential and the absence of fines which cause a cementing of the granulated material.

A spring plate between the tailskin plate and the rock helps to prevent a penetration of pea gravel into the steering gap. Vibrations of the TBM can cause a compaction of pea gravel so that a second blow is normally necessary.

About four to five rings behind the TBM, the pore space of the placed pea gravel will be filled in with a small viscous cement suspension in the bottom area to waive the drainage effect of the water transmitting annular gap. Thus the bottom segment will be secured in its position during loading by the back-up (courtesy of Herrenknecht AG).

About thirteen rings behind the TBM, the pore space of the pea gravel in the roof area can also be filled with cement suspension. In a second-operation work the annular gap will be repressed with a cement suspension with a lower pressure of about
2-3 bar. The annular void is now completely filled with a sufficiently stabilized material.

In the case of existing deformations, the direct bearing capability and relatively rigid segmental lining directly resists the deformations after the shield passage in connection with the annular gap backfilling. This can cause excessively high stresses in the case of high overburden or in swelling rock which cannot be taken up in extreme cases by the lining. Therefore efforts were undertaken to develop flexible lining systems which permit controlled convergence of the excavated cavity. By the use of a special mixture for the annular gap backfilling, a flexible support can also be realized with concrete segments, for example the use of a mixture of polystyrene balls and sand. Cement-milk-encased polystyrene balls would also be appropriate whereby the problem of separation would be avoided (Maidl et al. 2001, p.282).

Figure 3.3 Tests with a flexible backfilling material with high potential of deformation (Maidl 2001, p.282, Fig. 15-11)

Backfilling with mortar

In hard rock tunnelling where the geological conditions are characterized by a rock mass of low stability the annular gap will be grouted with mortar. As a general
rule, the backfill mortar is not taken into consideration as part of the static calculation of the tunnel, so there are no special requirements as regards its final compressive strength.

To achieve a good pumping of the backfill material, the mortar should show a sufficient flowability. When backfilled, a portion of the mixing water in the mortar will be released to the surrounding rock which activates the grain structure of the mortar as supporting medium. The amount of released water depends on the rock structure. But the release of filtration water can also result in a loss of volume of the backfill material in the annular gap. The extent of the loss of volume should be limited by a possible low water/high solids content in the backfill mixture.

A high compactness of the ground is reached by the addition of fine-grained components such as fly ash. For a quick stabilization of the granular structure, cement is usually used as the bonding agent. Retarding and stiffening behavior of the mortar must be adjusted in such a way that the mortar in the injection lines can still be easily injected even after longer TBM downtimes in order to minimize necessary flushing and cleaning measures of the injection lines.

The grouting of the annular gap can be realized through openings incorporated in the segments or simultaneously with the TBM advance by injection lines in the tailskin (see Figure 3.4).
Figure 3.4 Schematic diagram of the two grouting methods, backfilling through the segments and backfilling through the tailskin.
Grouting the annular gap through the segments requires that they are equipped with threaded connection pieces and optionally with sacrificial plastic non return (or check) valves to connect the grouting hoses. As a condition for a settlement controlled TBM advance process, the grouting material has to be injected as close as possible behind the shield. With the development of efficient shield tailskin sealing systems, the grouting of the tail void is now possible directly through the tailskin. Dependent on the diameter of the shield, a minimum of 4 to 8 injection lines are arranged at the periphery of the tailskin through which the mortar is injected into the annular gap. With this arrangement it is possible to grout simultaneously with the advance of the shield dramatically reducing penetration of soil into the gap. With continual filling of the annular gap as the TBM advances, the grouting between the rock and tunnel lining prevents a possible loosening up of the rock (courtesy of Herrenknecht AG).

The stabilization of the grouting mortar is essential for the limitation of deformations and the load bearing performance of the new built segment ring. The grouting mortar should therefore have good flow properties during the injection phase. After grouting, the mortar should be capable of taking up high shear stresses. To avoid negative effects on the operation process of the TBM, the hardening of the grouting mortar should not take place too fast. The mix proportions of the grouting mortar is therefore of particular significance.

3.2 Continuous grouting of the annular gap through the tailskin

The following describes the design and functioning of conventional grouting through the tailskin.

3.2.1 Design of conventional grouting system through the tailskin

Grouting in this manner has successfully been carried out for many years. Normal mortar is injected into the annular gap with one or more double piston pumps
or rotor pumps. Via a system of pipes in the shield shell the mortar is transported to the annular gap. The injection mechanism works in an axial direction and not in a radial direction as for the case when grouting through the segments.

The pipes in the tailskin are of oval section in order to maximize the flow cross sectional area with the lowest possible height. If the lines would have a circular cross section, either the wall thickness of the tailskin would have to be considerably larger or the lines would protrude into the inner area of the tailskin. Consequently the tailskin would be considerably heavier and damage to the lines during curved drives or similar would occur.

The oval lines have the same cross section of a comparable circular pipe with a nominal diameter of 50-60mm. The grouting mortar is pumped through a hose into the oval grouting lines (only oval because of reasons of space).

If the hardening of the mortar should be accelerated it is possible to mix it with additives, of which there are several variants available. One is the mixing of the mortar directly on the back-up of the TBM and the other variant comprises the addition of accelerator to the mortar mix at the point of injection into the annular gap. For the last variant, the grout line incorporates a further smaller line through which the accelerator is injected. Despite the similarity to the two component system which will be described later in this thesis, this grouting process differs from the two component system in the way that the addition of accelerator can be stopped at any time and go on with the injection of mortar without additives.

Since the mortar is quite reasonable, the system will still remain a standard variant for the annular gap backfilling.

3.2.2 Functioning of the conventional grouting system through the tailskin

The current state of the art of grouting the annular gap in soft ground is grouting immediately behind the shield through the tailskin, proving to be especially advantageous in soils which tend to sink like cohesiveless soils. The grouting of the
annular gap through the tailskin is both volume and pressure controlled to minimize potential surface settlement. The aim is a non positive bedding between the tunnel tube and the soil.

Grouting in this manner prevents excessive deformations of the segment rings and damage to the segments. A synchronization of grouting and shield advance leads to less ground entering the annular gap. Secondary grouting can thus be avoided as the gap due to settlement of the grout is constantly refilled.

During the tunnel boring process the grout is being pumped in the annular gap through a number of injection openings that are distributed around the circumference of the shield. Generally six or less injection openings are used. From these, the principal grout flow takes place in tangential direction to fill the annular gap. See Figure 3.5. The flow pattern is governed by continuity and differences in flow-resistance (Talmon et al. 2001) and is influenced by time effects because of ongoing hydration of cement and liquid loss.

The Dutch government established the Delft Cluster, a foundation in which the leading Delft Institutes on civil engineering co-operate, to invest increasingly in research and knowledge development in civil engineering. Geo Delft and Delft Hydraulics, together with participating end-users have initiated research to develop an understanding of the flow process involved in grouting. The philosophy was to focus on the physics of the rheological processes and to incorporate these in a mathematical model for the calculation of grout pressures around a tunnel lining (cited by Talmon et al. 2001). Thus two different grout injection strategies have been simulated, one with six equally distributed injection openings and the second one with only three injection openings.
Figure 3.5  Schematic of grout flow pattern in the annular gap. The grout is injected through six equally distributed injection openings (cited by Talmon et al. 2001, p.1, Figure 1)

With six injection openings the pressure distribution is equal. They are equally spaced at 60 degree intervals starting from the crown of the tunnel. In the case of only three injection openings, they are equally spaced at 120 degree intervals starting from the crown of the tunnel. Generally six openings will be installed in most shields with the possibility of activating only three openings when possible. The calculated grout pressures are shown in the following Figure 3.6 & Figure 3.7.

When using a small number of injection openings, the grout has to travel a longer distance. In this case, the pressure distribution may be affected to such an extent that the static pressure contribution may be obscured completely (Figure 3.6).

The distribution of the grout pressure is nearly static when grout is supplied by uniformly distributed injection openings (Figure 3.7).
Figure 3.6 Calculated pressure distribution at rear of TBM (3 injection openings near crest). Pressures at 0 and 4.1 m behind TBM (cited by Talmon et al. 2001, p. 5, Figure 5)

Figure 3.7 Calculated pressure distribution at rear of TBM (6 injection openings equally distributed). Pressures at 0 and 4.1 m behind TBM (cited by Talmon et al. 2001, p. 5, Figure 4)

The flow pattern is governed by both the continuity and the differences in flow resistance and determines the gross distribution of grout from the injection openings.
Differences in flow resistance govern local flow. Radial outflow will take place near the injection openings. The drag due to the velocity difference between moving grid and stationary frictional boundaries (the walls) is constant in the tail void. Consequently this will not lead to deviations from radial outflow.

However the pressure distribution along the first few meters behind the TBM, before the grout is hardened, is influenced by buoyancy and the stiffness of the tunnel lining.

Backfilling through the tailskin can be carried out directly when the annular gap emerges. With a simultaneous grouting through the tailskin during TBM advance the penetration of the soil into the annular gap can be reduced. A secondary grouting can be omitted because the cavity caused by settling of the grouting compound will permanently be filled.

Grouting through lines in the shield tailskin requires, in the event of stoppage or blockage, a method for rapid cleaning of the grout lines to prevent blockages caused by hardened mortar.
CHAPTER 4
GROUTING OF THE ANNULAR GAP WITH
SINGLE COMPONENT GROUTS AND EFFECTS ON THE TUNNEL LINING

Grouting the annular void is an injection of material between two boundaries, soil and lining. The grouting material flows inside the annular gap as long as the displacement of the tube which is caused by buoyancy is not stopped due to Archimedes' law.

The injected quantity of grouting material in the annular void depends on its pressure and compressibility. The final balance position depends on the rheological properties of the grouting compound when being injected and on the annular void thickness. When the relative displacements have stopped, the pressure that acts on the lining is the fluid pressure. The fluid pressure results from the flow just before it has stopped. At that time the soil and lining kinematics are not connected but when the grout has hardened, the soil load may act directly on the tunnel lining. As such, the grout acts only as a transfer medium. Its stiffness and strength has little impact; the stress redistribution is mainly governed by the soil and concrete creep.

4.1 Pressure and loads

Usually the grouting pressure will be selected such that it will be higher in the entire annular gap than the pressure resulting from overburden and groundwater.

With increasing distance from the injection openings the pressure in the mortar decreases because of the cohesive resistance of the mortar and the friction between grouting mortar and soil. Thus the flow path of the mortar is limited. See Figure 4.1.
Figure 4.1 Pressure distribution in the annular gap during grouting and parallel pushing forward of the sealing (Winselmann et al. 2000, p. 334, Figure 15)

Within the context of a research program, which was accomplished in cooperation with Philipp Holzmann AG, formerly a major German construction company, and Herrenknecht AG, the flow behavior and the pressure ratios of selected mortar mixes were examined in a simulated annular gap.

The flow or spreading behavior of the mortar in the annular gap could be made visible for the first time with colored tracer mortar. The apparatus employed for the investigation of the flow was a tank construction which reflected the dimensions in the annular gap and which could be filled under pressure.

In principle an arc-shaped penetration in the annular gap was observed with the examined mortar mixes (single component grouts).
The specific spreading behavior of these mortar mixes was also confirmed by the pressure values at the slide: with stiffer material, the value at the pressure transducer installed at the greatest distance from the injection point is the lowest because the higher shear strength absorbs the pressure more than with a more liquid mixture with which the pressure distribution is relatively constant along the slide (Thewes 1997, p. 1-20). Thus the above statement that the pressure in the mortar decreases with increasing distance from the injection opening could be verified from this practical test.

A too high grouting pressure in the annular gap can cause temporary or permanent damage to the segments and, in extreme cases, a reduction of the diameter of the segment ring.

A displacement of the ring being grouted relative to the connected ring that is still in the protection of the tailskin will be initiated if it is stressed by grouting pressure. The required pressure in the annular gap should be approximately equal to the actual resultant of earth and water pressure. A pressure of approx 1 to 2 bar too high generates an unacceptable surface pressure on edges and joints of the segmental lining.

Correct annular gap grouting should achieve a constant grouting pressure along the entire periphery and uniformly prestress the soil. The prestress of the soil acts not only during the actual grouting process, it is analogous to the bedding reaction in the soil – depending on the creep quality – permanently active. This means, that the ratio between horizontal and vertical tension that acts on the segment ring, is compared with the primary status, clearly balanced, which essentially reduces the deformations and the bending stress of the tunnel lining (Winselmann et al. 2000, pp. 327-334).

An essential requirement for efficient backfilling of the annular gap is the availability of suitable grouting equipment, to enable the tailskin gap to be completely filled at constant pressure in a controlled manner (Babendererde 2000, pp. 35-40).

Even with efficient grouting of the tail void, the rear part of the ring which will be subsequently loaded by the TBM advance thrust is critical because the ring is
to a great extent still not bedded within the protection of the shield. The hardening of the grouting mortar is not complete by the time the TBM advance thrust forces are exerted. Thus a movement of the segments cannot be prevented. When the ring comes out of the shield, extreme twisting may occur that might result in damage to the segments in form of spalling at the corners and edges at the contact surface. This is be described in more detail below.

The following external forces act on the tunnel ring:

- Pressure loads caused by the tail void grouting
- Lifting forces caused by buoyancy from possible groundwater to which the ring is subject as soon as it leaves the tailskin
- Weight of the TBM back-up acting on the segment ring in a downward manner as soon as the first pair of wheels reaches the ring.

With the development of a two component grout, the goal can be attained to have a grout mix that is optimized with regard to reduced time for setting (hardening process). External forces can then be taken without resulting damage.

Movements of the segment ring before it reaches the final bedding condition is considered to be the principal cause of damage to the segmental lining. Such movements can be caused by a too fast TBM advance procedure not allowing the consolidation process of the grouting material to be completed.

A special case is eccentric pressurization of the segment ring with grout. The ring that leaves the tailskin is effected on one side by the grouting while the other side is still in the protection of the tailskin. This results in a twisting and tilting of the segments towards the ring which was built before and the one following.
The pressurization on one side of the ring with injection material while the other side is still protected by the tailskin can cause asymmetrical pressure ratios. They are concentrated in the key stone area because the key stone presents the weakest point in the ring. This one displaces then downwards and will be twisted during the next TBM advance by the compression of the rings with resultant spalling and cracking of the segments. But cracks, spalling and deformation can also indicate that there is a lack of bedding due to an incomplete process of consolidation of mortar during loading or an incomplete grouting of the annular gap, especially in the crown.

A slow setting (hardening) process can lead to the floating of the tunnel tube with the consequence that it is susceptible for displacements by forces effecting the tube.

When TBM advance resumes after ring build, the newly installed ring is completely within the shield tailskin and subjected to the full thrust force. In this critical state, the ring that is not bedded yet is subjected to high longitudinal normal forces. The individual segmental rings are each independently subjected to the TBM advance forces. Each individual segment will shift until it has reached a stable position.
Since the loads from the TBM back-up weight and buoyancy cannot be prevented, the movements of the tube must be resisted with a faster setting (hardening) process. For this the cement factor of the injection mortar can be increased so that the hydration will be accelerated.

The combined effects of various factors such as curved tunnel alignments, fast TBM advance procedures, asymmetrical grouting pressures and additional loads in the form of TBM back-up weight, buoyancy, restricted tailskin sealing etc. all have an influence on damage to the tunnel lining. This thesis examines the development of a two component grouting material where the backfill composition and properties can be defined and adjusted to avoid the above effects and damages to the tunnel lining, stepping into a new and optimized grouting technology.

4.2 Bedding of the tunnel lining

In order to obtain an early and reliable bedding of the tunnel lining and to keep the segment rings during the building process in their positions, the annular void between the segment rings and the soil or rock has to be backfilled continuously during the tunnel operation.

Basic condition for a qualitatively high grouting is that the annular gap behind the tailskin will be continuously and reliably filled without cavities. Annular gap grouting taking place simultaneously with the TBM advance process is a prerequisite for a settlement free tunnel boring process. Continuous data recording, already state of the art in today’s tunnel boring process, must be employed to ensure that these requirements are fulfilled.

Uneven grouting can easily occur in the crown of the tunnel, generally due to a lack of volume stability. Thus there is a high danger of cavities in this area with the consequence of incomplete bedding of the key stone and subsequent susceptibility to damage.
An insufficient bedding of the segment ring in the soil and resultant damage to the segments can be originated by

- a reduced flowability of grout
- sedimentation features within the grouting material
- injection of harder grouting material remainder.

If continuous mixing of the grouting material does not take place, then flowability of the grouting mortar is reduced resulting in an incomplete bedding of the segment ring, in turn inducing both damage to the segments and surface settlements.
CHAPTER 5
INTERACTION BETWEEN TAIL VOID GROUTING
AND TUNNELING INDUCED SETTLEMENTS

During the course of excavation it is the task of the shield and the excavation system to support the ground until the final lining is installed. In order to fulfill this function the tunnel lining has to resist the active ground pressure and retain penetrating groundwater. For the majority of tunnel projects where extremely low limits of settlements are required special efforts are taken with tunnelling works. Minimum settlements and minimum ground disturbance will be achieved by exercising permanent support on the tunnel face, within the shield area and behind the shield.

This chapter deals with the settlement components during tunnel boring operation, settlements on surface and the settlements due to the grouting process.

5.1 Settlement components during tunnel boring operation

Loosening and disturbance of the natural layering of the ground around the void leads to stress dislocation and thus ground movements which may result in surface settlement.

Recent developments in tunneling technology allow for reductions in the disturbance of the ground surrounding the tunnel and the resultant stress redistribution and surface settlement. Generally settlement should be limited to 1:500 to avoid damage to flexible structures and 1:1000 for rigid, more sensitive buildings. In complex projects the main consideration will be the reduction of settlement to an absolute minimum.
The following factors influence the scale of settlement during a shield drive:

- Unexpected changes of ground condition.
- Insufficient support to the tunnel face.
- Insufficient support to the ground around the shield skin.
- Movement of ground caused by curve negotiation and steering corrections.
- Settlement caused by insufficient grouting of the segment ring annulus.

The grouting process which determines the loading on the tunnel lining is of importance with respect to subsurface settlements. This aspect will be highlighted in this thesis and commented upon in the following sections. The factors listed above that are not related to grouting will be ignored.

**Shield tunneling**

Settlements during shield tunneling can be sub-divided into the following categories:

- Settlement ahead of the TBM.
- Settlement above the TBM.
- Settlement behind the TBM.

These are indicated in the figure “Settlement Categories” (Settlement pattern during shield tunneling) below.
Figure 5.1 Settlement Categories (Maidl et al. 1995, p. 20)

Phases 1 & 2: Settlement due to ground water lowering or face excavation caused by the change of primary stress in tunnel lengthwise direction.

Phase 3: Settlement during passing of the shield due to structural transformation because of the driving of curves (overcut) and vibrations caused by the shield due to compaction of the soil around the shield; insufficient support of the void around the shield skin.

Phase 4: Settlement due to insufficient backfilling of the annular gap.

Phase 5: Following settlement as a result of draining of mixing water for grout into the excavation chamber and because of stress redistribution by shrinking of the setting of the mortar.
Insufficient backfilling of cavities during the annular gap grouting is frequently the main cause of settlement.

The first two settlement categories, settlement ahead of the TBM and settlement above the TBM, will be neglected within this thesis because the choice of the tunneling system and shield details itself are directed towards the reduction of settlement.

Focusing solely upon the grouting process, the topic of this thesis, possible resultant settlement behind the TBM is of interest.

**TBM Design**

The grouting of the segment annulus directly affects both the surface settlement and the quality of the ring build. The mortar injected serves directly to bed and backfill the segmental rings. The pressure of injection must be sufficient to guarantee complete filling of the annular gap, but should not exceed the static capabilities of the ring itself or lead to damage of the tailskin seal. Therefore the prescribed injection pressures and volumes should not be exceeded. This is achieved by using a volume control system with an overriding pressure limitation which is dependent upon shield advance rates.

The quality of the mortar used is a significant factor in restricting ring movement and distortion and in achieving complete filling of the ring annulus. A high sand content contributes considerably to the effectiveness of the mortar.

Each grout injection port is served by its own individual supply line, fed by a peristaltic pump. In this way exact control of the annular injection is accomplished around the tunnel circumference. The advantage of the peristaltic pump is that its supply is continuous as no suction stroke is required.

The equipment can be used either in manual, semi-automatic and automatic modes from the local control station or from the machine operator cabin. The parameters set for the grout injection system can be set via the visualization and the volumes of grout and pressures of injection recorded. See following Figure 5.2. The allocated limiting values for grouting parameter can be incorporated in the PLC and

The functioning of the various modes of operation are as follows:

Manual operation:

In manual mode the four injection pumps from pump A1 to pump A4 (see right column in Figure 5.2) are switched on and off individually via the control panel. The torque of the pump follows the position of the potentiometer which is controlled proportionally. Position of potentiometer at 50% in this case means half speed of rotation. If the annular gap is saturated with grout the corresponding injection point can be switched off via the injection pressure which is measured directly before the pilaster strip.

Figure 5.2 Grout Injection Parameters (CFJH4-DR2B2-2B9C4-JRB3M-DWC6G, GP6.0 1065, S-240/S-241, 18.12.2002, Herrenknecht AG)
Semi-automatic operation:

In semi-automatic mode the four injection pumps are switched on and off individually via the control panel. Activation of the injection points corresponds to manual operation. The difference is in switching on the injection points. In case of a new start of injection the injection point has first of all been switched on manually, during operation it is automatically switched on and off via the adjusted injection pressures.

Automatic operation:

In automatic mode the four injection pumps are individually switched on and off via the control panel. The required instantaneous grout injection quantity is calculated on the basis of the following parameters:

- Segment length in tunneling direction
- Injection quantity / advance
- Exceed grout quantity
- Share pump A1 - A4 → Total quantity
- Advance speed

As the pressure in the ring annulus is such an important parameter with respect to ground settlement a method of including pressure sensors in the steelwork of the tailskin as well as in the lines feeding through the tailskin has been developed.

These pressure sensors and surrounding steelwork are coated to resist adhesion of the injection mortar. See Figure 5.3.
The total number of pressure sensors is variable with cables being laid in the steelwork of the tailskin. Values from these pressure sensors are collected and integrated corresponding to the values from the standard sensors in both the data acquisition and the visualization (courtesy of Herrenknecht AG).

In order to prevent groundwater ingress into the shield, the annular gap is restricted at the end wall by a fixed sealing construction relatively to the tailskin in tunnel longitudinal direction. The gap between the segment and the inner surface of the tailskin plate will be tightened either with a rubber profile, with wire brushes or with spring steel plates. The common sealing is the wire brush seal. The more rows of wire brushes used the more the settlement risk will be reduced that may result from damage to a row of brushes. The chambers formed between the rows of wire brushes are filled with sealing grease by a pressure and volume controlled system. The sealing grease is fed into distribution ring mains by a pump situated on the TBM back-up.
**TBM Back-up system**

During actual TBM advance the time interval, which is available for the mortar, decreases at high advance speeds before the segment ring is loaded with external stresses like the weight of the TBM back-up or buoyancy from the groundwater.

The shield is followed by the first section of the TBM back-up system which is moveable. Because of its weight, the back-up system can exert a pressure downwards on the segment ring if the grout in the tail void is not sufficiently hardened with the result that the segment ring can then be pressed out of its form. This can cause an oval segment ring and consequently apart from cracks and spalling in the crown or on segments also an insufficient bedding and thus the danger of settlements on the surface.

As well as direct damage, e.g. by large point loads when using walking legs in the TBM back up that directly transmit the weight of the back-up to the tunnel lining, indirect damage in the crown of the tunnel lining can also result from back-up loads.

The walking legs transfer point loads on the segment in the invert. In the case where the grouting material is not sufficiently hardened, there is practically no support effect present so that lateral forces can be developed in the ring, in turn creating cracks.

### 5.2 Settlements on the surface

To avoid or reduce settlement behind the shield the annular gap has to be backfilled immediately during the tunneling process at the point of origin. Therefore mortar is injected under pressure. The original state of stresses of the soil can therefore be maintained to a large extent. The smaller the redistribution of stress in the soil body, then the smaller the soil movements will be kept which will show up at the surface as settlement (Jancseez et al. 2001, pp. 165-214).
In practical operation the settlement cavities were measured rectangular to the tunnel axis at the time \( t \) on the surface. They correspond to the function of a Gaussian distribution curve in their geometry (Figure 5.4).

**Figure 5.4** Shape of settlement trough caused by the tunnel operation. Description of the parameters (Jancsecz et al. 2001, p. 166)

The shape of settlement trough may be approximated as a normal probability distribution (Gaussian distribution curve) and expressed as:

\[
s(x) = s_{\text{max}} \cdot e^{-\frac{x^2}{2i^2}}
\]  

(5.1)

- \( s(x) \): Settlement at surface in distance \( x \) from the tunnel axis [m]
- \( s_{\text{max}} \): maximum settlement above tunnel crown [m]
- \( x \): Distance perpendicular to tunnel axis [m]
- \( i \): Distance of the point of inflection of the settlement cavity from the tunnel axis [m]

(cited by Ebenhöig et al. 1999).
The range of the settlement cavity is calculated by means of the inflection point. This represents the turning point of the Gaussian distribution in the distance $i$ from the tunnel axis. In dependence on the soil conditions and the tunneling method the range of the settlement cavity was measured based on a number of projects. The overall width of the settlement is in the range of $4\cdot i$ and $10\cdot i$.

Taking the Gaussian distribution as a basis, the width of the settlement cavity as well as the ordinates of the final settlement can be determined by calculation.

The settlement cavities developed at the surface correspond quantitatively to the withdrawal of soil and the deformation in tunnel direction as well as to the radial ground deformation. The relationship between the volume of the settlement cavities and the theoretical volume of excavation is described as ground loss in tunneling practice. The modern, mechanized and face supported state of the art tunnel boring machines permit only low stress redistribution and associated settlements. Essential for this are the precise operation of the shield and the nearly perfect realization of the annular gap grouting. The specific ground loss is therefore a quality parameter for shield tunneling. In order to comprehend the quality of tunneling, a tunnel drive with a specific ground loss $v_L$ of 0.8 % is categorized as a drive with small settlements (cited by Ebenhögl et al. 1999).

In such a way settlements can be determined as function of following input values:

- The specific ground loss $v_L$,  
- The empiric determined position of the inflection point $i$,  
- The tunnel diameter $D$,  
- The overburden above crown.

The settlements can therefore be formulated as function $s = f(v_L, i, D, i)$. The method after O'Reilly and New as well as a further method are applied to describe the range of the settlement cavity which works with the critical angle $\beta = f(\phi)$ of the settlement cavity. The decisive parameters determine themselves as follows:
Calculation of settlements (O’Reilly et al. 1982, pp. 173-181):

\[ s_{\text{max}} = \frac{v_l}{i \cdot \sqrt{2 \cdot \pi}} \cdot \frac{D^2}{2} \cdot \pi \]  
(5.2)

\[ i = 0.28 \cdot z_0 - 0.1 \text{(m)} \]  
(5.3)

\[ s = s_{\text{max}} \cdot e^{\frac{x^2}{2x^2}} \]  
(5.4)

Calculation of settlement with the critical angle \( \beta \)-theory:

\[ \beta = 45^\circ + \frac{\Phi}{2} \]  
(5.5)

\[ s_{\text{max}} = \frac{v_l}{i \cdot \sqrt{2 \cdot \pi}} \left( \frac{D}{2} \right)^2 \cdot \pi \]  
(5.6)

Point of inflection \( i(\beta) \) as \( f(\beta) \):

\[ i(\beta) = \frac{1}{3} \left[ \frac{D}{2 \cdot \sin(\beta)} + \left( \frac{t + D}{2} \right) \cdot \frac{1}{\tan(\beta)} \right] \]  
(5.7)

\[ s = s_{\text{max}} \cdot e^{\frac{x^2}{2x^2}} \]  
(5.8)

with

- \( z_0 \): Depth of tunnel axis (\( t + D/2 \))
- \( \Phi \): Inner angle of friction of the soil
- \( D \): Excavation diameter
- \( t \): Overburden above crown
- \( v_l \): Specific ground loss
- \( x \): Control variable rectangular to the tunnel axis [m].

Surface settlement cavities can be determined by the use of the above method of calculation. The majority of the existing database consisting of measurements at the surface is based upon the two calculation methods described above.
It is pointed out that this modified calculation procedure supplies incorrect results for high values of \( z \) (i.e. foundations near the tunnel roof). In cases where the difference in level between tunnel roof and foundation level is higher than the difference in level between foundation level and surface of land \((t-z)>z\), the procedure provides reliable results. Figure 5.5 illustrates the dependence on depth of the settlement cavity.

Figure 5.5 Dependence on depth of the settlement cavity (Jancsecz et al. 2001, p. 170, Figure 3)

It becomes obvious that with increasing overburden above crown the maximum settlement contributions in tunnel axis decrease and the range of the settlement cavity increases. The settlement of one foundation below surface in loose soils can be calculated with the “O’Reilly and New” method only with the assumption that one settlement cavity below surface is based on the same soil mechanical context than a settlement cavity on surface.
5.3 Settlements due to grouting process

The percentile of the settlements during shield passage is specified with a predetermined value of the settlement cavity in tunnel direction with 20 to 50% of the final settlement. Here the settlements that occur while the shield underpasses the considered point will be considered. This portion of settlements is influenced by overcut and the conical profile (if any) of the shield (Jancsecz et al. 2001, p. 176).

Settlements which arise from the annular gap grouting and temporarily retarded settlement procedures may be described as follow-on settlements. They occur after the shield passage. Due to the difference between the diameter of tailskin and the outer diameter of the segmental lining an annular gap develops at the tailskin. The annular gap (hollow space) is continuously grouted during TBM advance such that the difference in diameter is compensated.

The necessary quantity of grouting material is determined in such a way that the annular gap at the tailskin at profile cut and possible overcut is balanced. In such a way settlement that occurs due to closure of the annular gap are minimized. The rate of grout injection is determined in dependency of the TBM advance speed. From practice it is well-known, that the theoretically required quantity of injection/grouting material can be exceeded for a complete backfilling of the annular gap with grouting compound of up to 20 to 35%.

Nevertheless settlement may also develop, even with correctly accomplished annular gap grouting, dependant upon the material properties of the grouting material, and upon the development of strength as a function of time. They are included with 30 to 50% of the final settlement in the predicted calculations. Possibly elevations can be produced by an increased grouting pressure within this range and thus the overall dimension of the settlements can be reduced.

With this calculation method the path of the individual settlements is approached in sections by a Gaussian distribution. The referred distance for the settlements during shield passage is by definition the shield length. The corresponding length of the forward settlements results from the sliding angle in the Rankine special
case and the depth of the tunnel, while for the follow-on settlements a distance of one
tunnel diameter is determined. With the application of this method related to the
position of the shield, the settlement in tunnel axis can be determined.

In summary the settlement components can be recorded as follows (Jancsecz
et al. 2001, p. 165-207):

- Forward settlement: 0 to 15%,
- Settlement due to shield passage: 20 to 50%,
- Settlement due to annular gap grouting: 30 to 50%.

These values are verified by way of practical experience gained in tunneling
with slurry supported tunnel face in cohesive soils.

An understanding of the fundamental behavior of the grout in the annular gap
is needed in order to relate operational grouting conditions with grout pressures in the
tail void. To control soil deformations and forces acting on the tunnel lining, the grout
pressures along the first few meters behind the TBM have to be matched carefully
with the surroundings.

**Grouting pressures during tunneling**

The grouting pressures determine the loads exerted on the lining and on the
soil around the tunnel.

The grouting pressures for backfilling the annular gap at the end of the tailskin
have to be adapted to the geotechnical, hydrogeological and surrounding structural
conditions such as, for example, tunneling in urban areas with low overburden
between the tunnel crown and the foundations of the buildings or the minimum
distance to underground structures such as traffic or utility systems. To guarantee a
good distribution of the grouting mortar along the annular gap and thus a
circumferential bedding, a grouting pressure is required which is adapted to the these
conditions. The composition of the grouting mortar is important. It should be
constituted in a way that a fast support of the grain structure is given. Together with
the volume of grouting material, the grouting pressure represents another criteria for
the success of the tail void grouting. See following Figure 5.6 that shows the grouting
pressures at the grout lines dependant upon the respective differential water pressure to the shield axis.

Figure 5.6  Idealized pressure distribution at the shield shell after grouting of the annular gap (Jancsecz et al. 2001, p. 176, figure 7)
The required grouting pressures are determined as follows:

- Calculation of the total vertical tensions in the shield axis (see Appendix A).
- Distribution of the grouting pressures along the grout lines dependant upon the water pressure above shield axis.

Thus a distribution of the grouting pressures to be applied is set which is higher in the crown than in the total vertical stresses and which is lower than the calculated total stresses in the bottom. This method of calculation has been proven for the determination of the grouting pressures for the filling of the annular gap. See Figure 5.6 which represents the necessary distribution of the grouting pressures around the tunnel profile.

Accordingly, the differential water pressure for all grouting points above the shield axis will be subtracted from the total stresses in the shield axis and will be added for all points below the shield axis.

The following explains the grout pressure around the tunnel lining due to buoyancy forces after boring.

**Grout pressures due to buoyancy**

The tunnel lining, the grout and the soil are always enclosed by groundwater in soft ground tunneling. If the lining is in contact with the grout, then the grout is loaded by the water pressure and contact stresses between the lining and the grout.

If the lining is surrounded by liquid grout it can float upwards when it is released from the TBM. Grout has to provide sufficient resistance to overcome the buoyancy forces that occur in the first rings after the TBM. The buoyancy forces occur if the average density of the tunnel lining and the air that form the tunnel is less than the density of the grout.

The grout mortar can be designed to minimize buoyancy forces by reducing the density and/or decrease the yield strength. The yield strength changes the pressure distribution over the lining. On the assumption that the shear strength between the tunnel lining and the grout is small and the shear strength between the soil and the
grout determines the pressure distribution, the relation between the yield strength and the maximum buoyancy force that can be compensated by the grout mortar can be written as follows (Bezuijen et al. 2005, pp. 7-12):

\[ F = \tau_y \frac{D^2}{s} \]  

(5.9)

\( F \) = maximum force per meter tunnel lining that can be compensated by the yield stress in the grout.

\( \tau_y \) = shear strength of the grout

\( D \) = diameter of the tunnel

\( s \) = width of the tail void.

The buoyancy force \( k \) per meter lining exerted by the tunnel lining can be determined as follows:

\[ k = \frac{\pi}{4} D^2 (\rho_g - \rho_r)g \]  

(5.10)

\( \rho_g \) = density of grout

\( \rho_r \) = average density of the tunnel (lining and air)

\( g \) = acceleration of gravity

The equilibrium in a stable cross-section is reached when \( F \geq k \):

\[ \tau_y \frac{D^2}{s} \geq \frac{\pi}{4} D^2 (\rho_g - \rho_r)g \]  

(5.11)

\[ \tau_y \geq \frac{\pi}{4} s (\rho_g - \rho_r)g \]  

(5.12)

A stable cross-section can be achieved by using grout with high yield strength, a low density or by increasing the average density of the concrete of the tunnel (and/or dead weight or TBM back-up train).
If equation (5.12) is not fulfilled because the yield stress of the grout directly after the TBM is too low, this will result in an upward movement of the tunnel lining. “However, this upward movement will be stopped by the friction forces between the lining elements still in the TBM on one side and the elements in the already hardened or set in consolidated grout on the other side” (Bezuijen et al. 2005, pp. 7-12).

With the uplift loading case, the soil support is of major influence on the safety of the lining. Therefore the grout material specification and pressure should be considered very carefully.

The acting load in the uplift loading case on the tunnel lining (see Figure 5.7) is the sum of:

- The radial grout pressure \( \mathcal{E} \) hydrostatic water pressure + lining-grout contact pressure).
- The tangential grout loading (adhesion between the grout and the lining).
- The dead weight of the tunnel lining (Blom et al. 2003, pp. 1-6).

The equilibrium of the vertical forces is ensured with these loading components. The vertical component of the radial grout loading is equal to the dead weight of the tunnel and the vertical component of the tangential loading:

\[
\int \sigma_{\text{grout,radial,vertical}} = \text{Dead weight} + \int \tau_{\text{grout,tan,vertical}}
\]  

(Blom et al. 2003, pp. 1-6)

When the increase of the grout pressure (water pressure and lining-contact pressure) at the top and decrease at the bottom of the tunnel is not sufficient to compensate the uplifting force of the grout, the tunnel lining will move upwards. At the top of the tunnel ring the available gap is smaller than at the bottom of the ring. The plastic shear yield stress capacity limit of the grout is exceeded, so that the grout starts to flow from the top of the lining in sideway direction. Because of the relative difference in deformation between the lining and the soil there is a pressure development in the grout. The tangential stresses act along the circumference of the
tunnel with the maximum value of the plastic shear yield stress of the grout. That’s the moment when the equilibrium of the vertical forces is realized.

This initially acting load on the lining, the grout flow and the establishment of equilibrium of vertical forces was analyzed by Blom in a FEM calculation (Blom 2003, pp. 1-224).

The results of the FEM calculation give insights into the remaining grout pressure (water pressure and lining-grout contact pressure) and its distribution around the tunnel lining. The FEM analysis is based on a permanent contact between the tunnel lining and the grout; this means that the lining-grout contact pressure never drops below zero. The calculation of the uplift loading case, which is the loading during the assembly of the lining due to pressures from the injected material along the circumference of the lining, is controlled with a frame analysis. All loading is dissolved in radial and tangential components. A static system as shown in Figure 5.7 was used.

Figure 5.7  Acting load in the uplift loading case on tunnel lining, frame analyses (Blom 2002, p. 122, Figure 97)
The total dead weight of the lining is determined by following equation based on the frame analysis: \(2\pi rdb\gamma\)

Where 
- \(r\) = radius of lining  
- \(d\) = segmental thickness  
- \(b\) = (half) segmental width  
- \(\gamma\) = dead weight of lining.

The vertical force resulting from the tangential stresses for two sides of the tunnel is determined as follows: \(2rb\tau_{yield} \times 2\) with \(\tau_{yield} = \) max. plastic yield stress.

The equilibrium of the vertical forces is given by the vertical downward directed loading (dead weight and tangential stresses) and the upward directed loading by the grout pressure.

The local pressure increase at the crown of the ring is left out when the upward directed loading \(F_{up}\) is a pure hydrostatic loading with an equivalent specific weight that exactly compensates the dead weight and the tangential stresses.

\[
F_{up} = \pi r^2 b \gamma_{eq}
\]  \(\text{(5.14)}\)

Where \(F_{up}\) = upward directed loading  
- \(r\) = radius of lining  
- \(b\) = (half) segmental width  
- \(\gamma_{eq}\) = equivalent specific weight of the grout pressure

\[
(\gamma_{eq} = \frac{(2\pi r db \gamma + 2rb \tau_{yield} \times 2)}{\pi r^2 b})
\]  \(\text{(5.15)}\)

The equivalent specific weight of the grout pressure represents the addition of the always present hydrostatic water pressure and the grout-lining contact pressure. This means the grout-lining contact pressure is the subtraction of the hydrostatic water
pressure minus $\gamma_{eq}$ in kN/m$^3$. The equivalent specific weight of the grout pressure is also valid when the lining is embedded in an uniform soil continuum and loaded with hydrostatic water pressure involving the dead weight and the tangential stresses due to the grout-lining adhesion. “This means that the grout-lining contact behaves like a kind of uniform bedding. In this case the grout-lining contact is able to uniformly compensate the uplift force due to the hydrostatic water pressure” (Blom 2002, pp. 1-224).

The comparison of the FEM calculations with actual measurement data of tunnel projects in the Netherlands as done within the thesis of Blom gives the conclusion that buoyancy has occurred with incomplete grouting. Several stages in the assembly of the tunnel ring have been analyzed. It is shown that the distribution of the tangential stresses is highly non-uniform especially when the ring is within the TBM or just left the rear of the TBM.

To avoid on the one hand buoyancy that can occur with incomplete grouting and to guarantee the stabilization of the segment ring in the surrounding soil, the quality of the annular gap grouting is essential. The quality of the annular gap grouting highly depends on the quantity of the injected mortar. A complete backfilling of the annular gap reduces the occurring settlements to a minimum.

**Theoretical and real grout volume**

The quantity of mortar can be easily determined on the basis of geometrical relations considering overcut, conical profile of the shield and tail void geometry. The annular gap develops due to the difference in diameter of the soil that is excavated with the cutting wheel (inclusive overcut) in relation the outside diameter of the segmental lining. On this basis the volume of the annular gap can be calculated plus an additional consumption in praxis of 10 to 30 %. Usually 10 to 30 % more grout than the volume of the annular gap has to be applied because the grout volume can be reduced by 5 to 10% due to bleeding caused by consolidation (courtesy of Herrenknecht AG).
Volume control of the injected mortar takes place most precisely by determination of the difference of two sets of data at the storage tank before and/or after grouting. Measurement of the grout volume by recording the number of piston strokes of the injection pump is classified as unreliable due to the indeterminate portion of air in the mortar.

Continuous grouting through the tailskin dependant upon TBM advance speed permits optimal filling of the tail void.

The tail void undergoes a change of shape due to the stiffening process of the grouting mortar and to changes in stresses in the soil in the immediate vicinity of the annular gap. Thus, unavoidable settlements are experienced within the bounds of annular gap grouting but they can be reduced however to a minimum (Jancsecz et al. 2001, p. 195).
CHAPTER 6
GROUT CHARACTERISTICS AND SPECIFICATION
FOR GROUT EQUIPMENT

This chapter deals with the composition of grouting material and the adjustment of backfill material to specific project or geological requirements including the specification of grouting equipment.

6.1 Grout characteristics

The general characteristics of the grout shall satisfy the requirements for grouting material as given in chapter 6.1.1.

6.1.1 Requirements for grouting material

The grouting mortar must be constituted such that

- It reaches at least the strength of the surrounding ground
- Has a low volume decrease after hardening
- However shows an increased water impermeability
- Does not affect the groundwater
- Does not separate during transportation
- It is easy to pump over extended distances, irrespective of the distance or time involved
- It guarantees a complete backfilling of the tail void and thus provides a long term homogeneous, stable and low permeability ring around the tunnel lining
• It resists segregation and bleeding to avoid blockages in grout lines, pumps and tail seals
• It resists dilution by groundwater
• It resists washout from water entering the void from the surrounding soil
• It has a low emission of filtration water to ensure its stability of volume and filter strength
• It exhibits sufficient shear strength after a relatively short time
• The hydration of the grout should not progress too fast to avoid a plug in the grouting lines especially regarding the grouting through the tailskin shell
• In case of downtime, the setting (hardening) of the grout can be retarded.
• The strength / elastic modulus of the grout corresponds to the surrounding soil strength.

(EFNARC, 2005, p.16)

Any drift of the consistency of the grouting mortar must be counteracted either by quick handling or by chemical additives.

It is essential that the grout properties are adjusted to the planned TBM advance speed so that the working properties or setting time of the grout, irrespective of downtimes or variations of TBM advance speed, are optimized to avoid blockages of injection lines and pumps.

The selection of the grout type and composition of the backfill mix depends upon the particular tunnel requirements, such as the risk of settlement or the need for waterproofing.

Chapter 6.1.2 discusses the composition of the state of the art of the grouting compound.
6.1.2 Composition of the state of the art of the grouting compound

The grout is assumed to be a well-mixed and very coherent fluid with water, particles and cement. The rheological properties largely depend on the particles and the cement.

Usually the annular gap is grouted with a hydraulically hardened fine mortar consisting of water, sand, filling material, bentonite and cement.

The following table shows the composition by percentage of the grouting mortar used at different projects.

Table 6.1 Composition by percentage of the grouting mortar of various shield tunneling projects (Courtesy of Herrenknecht AG)

<table>
<thead>
<tr>
<th>Mix [% by mass]</th>
<th>Metro Taipei (Taiwan) Lot C201</th>
<th>Metro Taipei (Taiwan) Lot C264</th>
<th>Mülheim (Germany) Lot BA 8</th>
<th>Duisburg (Germany) Lot TA7/8a</th>
<th>Metro Essen (Germany)</th>
<th>Cologne (Germany) Lot M1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>53.1</td>
<td>48.9</td>
<td>56.3 (Sand 0/4)</td>
<td>54.8 (Sand 2/2)</td>
<td>54.5 (Sand 2/2)</td>
<td>58.2</td>
</tr>
<tr>
<td>Filling material</td>
<td>22.6</td>
<td>27.4</td>
<td>25.8</td>
<td>25.3</td>
<td>25.0</td>
<td>24.6</td>
</tr>
<tr>
<td>Cement</td>
<td>2.2</td>
<td>8.8</td>
<td>-</td>
<td>2.5</td>
<td>5.0</td>
<td>3.7</td>
</tr>
<tr>
<td>Bentonite</td>
<td>2.2</td>
<td>1.0</td>
<td>2.4</td>
<td>1.5</td>
<td>-</td>
<td>1.2</td>
</tr>
<tr>
<td>Water</td>
<td>20.9</td>
<td>13.9</td>
<td>15.5</td>
<td>15.9</td>
<td>15.5</td>
<td>12.3</td>
</tr>
<tr>
<td>Water-cement ratio</td>
<td>0.84</td>
<td>0.39</td>
<td>0.6</td>
<td>0.57</td>
<td>0.52</td>
<td>0.43</td>
</tr>
</tbody>
</table>

Sand represents the main part of the aggregates. Its grain size is between 0/2 millimeter respectively 0/4 millimeter. The grain size distribution curve must be carefully coordinated in order that as few cavities in the grain structure as possible are
present. Thus the demand for the filter strength is fulfilled as well as the required stability of volume.

Filling material is quantitatively the next smaller additive in the mortar after sand. Usually fly ash is used as a filling material. Fly ash in the range of 2/40 \( \mu \text{m} \) grain size functions as filler in the finest voids of the matrix between the cement and aggregate particles; increasing the filter strength. Fly ash displaces the existing interstitial water and thereby lowers the water demand, improving the working properties of the fresh mortar with the same water content. Coal fly ash belongs in contrary to brown coal fly ash due to the low CaO/C\text{Cl}_{2}-content to the pure pozzolan. Coal fly ash reacts with only water not hydraulically but needs Ca(OH)\(_2\) for the reaction.

Bentonite as aggregate provides a paste-like consistency of the mortar which increases the shear strength. The working properties are not impaired by the thixotropic characteristics.

The content of cement in the composition of the grouting material should be as low as possible in order to prevent blocking of the grout lines due to premature hardening during unscheduled stops.

To maximize the flow characteristics of the fresh mortar, a high water-cement ratio will generally be chosen.

The tunnel projects listed above include water-cement ratios in the range of 0.42 to 0.6.

The smallest grout hose or grout line through which the backfill material must pass needs to have a diameter that is at least three times greater than the maximum particle size of the aggregate used in the grout.
6.1.3 Retarding behavior of the grouting compound

The retarding behavior influences the workability of the grouting compound. A retarder is a chemical agent to slow down the chemical hardening of the grout and thus increase the time of the workability of the grout.

During a planned or longer downtime the retarding behavior of the grouting mortar should be adjusted in the way that steering movements of the shield tunneling machine are not hindered by hardened grouting material. The tailskin and tailskin seal can become blocked if the mortar hardens too fast.

The mortar has to be kept free-flowing in the grout lines especially during downtimes. During scheduled downtimes of the TBM the mortar can be kept flowable by adding retarding agents. Normal practice during expected downtimes is to leave out the cement factor from the mortar and increase the amount of bentonite. The bentonite temporarily takes over the support of the tail void.

During continuous TBM advance however, a fast hardening of the grouting material is desirable. This can be reached by increasing the cement factor or the portion of coarser components in the grout. A faster stiffening will be reached by reducing the water-cement ratio.

However, both of these measures lower the pumpability of the mortar and therefore increase the risk of blockages. The increased time needed for cleaning of the grouting lines is seen as problematic.

With an increase of coarser aggregates in the grouting compound a faster drainage should be attained. The addition of coarser aggregates up to approximately 4 mm would create a grain structure, that assists in distribution the forces and reduces the movements of the tunnel tube.

A further possibility to accelerate the chemical hydration is to increase the grouting pressure during the injection. With this, the filter water will be squeezed out and the mortar sets faster. Simultaneously the strength increases because there are few cavities existing in the retarded mortar that is filled with water.
Increase of the grouting pressure especially in loose soils brings about a danger of lateral infiltration of the mortar. The mortar can now drain into the soil leading to an additional consumption of grouting material. Deformation of the segment ring must also be considered with increased grouting pressure.

An alternative for reducing the time of hydration is the addition of solidification accelerators directly at the injection nozzle or through pressure-resistant flow mixers that are connected to the feed line, vastly reducing the process time.

More detailed information about the process during the hardening of the grouting material would serve to warn of the position of the segment ring during the grouting of a ring. Thus the influence of the soil would be considered.

In summary, one can say that to fulfill the demands of a suitable grouting compound, the exact mixture adapted to the prevailing soil conditions has to be determined by tests and the selected mortar mix has to be controlled with testing of the materials.

Investigations regarding the retarding, plastic and setting behavior, stability of volume and the delivery of filtration water must be conducted as the basis for a suitable backfill mix. Such mix should also be environmentally acceptable.

6.2 Specification for grout equipment

The foundation of bored tunnels is assured by grouting the annular gap surrounding the tunnel lining. The grouting pressure governs the loading on the lining and is one of the influences that determines surface settlement.

The grouting pressure has a great influence on deformation of the surrounding ground. The pressure distribution in the grouting compound and the time taken for hardening of the grout is therefore of interest.
6.2.1 Grouting process

To achieve a reduction of bending stresses in the tunnel lining as well as the avoidance of settlement at the surface, the grouting process should be realized through the shield. In stable soil conditions or to achieve greater economy, it is also possible to realize the grouting process through openings in the tunnel lining segments.

For grouting through openings in the segments, a minimum of four injection openings are necessary. The arrangement of the injection nozzles should be checked to achieve a continuous grouting. An secondary grouting should be realized, especially in the crown area, making it an essential requirement that the crown area is equipped with an injection nozzle. In case of movement of strata the secondary grouting should not be limited only to the crown area.

In the event of a planned downtime, the shield has to be moved forward such that the tailskin sealing is located directly behind the injection opening in the tunnel lining. The remaining injection openings have to be sealed carefully against penetration of water.

Also, when grouting through the tailskin, a minimum of four injection nozzles should be arranged axially along the shield. The form, the surface quality and the accessibility of the grouting lines should be designed in such a way that blockages are avoided and/or cleared.

The grouting process of both backfilling methods, either through the tailskin or through the segments, is discussed in chapter 3.
6.2.2 Grouting pressure

"To provide subgrade reaction as bedding for the lining and reduction of settlements on the surface, the tail void has to be filled with grout" (Ebenhög et al. 1999, p. 6). In order to optimize the process of tail void grouting not only the quality of the mortar but also the grouting pressure needs to be established (Ebenhög et al. 1999, pp. 1-15).

Consideration must be given that the prescribed minimum and maximum grouting pressures should be maintained to enable a complete back-grouting of the annular gap without damaging the segments.

The minimum grouting pressure should be selected so that the annular gap is filled without any cavities and that penetration of the surrounding soil and groundwater in the annular gap will be avoided (Maidl et al. 2001, p. 296). The theoretical minimum injection pressure should be at least the same value than the ambient pressure in the annular void resulting from soil burden, earth loads and water pressure.

For a good distribution of mortar and thus a secure backfilling of the segmental ring it is sometimes useful to inject initially with a lower pressure and afterwards with increased pressure.

It must be considered that the pressure at the pump does not correspond with the pressure in the injection nozzle or with the pressure in the tail void. The set pump pressure must be higher than the desired maximum value in the tail void to compensate pressure drop in the lines.

A drop of the grouting pressure with constant pressure volume flow points to a drainage of mortar into gaps, fissures and pores. The grout can also accumulate under a kind of diaphragm sealing layer and give rise to soil heaves.
6.2.3 Quantity and capability of grouting compound

The quantity of grouting mortar actually injected for each TBM advance has to be compared with the theoretical value. The theoretical annular gap is calculated from the difference of the theoretically excavated tunnel face (consideration of possible overcut) and the circular area which is formed by the outside diameter of the tunnel lining segments.

Dimensioning of the grout injection pumps in relation to the capacity of the grouting process to be installed, should include an over dimensioning to be able to have reserve capacity in relation to the planned TBM advance speed.

Determination of backfilling system capacity

The determination of backfilling system capacity is largely defined by the size of the annular gap and the shield advance speed.

a) The amount of grout in the annular gap is determined by:

- Theoretical volume \( V_{RS} [m^3] \) of an annular gap per meter of advance.
  \[
  V_{RS} = \left( D_2^2 - D_1^2 \right) \times \frac{\pi}{4} \times L_T \ [m^3] \tag{6.1}
  \]

  \( D_2 \ [m] = \) Diameter of the shield cutting edge  
  \( D_1 \ [m] = \) Outside diameter of the segment ring  
  \( L_T \ [m] = \) Segment length

- The non-compacted amount of grout \( V_M [m^3] \) for filling the annular gap taking extra consumption into account.
  \[
  V_M = \frac{V_{RS} \times L_T}{(1 - \mu_1) \times (1 - \mu_2)} \ [m^3] \tag{6.2}
  \]

  \( \mu_1 \ [%] = \) Extra consumption as a result of the grout moving into the cavities of the surrounding rock (pore volume).  
  \( \mu_2 \ [%] = \) Mortar compaction under injection pressure.
b) The pump performance \( Q [\text{m}^3/\text{h}] \) is determined by:

\[
Q \left[ \frac{\text{m}^3}{\text{h}} \right] = V_M \times \mu_{SM} \times \frac{1}{(1-\mu_3)\mu_4}
\]

(6.3)

\( \mu_{SM} \left[ \frac{m}{h} \right] \) = max. advance speed of shield.

\( \mu_3 [\%] \) = Coefficient for the filling of the cylinder depending on the consistency of the grout.

\( \mu_4 [\%] \) = Ratio of the stroke time of the transport cylinder to the switch-over time of the rotor distributors (Delay time)

(Bortscheller et al 1989, p. 97).

Comparison of the effective grout consumption with the theoretical volume per meter of advancement with an example of the tunnel project Airport Light Rail Hamburg.

The volume \( V_{RS} [\text{m}^3] \) of the annular gap per meter of advance can be calculated using the above equation with the example of the project Airport Light Rail Hamburg. (Project description, see Appendix B). The volume amounts to 4.3 \( \text{m}^3 \).

\[
V_{RS} = \left( D_2^2 - D_1^2 \right) \times \frac{\pi}{4} \times L_T = \left( 6.87^2 - 6.6^2 \right) \times \frac{\pi}{4} \times 1.50 = 4.3 \text{m}^3
\]

(6.4)

\( D_2 [\text{m}] \) = Diameter of the shield cutting edge = 6.87 m

\( D_1 [\text{m}] \) = Outside diameter of the segment ring = 6.60 m

\( L_T [\text{m}] \) = Segment length = 1.50 m

Taking an extra consumption of 11 \% of mortar into account, the required grout volume per meter of advancement is 4.8 \( \text{m}^3 \). The extra consumption of grout is based on practical experience and is normally between 10 to 30 \%. 
The effective grout consumption as shown in Figure 6.1 is based on the documentation of the operator of the grout plant at the project Airport Light Rail Hamburg. The quantity of injected grout was determined both from weighing cells and via the number of strokes of the injection pump. The analysis of this data set is illustrated in Figure 6.1.

Figure 6.1  Effective grout consumption for the tunnel project Airport Light Rail Hamburg (theoretical volume per advancement: 4.8 m³) (Bilfinger Berger AG, jobsite Airport Light Rail Tunnel Hamburg, 09.01.2006)
Analysis of Figure 6.1 shows that the average grout consumption via the determination from weighing cells amounts to 4.75m³ per advance and 4.86m³ in average per advance from the number of piston strokes. Both methods show a good quantitative correlation ratio to the theoretical calculated value of 4.8m³.

The required quantity of grout has to be provided in time for the backfilling of the annular gap. The supply of the backfilling material, the according equipment and the grout transport will be explained in the following section.

6.2.4 Grout equipment and grout transport

The grout transport from the surface to the injection point is described in the following sections together with a description of grout pressures control and the different possibilities for checking the quantity of grouting material.

Grout transport

The grout is mixed outside the tunnel. The grout transport to the injection point can be realized either with grout cars (track-bound or other vehicles) and then passed on to a grout pump or by piping along the entire tunnel length. In case of long pumping sections, a good flowability of the grouting material is necessary to avoid blockages within the pipes.

The volume of the grout cars is designed in such a way that sufficient reserves of mortar are available in the shield taking the cycles of the supply train into consideration.

The occurrence of sedimentation of backfill material during the transport with grout cars must be prevented. Therefore, the grout cars are equipped with agitators which permanently mix the mortar during transport and standing times. An intensive re-mixing with a high rotation speed (n > 50 min⁻¹) should be accomplished when the mortar arrives at the shield in the case where it is transported by grout car not equipped with agitators. A permanent mixing of the grout is preferred if there are on
the one hand long transportation distances and on the other hand long and unplanned downtimes.

The transportation systems should be designed in the way that a sufficient quantity of grouting material can be transported to the injection points.

**Grout pumps**

The grout pumps are generally installed on the back-up system so that it is also possible for pumps with a lower suction height to empty completely the grout car. "The grout pump charges a distributor providing grout, volume- or pressure-controlled, to the individual injection points" (Maidl et al. 1995, p. 185).

The arrangement of several hydraulically driven grout pumps for the direct charging of the injection points facilitates simultaneous grouting at several points axially arranged around the periphery of the annular gap between the excavated diameter and the tunnel outside diameter. In order to guarantee reliable grouting conditions a separate pump is allocated to each injection line / point.

**Control of grout pressures and volume of grouting material**

The grouting process including the control of the grout pressures and the control of the injected quantity of grouting material is generally carried out simultaneously to the TBM advance and is computer controlled (with manual override).

The grouting equipment must guarantee that an advance of the shield is only possible with an adequate grouting of the annular gap. Where pressure falls below a preset minimum, the advance must be stopped. In case of exceeding the preset maximum grouting pressure, dependent on the load bearing performance of the segment, it should be either disconnected or changed to another connection piece.

The measurement of the grouting pressure should be undertaken with the availability of reserve or redundant pressure sensors for security reasons. The quantity of grouting material as well as the grouting pressure should be permanently recorded
and controlled. Therefore all essential operational parameters are registered for monitoring purposes.

The control of the quantity of injected grouting material can be achieved using one of the four methods listed as follows:

1. Preselection of the number of pump strokes
2. Reading of level indicator in the grout tank
3. Weighing of grout cars
4. Weighing cells

1. The control of the quantity of grouting material is realized at present via the preselection of the number of pump strokes. This proceeding supposes a complete filling ratio of the piston. Since with each stroke of the pump an approximately constant volume of grouting material will be taken, the quantity of the mortar already injected can be determined with the number of piston strokes.

The theoretical quantity of grouting material can be compared with the injected mass. With this it can be determined if the mortar penetrates in the surrounding soil and if the characteristic of the stiffening process must be changed or if there are voids in the annular gap that are not injected.

2. Another current practice is to determine the quantity of the injected mortar by recording the level indicator in the grout tank before and after the grouting process in order to calculate the volume.

3. Another procedure, independent of operation of the grout pump, is to weigh the grout cars when they are full and later empty in order to back calculate over the density. Errors of measurements because of deposits and residuals in the grout cars would not occur.

4. Load cells may also be used to determine the quantity of injected mortar. Here, mortar is mixed outside the tunnel and transported by means of a mortar tank to the TBM back up where the complete unit with fresh mortar is unloaded to its final position on load cells. Thus, the total weight (including the mortar) can be per-
manently displayed. By adjusting the weight at the start and end of TBM advance, the quantity of mortar injected can be calculated and displayed.

Minimum / maximum injection pressure can be controlled by pressure level monitoring. The injection points in the tailskin are equipped with pressure transducers to measure the pressures in the individual grout lines. The disadvantage of this method is that a small drifts in mix consistency, for example caused by a stiffening of the grouting material, a higher pressure will be present in the annular gap than will be effectively measured.

Since the pressure level monitoring takes precedence over the volume control, it is possible that the injection process at the nozzle is cut off even though the annular space is not yet completely filled and the maximum pressure not achieved in the entire annular gap. Therefore, the volume of grouting mortar supplied should not adversely affect the flow / pressure characteristics substantially during the grouting process. Data relating to the injected volume and pressure of the individual injection points can be taken from a display screen in the TBM control cabin.

The pressure in the annular gap can permanently be controlled within the adjustable limit values for the switch-on / off pressure of the grout pumps. If required the operating data of the grout injection can be stored by means of a so-called process data acquisition and visualisation and is thus available at any time.

Figure 6.2 shows a schematic diagram of grouting including all necessary components for the backfilling process up to the injection points at the end of the tailskin.
6.3 Single component and two component grouts

The selection of what type of grout to use for backfilling the annular void depend on the risk of settlement or the need for water-tightness and durability of the tunnel.

There are two common types of grout, single component grouts (moisture cure) and two component grouts (chemical cure). The single component grouts are generally composed of aggregates such as sands and gravels, cement, water and additives. They remain the most popular choice of mix for backfilling of the annular gap.

Table 6.2 shows the properties for single component grouts. The state of the art of the single component grouting process is described in chapter 3.
Table 6.2  Plastic consistency for single component grouts (EFNARC 2005, p. 17)

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Test methods</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bleeding</td>
<td>EN 480-4: 1997</td>
<td>Less than 1 % up to the initial set or initial stiffening time in the case of active and semi-active grouts or 72 hours in the case of an inert grout.</td>
</tr>
<tr>
<td>Setting time for Active grouts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Method will depend on maximum aggregate size:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-2 mm:</td>
<td>Vicat test to EN 413: 1995</td>
<td>Initial setting time within +3 h and − 15 min of the stated setting time.</td>
</tr>
<tr>
<td>&gt; 2 mm:</td>
<td>Penetration test similar to setting time method of EN 413: 1995</td>
<td>Final setting time no later than 4 h after initial setting time.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Temperature to be ± 1°C of the temperature used in the proving trials.</td>
</tr>
<tr>
<td>Stiffening time for Semi-Inert grouts</td>
<td>As above</td>
<td>Initial setting time within +4 h and- 1 h of the stated setting time.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Final setting time not later than 12 h after initial setting time.</td>
</tr>
<tr>
<td>Workability</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slump test</td>
<td>EN 413-2: 1995</td>
<td>± 25 mm of stated Slump value</td>
</tr>
<tr>
<td>Spread Table</td>
<td>ASTM C230</td>
<td>± 10 % of stated spread</td>
</tr>
</tbody>
</table>
The two component grouts are generally composed of water, bentonite, cement, a stabilizer and a hardener.

The specific density of single component grouts is between 1.8 and 2.2 kg/m$^3$, whereas the specific density of two component grouts is generally lower because of higher fluid content.

For both grout types, single and two component grouts, additives such as bentonite, fly ash and/or silica fume are common. The additives are used to improve the grout properties such as bleeding and pumpability. The properties of various constituents of additives and admixtures vary to suit the conditions and requirements of a project by providing a suitable mix design to suit the pumping and performance requirements.

The physical properties of the two grout types vary. The single component grouts that are either mortars consisting of gravel, silica, cement and additives or inert grouts, generally consisting of fine sand, silica and fly-ash, have different hardening times.

With mortars, the cement starts hardening after a number of hours, whereby the puzzolanic hardening of the inert grouts starts hardening at a very slow pace after weeks. The advantage of two component grouts in comparison is that the chemical grouts harden very quickly when mixed (time base: minutes). In permeable soil all types of grout suffer fluid loss when pressurized.

Within this thesis several tests will be described for the two component backfill mix design to meet among other things the requirements regarding pumping and performance especially with respect to of avoiding grout washout in the annular gap in permeable soils and of attaining a quick hardening of the two component backfill mix in order to take the loads acting on the tunnel lining.

The use of two component grout provides greater flexibility in varying the ratio of the two components A and B. Component A can be described as a stabilized main component consisting of water, bentonite, cement and a stabilizer and component B as the activating component of the system consisting of a sodium silicate.
They can be divided into two categories:

a) a **mortar** consistency component A with a **liquid** component B

b) a **liquid** consistency component A with a **liquid** component B

For a) the component A should have the properties as stated for the single component grouts in table 6.2 with the exception of setting time requirements. The properties of component B should be described by the manufacturer or supplier of the product. The mix of both components should fulfill the specific project requirements.

For b) both components have a liquid consistency. Component A should still fulfill the requirements as stated in table 6.2 except for the setting time and workability requirements. The workability of component A should be measured by a Marsh Cone, a device to determine the viscosity of the material. It should give a flow time within 15 seconds of that recommended by the supplier of the admixtures. The quality of component B should regularly be determined by tests or by a Quality Assurance Certificate provided by the manufacturer (EFNARC 2005, p. 17).

The fine grained main constituent of the backfill material (component A) can be mixed outside the tunnel and can then be pumped to the TBM. Component B (hardener) is not added until the end of the supply line at the face of the annular gap. The two component mix combines a retarded (stabilized) material with an accelerator at the injection port at the tailskin of the TBM. When mixed, the two components react within a short time to a gel which begins to solidify afterwards.

The setting time of the suspension can be varied and hence the extent to which the mix will penetrate the ground. The effectiveness of the filling of the annular gap with a two component mix should be higher than with traditional grouting methods as the shorter setting time targets filling the annular gap only and minimizes the potential for the mix to be diluted or segregated by groundwater or slurry.

The annular gap backfill mix is designed for the following characteristics:

- Efficient fillability
- Efficient flowability
- Quicker hardening and thus generation of strength
- Resistance to segregation
• To be transportable over long distances
• Resistance to dilution by groundwater
• Less volume reduction during hardening than conventional grout.

(EFNARC 2005, p. 16.)
CHAPTER 7
DEVELOPMENT OF DYNAMIC GROUTING SYSTEMS

This chapter introduces the dynamic grouting system used to optimize a two component backfill system to find the best possible combination of grouting specification, material and equipment including the components used for transport and mixing of the grout (see for an overview of chapter 7 Figure 7.1 on the following page).

Dynamic grouting systems as the system described in this research use either of the following backfill variants:
1. Low pressure two component grouting system (max. 16 bar pressure).
2. High pressure two component grouting system (max. 120 bar pressure).
3. Premixing variant (two component mix).

The thesis focuses on the development of a system incorporating a low pressure backfill solution. Research was carried out to find the optimum composition for a two component backfill material for specific soil conditions.

All grouting systems require attention to rheological characteristics of grouts, change of rheological properties, consequences of fluid loss and the frictional properties at the grout/soil interface.

In the context of geological conditions a grouting compound has to be designed to avoid segregation of the backfill and wash out resulting from groundwater flow that would otherwise lead to improper bedding of the tunnel lining.

As mentioned in chapter 1.2 the objectives of this thesis are to find a backfill compound to avoid short term convergence of the annulus as well as long term washout of grouting compound by groundwater.
Figure 7.1 Overview of chapter 7.

- Development of dynamic grouting systems
  - Parameters influencing the dynamic grouting systems
    - 2-C low pressure system
      - Function principle & structure of 2-C low pressure system
      - First application to tunnel construction
    - 2-C high pressure system
      - Design
      - Function
      - Experiences
    - Premix variant
      - Design
      - Function
      - Development steps
  - Laboratory Tests
    - Active Mortar Tests
      - Test equip.
      - Test course with two products
      - Results of active mortar tests
    - Develop. steps of accelerator injector
    - Develop. of 2-C mixing formula against grout washout
      - General assessment of 2-C backfill material
      - Testing methods & formulas for 2-C mix for permeable soils
      - Testing results
    - Washout resistance test of 2-C backfill material
      - 2-C backfill material
      - Test set-up & test material
      - Course of testing
      - Result
    - Field testing & investigation
      - 2-C backfilling material & influence on convergences in the annular gap
Furthermore the injection compound contributes to the water-tightness and durability of the tunnel. The grouting process should be improved with regards to a complete filling of the annular gap for following reasons:

- Bedding of the segments in the surrounding subsoil. The segments must be well integrated into the soil to take the various loads during tunnel construction as well as operation such as thrust forces and wheel loads of the TBM back up system.

- A good interlocking is achieved between segmental lining and geology. As a result transferred stresses are minimized and surface settlements are kept to a minimum.

- The grout layer acts as a protective cover around the outside of the segments.

- The grout layer improves the water-tightness of the tunnel and as a result less defective spots in the seal can be expected.

After the segment ring is erected it should neither float nor drop under loading of the TBM back-up. It is mandatory for the grouting material to have sufficient inner shear resistance right after injection.

A backfill material with good flow properties which does not lead to blockages in the supply lines but starts to solidify once the gap is filled would be ideal.

As a consequence the following aspects should be taken into account:

- The composition of the backfill material
- The type of admixtures and additives
- Setting and rheological characteristics of the mix
- Working properties, shrinkage characteristics, grouting pressures
- Long term durability and strength requirements of the mix.

(EFNARC 2005, p. 16)
7.1 Definition of the parameters influencing the dynamic grouting system

The parameters which have an influence on the two component grouting system can generally be divided into three main groups:

a) Requirements relating to the rheological properties (grout consistency)
b) External variables and
c) Technical variables.

The parameters assigned to the groups are roughly defined below. The parameter definition is a preliminary stage to the tests that have been realized within the context of the development of a dynamic grouting system.

a) Requirements on the rheological properties (grout consistency)

The following important requirements are to be met by the backfill material:

- Sufficient stability, good flow characteristics and easy to pump
- Low release of filtration water.
- Resistance against segregation and bleeding in order not to block lines, pumps and tail seals.
- Good working properties of the material until backfill is complete
- Provision of a homogeneous, stable ring of low permeability around the tunnel lining.

The essential parameters for the characterization of grouts are yield stress and viscosity (cited by Talmon et al. 2001, p. 2). In order to achieve a sufficient degree of backfill of the annular gap and to avoid an excessive consumption of grouting material, special requirements apply to the characteristics of the construction materials to be used both in fresh and hardened conditions. In order to obtain a non-positive optimum backfilling, the grout should be a free-flowing suspension showing stability of volume even under pressure. It should resist dilution by groundwater.

To understand the grout properties immediately after injection it is necessary to understand the effects of consolidation. Consolidation could lead to expelling of water and a decrease in porosity. If the grout layer is consolidated it will provide the
necessary strength to act as a foundation for the tunnel lining even before hardening starts. Unconsolidated grout bears the risk that the shear strength is too low to counterbalance the buoyancy forces of the tunnel. Furthermore consolidation increases the flow resistance thus directly affecting the pressure distribution behind the TBM during the boring process.

Figure 7.2 Consolidating grout around a tunnel lining and detail (Bezuijen 2003, p. 4)

To prevent shifting of individual segments or entire rings against each other, it is necessary for the grout to have sufficient shear strength after only six to eight hours upon injection to safely counterbalance the loads induced by the TBM backup. In its final state, the backfill material should reach a shear strength and stiffness at least identical to the parameters of the surrounding soil. Thus a permanent effective bedding of the tunnel tube in the surrounding soil/rock can be ensured.
b) External variables

External parameters having an influence on the dynamic grouting material are:

- Grouting pressure (the pressure distribution farthest away from the TBM is influenced by buoyancy and stiffness of the tunnel lining until the grout is hardened).
- Temperature of:
  - The two components
  - Basic material like aggregates, water and binding agent
  - Air
  - Surrounding components
  - Water content and permeability of the surrounding soil.

c) Technical variables

The technical variables are mainly the grouting equipment itself including all necessary pumps, the mixing energy during the mixing process and the number of injection ports. The aim is to achieve a constant pressure and a controlled backfill of the annular void matching with the TBM advance.

7.2 Two component low pressure annular gap backfilling system

The operating principle as well as the structure of the low pressure two component backfill system is described also giving a brief description of its first application in tunnel construction. By presentation of the results of active mortar tests can be shown that the backfill with two component backfill material through the injection lines is possible.

Washout-resistance tests in permeable soils show that a customized mix and the backfill system meet the objectives listed in chapter 7.2.6.

A key question is if convergences in the tail void can be kept to a minimum by means of two component dynamic grouting material. Respective tests undertaken by Herrenknecht AG on a jobsite in Italy are discussed in chapter 7.2.7.
7.2.1 Function principle and structure of the two component low pressure backfilling system

The following two sections provide an overview of the method and the installation of the two component low pressure backfill system. The sequence of operation for the two component grouts are outlined.

Operating principle of the low pressure backfill system

This system is one of three dynamic grouting methods to backfill the annular gap with two component material to avoid surface settlement. The main advantages of this two component system are the quick stabilization of the ring due to a short time to reach sufficient strength and the working properties of the grout, which are independent of idle times or advance speed and the pumpability over longer distances. Compared to the single component grouts where the length of the insufficiently supported zone is of crucial influence on the movement of the tunnel, the shear force at the TBM and the moments in the lining, the two component backfill material is also advantageous because the movements and momentums can be reduced by limiting the extent of this zone by changing the hardening or consolidation properties of the grout.

With the low pressure two component backfill system a liquid grout mixture (component A) capable of flowing is mixed with an accelerator (component B) on a short section in the rear part of the TBM tailskin. The mixed components are then injected into the annular gap where the grout sets and stabilizes quickly.

Component A mainly consists of water (approximately 70 to 80 %), cement, bentonite and a stabilizer. The stabilizing agent avoids an early hardening of the component facilitating up to 36 hours of storage before the effects of hardening set in. Component B is an accelerator added at the end of the tailskin. As soon as this accelerator is in contact with component A the two component mix starts to harden. The mixing ratio is adapted to the prevailing soil conditions and is generally in the range of approximately 90% A and 10% B.
The materials used for the two component injection have a lower viscosity than conventional mortar and can easily be pumped. This is beneficial to the overall design of such a grouting system because smaller pipe diameters are possible, lower pump capacity is required and the grout lines can have smaller internal diameters resulting in more economical solutions than conventional mortar systems.

Key disadvantage of the two component system was until now its limited use in the presence of groundwater flows. Here the grout mixture segregated and could therefore not completely harden or was even washed out. Chapter 7.2.6.1 of this thesis will discuss tests carried out and show how the two component mix was adjusted to withstand segregation and water-washout.

Structure of low pressure backfilling system

Figure 7.3 shows a schematic of the low pressure two component grouting system including all necessary components for the backfill process up to the point of injection at the end of the tailskin.

The low pressure two component injection system consists of the following main components:

- 1 tank for the accelerator (component B)
- 1 tank for the base mix (component A)
- Eccentric screw pumps for component A
- Eccentric screw pumps for component B

plus flowmeters, pressure transducers, installation material such as hoses and pipes and electrical installations.
Figure 7.3 Schematic diagram of the low pressure two component grouting system (courtesy of Herrenknecht AG)
The two tanks for components A & B are located on the TBM backup. From the grout injection unit located on the backup component A is pumped via a 30 mm diameter injection line to the tailskin. With an intended minimal delay of 60 seconds the accelerator is pumped via a 6 mm diameter pipe to a valve unit. From there it flows through a separate hose inside the 30 mm diameter injection line towards the injector where the two components are mixed.

Both components are transported by means of electrically driven eccentric screw pumps. In each injection line a flow-meter and a pressure gauge is installed. The pressure gauge in the component A line is used for processes control while the pressure of component B is only displayed on the control panel. The mixed backfill material penetrates into the annular gap after travelling a short distance inside the tailskin. To avoid dripping of component B upon shutdown of the accelerator pump a directional control valve is installed in the B-component line just before entering into the tailskin.

The two component grouting system can be operated in either automatic, semiautomatic or manual mode. For two component grouting generally the automatic mode is used whereby the component ratio is preset and the flow rate of the grout is controlled by the advance rate of the shield.

The manual mode is a service mode for cleaning. In manual mode each line can be chosen separately and each pump can be adjusted individually.

In semiautomatic mode the percentage of component B is programmed individually for each grout line.

After the grouting mode is selected, the sequence of operation for two component grout is as follows:
1. Start of excavation and advance cycle
2. Injection of backfill component A starts with 1
3. After approximately 60 seconds (or as set on the grout injection unit) injection of component B commences
4. Continuous backfill with the mix of components A and B
5. Injection of component B (accelerator) stops just prior to completion of excavation stroke

6. Excavation and backfill component A stops simultaneously.

7.2.2 First time application of two component grout in tunnel construction

In Japan the two component grout system has been used for over twenty years for the filling of tail voids in shield tunneling (Feddes et al. 2001, pp. 809-815).

Simultaneous backfill grouting with the use of two component grout was carried out in shield tunneling for the first time in 1982 in the construction of No. 4 line of the Osaka Subway in Japan. “Since then, this method has been introduced in many regions of the world, such as Asia, Europe and America, reducing the settlement associated with shield tunneling” (citation by Hashimoto et al. 2004, pp.1-8).

In the past and at present accelerated mortar mixes were used on various shield tunneling projects in Europe such as the Metro Genova, Botlekspoortunnel and Dublin Port Tunnel (for project descriptions, see Appendix B).

Common to all these projects except the Botlekspoortunnel is that the annular gap was grouted through openings in the segments. The Botlekspoortunnel deserves a closer look because tests were conducted on the Herrenknecht AG EPB-Shield during erection of 255 m of tunnel (170 rings) to compare the Japanese two component grout ETAC to traditional grouts. Apart from the test section, backfill was done with conventional mortar through injection lines in the tailskin. 12 injection lines (50 mm diameter) were uniformly distributed around the tailskin.

The project team for the field tests comprised three parties, the Nederlandse Bouwstoffen Combinatie, BTC Studiedienst Boren and GeoDelft. Furthermore the grouting test was supported by the producer of the ETAC material, the TAC Corporation and by the Geo Research Institute of Osaka, both from Japan.
The aim of the test was to show the following predicted advantages of this two component ETAC grout:

1. More efficient tunnel boring process
2. Quicker and better support of the tunnel lining
3. Reduced environmental effects

(Feddema et al. 2001, pp. 809-815).

However the injection of the ETAC two component grout could not be realized through the injection lines in the shield because they were not suitable to keep the two components apart from each other before entering the tail void. Instead the ETAC grout was injected directly into the annular gap through two pre-installed ports in the crown of the segments as shown in Figure 7.4.

Figure 7.4 Injection methods used for tests with ETAC and conventional backfilling of the annular gap at the Botlekspoor tunnel (Fedema et al. 2001, pp. 810)
The comparison of the grouting efficiency with ETAC and traditional mortar showed that the ETAC system would have had to be modified to allow grouting through injection lines in the tailskin.

The conventional backfill system as installed in the project Botlekspoortunnel was a fully integrated system and the contractors were more experienced in using this system. A comparison between the two grouting systems was difficult and was later regarded as not suitable.

On the tunnel projects West Side CSO Portland and Metro Line 1 Naples the customers requested for a two component grouting system as an alternative to standard solutions to achieve the following goals:

a) Quicker bedding of the segment ring
b) No cleaning of the grout lines in case of downtimes and thus enabling a quicker start up of the TBM advance
c) Exact control of grouting quantities
d) Cost savings for grout pumps

Three competitive dynamic two component grouting systems were developed as alternatives to conventional grouting systems using single component grouts (hydraulically hardened fine mortars). These systems are discussed in the thesis. One of these systems, the low pressure dynamic grouting system will be highlighted as a preferred solution from the technical and handling point of view.

The low pressure two component backfill system developed by Herrenknecht AG differs in two major points from the ETAC system:

1. The design and arrangement of the grout lines for backfilling of the annular gap.
2. The grouting process itself.

1. Design and arrangement of grout lines

The design of the ETAC grouting system is characterized by injection lines welded on the outside of the shield as shown in Figure 7.5.
The ETAC design has the disadvantage that the grout lines are exposed to external influences such as external stresses with the danger of getting damaged or broken.

An arrangement of the injection lines inside the steel structure of the tailskin as illustrated in Figure 7.6 has the following technical advantages (http://www.tac-co.com/etac/index.html):

- Maintenance and repair of injection lines under atmospheric conditions
- Exchange of injection lines (only for premix variant!)
- Protection of injection lines against external influences
- Lower overall height resulting in a geometrical advantage
- No problems with the launch seal during start-up phase of TBM. Launch seal can be fitted tight around the shield because the shield structure has a smooth surface.
2. Grouting process

With the Japanese design the components A and B are being pumped via hose pipes into the injection line where both components are mixed. The backfill mix is injected through a nozzle that can be positioned by mean of hydraulics. During injection the nozzle is extended into the annular gap. Upon completion of the backfill process the nozzle is retracted and the line is flushed with water to clean out any remaining grout.

This method is comparable with the premix design of Herrenknecht AG, the third type of dynamic two component grouting system. This premix variant (described in chapter 7.4) is an optimization of the Japanese system with the difference that the two components are pumped separately to the tail shield and are mixed just prior to being injected through the tail shield ports. Both components are premixed on the TBM backup. A further difference is the protection of the lines inside the shield. The system incorporates special ports, hydraulically operated poppets and clean out valves. A flushing of the lines for cleaning is also possible. To minimize risk in the event of damage all ports are interchangeable.

For the two component low pressure system both components A & B are pumped separately via injection lines into the tailskin where the material is mixed at
the end of the tailskin before entering into the annular gap. The accelerator injecting-nozzle can not be moved hydraulically. This is not necessary because the cleaning of the injection lines can be achieved by flushing the line with component A as it does not react without the addition of accelerator.

The developed dynamic two component grouting systems represent an alternative to the present grouting systems. On the projects West Side CSO Portland and Metro Line 1 Naples (Project descriptions, see Appendix B), the application of a two component mortar injection through the tailskin was intended.

The TBMs were equipped with four frequency controlled screw pumps for the mortar and four peristaltic pumps for the accelerator.

The mixing between component A and component B takes place shortly before the mix exits the tailskin. The accelerator is injected into the mortar via a nozzle. With the test set-up described in the next section, it can be verified that the backfilling of the annular gap through the tailskin with two components is possible and that clogging in the lines due to hardening of the backfill material can be avoided.

7.2.3 Active Mortar Tests

A test set-up was designed and built by Herrenknecht AG for modeling the mixing function of the two component mortar in the tailskin and for modeling the reaction of the two components to be used for the project West Side CSO Portland.

For this active mortar tests were undertaken with backfill components manufactured by two different suppliers, Condat Corporation from France and Mapei SpA from Italy (data sheets of the components see Appendix C). The products of both suppliers were evaluated for grouting of the Portland tunnels.
The objectives of the tests were:
- to achieve a homogeneous filling of the annular gap,
- to identify if the final mixes effected by flow rate and/or mortar pressure
- to evaluate clogging problems in the accelerator line.

7.2.3.1 Test equipment for active mortar tests with two component backfill material

The general layout of the test set-up is illustrated in Figure 7.7. It consisted of two tanks, one for component A (base mortar) and the second for component B (accelerator). Each tank was connected to the mixing line connected to the mixing chamber.

Figure 7.7 Scheme: test set up for active mortar tests
The base mortar was mixed and pumped to the grouting line by means of a 4 kW pump. The accelerator was pumped through a ½ inch line to the injection line.

The injection pipe consisted of an outer pipe with an internal diameter of 250 mm. Within this pipe a pipe pig was located through which the injection line with a nominal diameter of 50 mm was lead. The pipe pig and the injection line were installed movable on a frame in order to vary test settlement.

The duct for the accelerator supply was installed centered in the injection line as a plastic hose inside of the injecting line. By changing the length of the plastic hose, the position of mixing component A and component B could be varied.

The injection nozzle for injecting the accelerator is a tube closed at one end. It contained lateral bores of small diameter with small recesses in which plastic seals were fixed to close the bores. In operation the seals were raised by the accelerator-pressure.

In order to be able to monitor the test at any time, a data logger was used. For each of the two component supply lines the pressures and the flow-rates were measured. In addition the pressure at the end of the injection pipe and the frequencies of the pumps were measured.

The pressures were displayed on pressure gauges and pressure transducers were used to convert the signals for the data logger. The flow rates were determined by means of inductive flow meters. The signals were digitally recorded in one second intervals. The tests worked as follows:

A piston was used to seal the chamber water-tight and a certain pressure within the chamber was retained. Once that pressure was reached, the piston started moving backwards and the chamber was filled with mortar.

Both lines for component A and component B as well as the mixing chamber were equipped with flow meters and a pressure gauges.
7.2.3.2 Active Mortar Test with Condat products

The products Condastab and Condacc manufactured by Condat / France were tested first.

Condat two component mortar

The composition of the mortar mix used for the tests corresponds to the mortar mix used for Metro Line 1 Naples.

The two component test-mix lead to the following Condat recommendations for the Project West Side:

<table>
<thead>
<tr>
<th>Component</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>801.0 kg</td>
</tr>
<tr>
<td>Bentonite</td>
<td>46.8 kg</td>
</tr>
<tr>
<td>Cement</td>
<td>241.8 kg</td>
</tr>
<tr>
<td>Condastab</td>
<td>2.6 kg (Condat)</td>
</tr>
<tr>
<td>Condacc</td>
<td>137.0 kg (Condat)</td>
</tr>
</tbody>
</table>

Condastab is a stabilizer added to the base mortar (Component A) to avoid the hydration of cement. Condacc is the accelerator which is mixed with the base in the mortar line. The ratio is 9 parts component A to one part component B (accelerator).

Figure 7.8 depicts the setting behavior of the backfilling material consisting of base mortar (A) and accelerator (B). After 10 minutes the hardening process slowed down.
Figure 7.8 Setting behavior of active mortar (two component grout) with products of Condac

Testing Program for active mortar tests

The test program for the active mortar tests (two component mortar) consisted of:

- Calibration tests
- Mixing tests
- Start-stop tests.

The calibration tests were necessary to determine the required pressure to move the piston. Water was then pumped into the chamber until the piston started to move. The chamber pressure was monitored. Within the calibration tests the characteristics of the pumps were checked and frequency, pressure and flow rates were monitored at different stages.

In mixing tests different flow rates were tested and analyzed with respect to the homogeneity of the mix. The flow rates were chosen based on flow rates
frequently found in real TBM applications. Different types of mixing conditions were
tested, i.e. different injector types and different mixing locations.

In real applications supply of the two components has to be cut off in stages to
avoid any hardening of the grout in the mortar mixing line when interrupting the
grouting process.

*Start-stop-tests* were carried out to identify the necessary delay between cut-
off of the base mix supply and supply of the accelerator. Based on the observations in
the mixing tests, the delays were selected.

For emergency stops (i.e. supply of both components cut off at the same time)
re-start tests were undertaken.

Tests for breaking up blockages in the grouting line have been performed. For
both tests a blockage of mixed mortar, approximately 15 cm long, was plugged into
the end of the mixing line. In a first test a shutdown period of 14 h and in a second
test a shutdown period of more than 60 h were simulated.

**Results of test program**

- The *calibration tests* showed that the piston started moving if the
  chamber pressure exceeded 1.9 bar. See Figure 7.9. This value may be
  exceeded in the beginning because of the difference between adhesion
  and sliding friction. Also the value is slightly dependent on velocity and
to a lesser extent on time.
The pumping tests showed that the flow rate of the pump is not affected by pressure changes while the flow rate of a larger spiral pump reacted sensitively to pressure changes. Manual frequency adjustment was necessary to maintain a constant flow rate during the tests.

The mixing tests started with the injector in the back-most piston position that is the best to prevent clogging. Figure 7.10 depicts a typical view of the mixed mortar approximately 10 minutes after the start of the test.
To prevent the clogging of grout lines a staged shut-down was implemented. First the accelerator supply was switched off and 10 seconds later the base mortar pump. The result of the start-stop-testing is shown in Figure 7.11. The injector is clearly visible in the center of the pipe in Figure 7.11. The visible injector shows that a flushing of the line with component A for 10 seconds after the component B flow was stopped was sufficient to prevent the line from clogging.

Figure 7.11 Injector after 10 seconds delay between switching-off of accelerator and base mortar flow (Start-stop-testing)

Also some start-restart-tests have been performed. Shortly after the beginning of the test the staged shut-down was implemented.

Using a staged start-up is essential because if there is any clogging in the mortar line, the accelerator starts running backwards towards the base mortar pump. The two blockage removal tests showed that the pressure increase in the mortar line was not significant.

With the test program performed it is shown that backfilling the annular gap with two components in TBM tunneling through lines incorporated in the tailskin is possible. Pressurized conditions (see Figure 7.9) and different flow rates have been
simulated. It was found that there is no interdependence of flow rate and homogeneity.

The suitability of the two component system referring to clogging and cleaning behavior was tested under realistic conditions with the result that staged start-up and shut-down provide good means to minimize the risk of clogging.

7.2.3.3 Active Mortar Tests with products from Mapei

The same tests and test set-up for the products from supplier Mapei SpA of Italy were conducted in order to specify the requirements for the grouting components to be used in Portland.

Mapei two component mortar

The mix with products from Mapai is composed as follows:

<table>
<thead>
<tr>
<th></th>
<th>Formula #1</th>
<th>Formula #2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>870.0 kg</td>
<td>842.0 kg</td>
</tr>
<tr>
<td>Bentonite</td>
<td>34.7 kg</td>
<td>35.8 kg</td>
</tr>
<tr>
<td>Cement</td>
<td>231.0 kg</td>
<td>238.0 kg</td>
</tr>
<tr>
<td>Fly ash</td>
<td>46.7 kg</td>
<td>101.0 kg</td>
</tr>
<tr>
<td>Mapeistab</td>
<td>2.3 kg</td>
<td>2.4 kg</td>
</tr>
<tr>
<td>Mapeiquick</td>
<td>51.0 kg</td>
<td>83.0 kg</td>
</tr>
</tbody>
</table>

Mapeistab is a stabilizer that is added to component A (base mortar) to avoid hydration of cement. Mapeiquick is the accelerator mixed with component A in the mortar line.

Herrenknecht AG received two different mixes from Mapei SpA using different cements. The main difference between the two mortar formulae was the content of fly ash and water. The other ingredients needed to be adjusted in order to maintain certain properties of the fresh and hardening mortar.

To gain a first impression of the properties of the grouting material of the two different formulas some hand-mixing tests were performed. These quantities were rather small and a laboratory style of mixer was used. Ten to fifteen minutes after the
accelerator was mixed with the base mortar (component A) the sample was turned over and a “cake” was created. Figure 7.12 shows the hardening mortar cakes. The four cakes are made with different mixes.

Figure 7.12 Setting behavior with different formulas of active mortar with products of Mapai SpA

However, after visual inspection of the cores and penetration tests by hand there was no obvious difference in the behavior of the two types of cement. Between the two formulas there are visual differences as well as differences in strength because the water content of formula 1 is higher than the content of formula 2 where excess water was visible in the third and fourth sample. Also a slightly higher “slump” was noticed.
Testing program for active mortars tests

For the Mapai products two mixing tests and clogging tests were also performed. Earlier tests with the Condat products showed that there are no significant influences of the flow rate, position of the injector and the type of injector. This is the reason why the test series was limited to two identical tests in terms of flow rate and injector set-up.

Clogging tests were conducted by drying the injector under air, a situation unlikely to occur only under real conditions.

The test was performed by not cleaning the injector between the test runs. For the Mapei product the drying period was two months.

The results of the test program with the product manufactured by Mapei can be summarized as follows:

The first mixing test revealed some problems because the mortar did not harden as expected from the samples. The reason was a long delay between stopping the flows of both components A and B.

The mixing tube was only filled with fluid base mix. This prevented any clogging of the lines and the injector.

In the second mixing test the flow in both injection lines was switched off at the same time. The results were a solid mortar-body as illustrated in Figure 7.13 and a clogged injection line A.

Figure 7.13 Mixing test: Material immediately after opening the flange
Clogging tests with the injector dried under air showed that the injector was still operative. Water was pumped through the injector to examine a possible impairment of the spraying pattern. A slightly asymmetrical pattern was visible in the beginning of the test adjusting itself within seconds.

The visual inspection of the injector and the sleeves revealed no signs of wear even though the same injector was used in three different testing programs over a total period of more than four months. In total 25 tests were conducted.

The test program performed with Mapei products showed that it is possible to backfill the annular gap of the TBM through the tailskin without the mortar lines getting blocked by hardened material. Staged start-up and shut-down again showed to be an appropriate means of avoiding clogging.

7.2.3.4 Results of active mortar tests with products from two different suppliers

Tests have been performed with products from both manufacturers, Condat and Mapei. The tests have formed the basis for the first application of the two component low pressure backfill system in two Mixshields of Herrenknecht AG used on the project West Side CSO Portland. In the test series an initial calibration test was followed by tests to examine the mixing characteristics of products of both suppliers. Good mixing was achieved with a chamber pressure of 3 bar. The result was a well-mixed mortar body with the specified hardening properties.

A further focus of the active mortar tests was to identify means to avoid clogging in the injection-lines. As a general result staged start-up and shut-down of mortar and accelerator pumps are recommended for this purpose.

Within the framework of these tests at Herrenknecht AG, not only the mortar mixture was developed but also different accelerator injector types.

The active mortar mixing system comprises an injection line (DN 30mm), an accelerator line (DN 6mm) inside the 30mm diameter line for component A, and a
mixing nozzle located close to the rear end of the shield tail as illustrated in Figure 7.14.

Figure 7.14 Schematic of shield tail with the position of the injector.

1  Inspection hatch  
2  Flexible pipe (accelerator line)  
3  Mixing nozzle

An appropriate mixing section within the grout line minimizes the risk of blockages in the grout lines.

An important feature of the two component grouting system is the correct positioning of the injector at the shield tail facilitating cleaning of the grout line by switching off the accelerator supply earlier than the supply of the base mix. Component A is used to flush and clean the injection line. Thus no grout with accelerator remains in the pipe. If, for any reason that may occur, the correctly chosen injector location minimizes the section to be cleaned. Both accelerator pipe and the injector are designed as low-cost parts that should be replaced at regular intervals. In very difficult clogging conditions the entire accelerator line can be pushed back and retrieved from the grout pipe.

The following illustrates the steps to development an appropriate injector.
7.2.4 Development steps of an optimum low pressure injector design for B-component injection

The two component annular gap backfill system is an alternative to the conventional systems.

Until now the mortar mixture was injected through a piper cross section-with nominal diameter of 50 mm and 65 mm respectively in the annular gap. At present both systems are installed on Herrenknecht TBMs. The conventional system suits as fail-over system.

Figure 7.15 shows the circular pipe cross section of the two component grouting system installed parallel to the conventional oval injection profile. The pipe cross section of the suspension line is a circular section with a nominal diameter of 30 mm. Through this line component A is injected. Inside the 30 mm diameter line the injection hose for component B with a nominal diameter of 6 mm is visible.

Figure 7.15 Conductor cross sections of the two component system with redundant design (Drawing number 1582-001-003-01, 04.03.2005, Herrenknecht AG)
During TBM advance with a two component grouting system, the two components are injected with a maximum pressure of 16 bar.

With the two component injection, improved flow properties of the injection medium can be obtained due to its liquid consistency. The consistency influences the size of the injection pipe cross section. With a liquid two component medium a much smaller profile can be selected, having the advantage that smaller pumps can be used for the annular gap backfilling.

In this thesis experiences have been gathered to describe the development of the two component backfill system both with small-scale tests and practical experience. The objective is to extend the knowledge with regards to the constitution of the injection mix and design of the nozzle for the injection of component B.

In the following, the development steps of different injector types for the low pressure two component grouting system is summarized in detail in Table 7.1

Table 7.1 Development steps of an appropriate injector design for component B.

<table>
<thead>
<tr>
<th>Development steps</th>
<th>Injector Design</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>N° 1</td>
<td>Injector with four bore cross sections and four packers.</td>
<td>Installed in the projects West Side CSO Portland and Metro Line 1 Naples. Clogging of injection lines because material collected under the packers (silicone rings).</td>
</tr>
<tr>
<td>N° 2</td>
<td>Injector with one bore cross section and one packer.</td>
<td>Shorter design and thus more flexible. Washer at the injector end for better distribution of B-component in the base mix (component A).</td>
</tr>
<tr>
<td>N° 3</td>
<td>Injector with a steel casing</td>
<td>Robust design with steel casing. No rubber sealing (silicone rings). No material clogging at the injector outlet due to leakage. Easy to disassemble.</td>
</tr>
</tbody>
</table>
7.2.4.1 Step No 1: Injector with four bore cross sections and four packers

An injector with four bores and four packers (silicone rings) was designed by Herrenknecht AG as shown in Figure 7.16.

Figure 7.16 Injector for component B with packers. (1. Silicone packers, 2. Injection openings).

Via this injector the B-component is injected into the suspension (component A) resulting in a homogenous backfill mix.

With increasing pressure in the accelerator hose the silicone sealing rings closing the openings of the injector are lifted and allow component B to flow out. Due to the beveled profile in which the silicone packers are placed, the accelerator is deviated in a radial direction and component B is homogeneously mixed with the base backfill material. The mix starts hardening after a relatively short time and is capable of bearing load.

Upon completion of the injection flow of component B is switched off first. Due to the decreasing counter pressure, the silicone packers close the injector openings while component A is still flowing in order to flush the line and to clean the injector from the accelerator to avoided clogging.

This injector type was installed in two Mixshields for the project West Side CSO Portland (Project description, see Appendix B) after the active mortar tests
described in chapter 7.2.3. The active mortar tests showed that a homogenous two component mix is achieved.

On site experience gained with this injector type during the EPB excavation on the project Metro Line 1 Naples showed that this design is disadvantageous because material is accumulated below the silicone rings resulting in improper accelerator distribution in the mix. Material accumulations at the corners of the sealing surface caused the silicone rings not to seal properly. Blockages in the injection lines occurred because base mix could enter the injector.

7.2.4.2 Step No 2: Injector with one bore cross section and one packer

The injector design as described in step 1 was improved. The objective was to avoid injection material accumulating below the packers and that maintenance of the injector via a lock is possible.

The experience gained with the initial injector design showed that after a short application time (over about 6 meters of TBM advance) the rubber lip at the injector was damaged with the result that the packer was clogged with material. This led to blockage of the injection line and complete destruction of the silicone seals resulting in blocked openings. Design changes were made: a protecting cage consisting of three steel rods was welded to the injector head to avoid loss of silicone rings. This modification led to an increased life span of the nozzle; 37 rings were erected with the same nozzle. During the visual inspection of the nozzle the silicone rings were still present as shown in Figure 7.17.
After a week of excavation the openings of the injector and the injection lines for component A clogged again because of loose silicone rings allowing the grout to enter the nozzle. The lines became blocked at an injection pressure in excess of 5 bar. The blockages could be removed with an injection pressure higher 16 bar.

The design of the injector was still not satisfactory because replacement of a single injector took three hours. After the replacement of the injector in one line another would soon be blocked.

Instead of using 4 bores an injector with a larger diameter was designed, equipped with only one injection bore and one packer. The injector is shorter and consequently easier to service via lock even under high pressure.

A further feature is a washer at the end of the injector. It facilitates better distribution of the accelerator in the component A (see Figure 7.18).
Figure 7.18 Optimized injector design (one bore and one packer).

This design was still not satisfactory with regards to operation. The aim was to increase the life span of the injector under higher injection pressures to allow for several weeks of excavation without injector replacements. This lead to the third design.

7.2.4.3 Step N° 3: Injector with a steel casing

A new injector was designed with the condition that the outlet of the injector is sealed while there is no flow of component B through the accelerator line. This injector design differs from the previous designs in the way that it does not contain rubbers to close the opening. This new injector type consists of following parts (see Figure 7.19):

- Compression spring
- Support of the spring to give tension to the spring with the screw
- Hexagon nut
- Steel casing
- Support on the steel case to tension the spring
- Screw
- Plate as sealing washer of the injector.
Figure 7.19 Schematic representation of the mechanism of a new injector type (Cresto, Herrenknecht AG, 2005, p. 3)

The injector at the end of the accelerator line opens at a pressure of 5 bar. It comprises a spring housed in a steel casing. The compression spring is fixed on one side to the case, on the other side a conical valve gate is attached which seals the outlet of the injector.

By means of a screw the spring load can be adjusted so that the valve gate opens at a defined pressure difference. Then the accelerator can flow out of the injector and mixes with the base mortar. At the end of the injection process the pressure in the accelerator line drops and the gate seals the outlet of the injector.

This system only works if the pressure in the base mortar line is less than in the accelerator line so that no mortar can penetrate into the injector. Due to its robust and hydrodynamic shape the injector steel body is well protected against wear resulting from material flow.

If the injector is removed from the tailskin it can easily be cleaned. The risk to damage the injector body during disassembly is minimized by its dimensions.

This new injector design (N°3) was tested in one of two EPB-Shields used on the construction of the Metro Line 1 in Naples. The injector was installed as close as
possible to the rear end of the tailskin to enable easy cleaning of the injection lines and to avoid blocking of the line due to remaining B-component around the injector. (See Figure 7.20).

Figure 7.20 Design 3 injector for B-component installed in Ø30 mm grout line (EPB-Shield, Metro Line 1 Naples). Arrangement of injection groups A1 to A4 in the tailskin. (Lines 2, 3, 6 & 7 – DN30 mm, Lines 1, 4, 5 & 8 – DN50 mm)

Before installation in the two component backfill-system the injector was factory tested using water instead of accelerator. Using this injector on site it will open at 5 bar plus grout pressure. When the injection of component B is stopped, the injector closes slowly until reaching 2 bar. Figure 7.21 shows the injector during the test with water.
Figure 7.21 Factory-test to verify the function of the new injector design.

The application of the injector in the project Metro Line 1 Naples showed that:

- The injector welded to a pipe in the connection plate in the tailskin could easily be removed from the line.
- The injector was working well; opening and closing within the defined pressure range, e.g., from 3 to 8 bar, preventing material from entering the accelerator line.

Since the two component system, with maximum injection pressures of 16 bar, was first installed and tested in the Herrenknecht TBM for the projects West Side CSO Portland and Metro Line 1 Naples, it has now been adopted in several Herrenknecht machines in European and international projects summarized in Figure 9.1 (chapter 9).
7.2.5 Definition of a two component mixing formula against grout washout in the annular gap

In chapter 7.2.3 the tests for two component grouts have been discussed in a test set up to meet the specific project requirements of backfilling the annular gap for the projects West Side CSO Portland and Metro Line 1 Naples. One result was the development of an injector for the accelerator line. The injector is more robust, has extremely low maintenance requirements and generates a homogenous two component mix.

The objective of this chapter is the definition of the most suitable mixing formula for highly permeable soils where groundwater flow leads to a wash out of backfill material in the annular gap, as encountered in the project West Side CSO Portland (Project description, see Appendix B). Because of problems with the application of the dynamic grouting system and difficulties to adjust the two component mix to the permeable soil conditions encountered on the project West Side CSO Portland, the site management decided very early in the project to use the conventional backfill system for the rest of the tunnel section.

To handle backfilling in soil conditions as encountered on the project West Side CSO Portland, various mortar tests have been carried out. New formulae were defined and comparison tests have been conducted. Five formulae (see Figure 7.5) with different water, bentonite and cement concentration have been compared to define the most suitable formula for a shorter hardening time of the grout.

Modifications to the formula to meet requirements to avoid wash-out have been tested in an experimental set up described in chapter 7.2.6. It is shown that the formula of the two component mix is stable in highly permeable soils with high water pressure.
7.2.5.1 General criteria of two component backfilling material

The tests described below (see Table 7.2) validate that this newly developed dynamic grouting material fulfills the testing requirements defined in EFNARC (EFNARC 2005, p. 17) and

- Undergoes little separation or dilution either in ground with abundant groundwater or in running water
- Is self supporting and will provide good filling properties at the same time as its flowability is adequate
- Is a material with a low specific gravity to avoid heavy load on the lining
- Is easy to handle on the construction site
- Is economical and not harmful to the environment.
Table 7.2  Tests used to assess two component backfilling material (laboratory and/or field tests)

<table>
<thead>
<tr>
<th>2-Component-mixture performance characteristics (Testing requirements)</th>
<th>Test methods</th>
<th>Test Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bleeding and segregation of 2-C-mixture</td>
<td>- Inclined Tube test</td>
<td>&lt; 4% bleeding of 2-C-mixture</td>
</tr>
<tr>
<td></td>
<td>- Baroid filter press</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Wick-Induced Bleed test</td>
<td></td>
</tr>
<tr>
<td>Flow time of mixture and viscosity</td>
<td>Marsh Cone</td>
<td></td>
</tr>
<tr>
<td>Consolidation, sedimentation of mixture</td>
<td>- Sedimentation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Consolidation test</td>
<td></td>
</tr>
<tr>
<td>Setting time of mixture</td>
<td>Vicat Test</td>
<td>- 5-10 kN/m² at 30 minutes,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- 0.5 MPa at 1 hour,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- 2 MPa at 2 hour</td>
</tr>
<tr>
<td>Gradation of mixture (all aggregates)</td>
<td>Grading curves (Standard Test method for particle-</td>
<td>Well graded</td>
</tr>
<tr>
<td></td>
<td>size-analysis of soils)</td>
<td></td>
</tr>
<tr>
<td>Workability (easy pumpable)</td>
<td>Standard slump cone test</td>
<td></td>
</tr>
<tr>
<td>Shear strength; internal friction</td>
<td>- Triaxial cell test</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Cone Penetrometer test</td>
<td></td>
</tr>
<tr>
<td>Unconfined compressive strength of backfilling material</td>
<td>Standard cube test</td>
<td>- after 24 hrs: 1 N/mm²,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- after 28 d: &gt; 1 N/mm²,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt; 3 N/mm²</td>
</tr>
<tr>
<td>Permeability</td>
<td>Laboratory permeability test</td>
<td>&lt; 10⁻⁷ m/s</td>
</tr>
<tr>
<td>Cohesion</td>
<td>Laboratory vane apparatus</td>
<td></td>
</tr>
</tbody>
</table>
7.2.5.2 Testing methods and formulas for two component mix (Condat products) for application in permeable soils

As a first step, a small scale test was conducted with products from Condat. The following tests were based on the geological conditions of the project West Side CSO Portland (Project description, see Appendix B) because the soils encountered had a very high permeability discovered when trying to backfill the annular gap in the launch phase of TBM resulting in wash out of backfill material in the annular gap.

Table 7.3 shows the essential soil properties on the West Side CSO Portland project. The soil conditions were used as reference soil because of its permeability to investigate the effect of the properties of the backfill mix to permeable soils.

As a second step, five formulas (see Table 7.5) were developed to compare the different characteristics of the mixes and to take the most suitable one for the follow-up tests. A test set up was developed to prove that the selected backfill mix composition withstands the washout in permeable soils and running water conditions. Rapid setting is required in strata where groundwater flow may displace the grout during injection.

Table 7.3 Soil-mechanical parameters, project West Side CSO Portland

<table>
<thead>
<tr>
<th>Layer</th>
<th>Bulk density [kN/m²]</th>
<th>Buoyant unit weight [kN/m³]</th>
<th>Inner angle of friction [°]</th>
<th>Cohesion of soil [kPa]</th>
<th>Young's modulus [MPa]</th>
<th>Poisson's ratio [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fill</td>
<td>20 (*)</td>
<td>11 (estimation)</td>
<td>30</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Sand/Silt Alluvium</td>
<td>17.9</td>
<td>10 (estimation)</td>
<td>25 - 39</td>
<td>0</td>
<td>17.5</td>
<td>0.35</td>
</tr>
<tr>
<td>Gravel Alluvium</td>
<td>22.3</td>
<td>13 (estimation)</td>
<td>40</td>
<td>0</td>
<td>73.2</td>
<td>0.3</td>
</tr>
<tr>
<td>Troutdale Formation — very dense gravel with-in a fine-grained matrix of clayey silt to sand</td>
<td>22.6</td>
<td>13 (estimation)</td>
<td>40</td>
<td>0</td>
<td>97.6</td>
<td>0.3</td>
</tr>
</tbody>
</table>
7.2.5.2.1 Preliminary tests

A series of four tests listed below were undertaken based on the geological conditions of the West Side CSO Portland project.

1. Development of viscosity with time
2. Hardening process of liquid A captured inside mortar
3. Evaluation of the influence of water on hardened two component mix
4. Comparison of the hardening process of the two component mix placed in air, water or liquid A.

Test 1: Development of viscosity with time

The backfill mix is composed of a liquid component A and a liquid component B. The component A comprises:

<table>
<thead>
<tr>
<th>Component A</th>
<th>Component B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>801.0 kg</td>
</tr>
<tr>
<td>Bentonite</td>
<td>46.8 kg</td>
</tr>
<tr>
<td>Cement</td>
<td>241.8 kg</td>
</tr>
<tr>
<td>Condastab</td>
<td>2.6 kg</td>
</tr>
<tr>
<td>Condacc</td>
<td>137.0 kg</td>
</tr>
</tbody>
</table>

The backfill mix was adjusted to the permeable soil conditions of the project West Side CSO Portland in terms of quicker hardening of the two component mix in the annular gap despite high water inflow. The mixture shown above is sufficient for 1000 liters of backfill mix.

Condastab is a stabilizer, which is added in form of powder to the base mortar to avoid the hydration of the cement.

The liquid component B, an accelerator additive, is Condacc. It is mixed with liquid A at the end of the mortar line. The ratio is 9:1.

Condastab (stabilizer) and Condacc (accelerator) are both products manufactured by the French company Condat. A key quality for the freshly prepared component A must be that it can be pumped easily into the grout lines, i.e. must have
a relatively low viscosity. In the tests the flow time of a given quantity of grout from a
cone was used as a measure for the viscosity.

The viscosity was tested with a Marsh Cone. Table 7.4 shows that during the
first 72 hours, the Marsh viscosity of liquid A was stable. This is an indication that
problems during injection as a result of stiffening is avoided - component A can be
used without any problems for the two component mix. The only condition was to
agitate liquid A to avoid segregation of water and to keep the A-component easily
workable.

Table 7.4  Development of viscosity with time.

<table>
<thead>
<tr>
<th></th>
<th>Marsh Viscosity (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Just after mixing</td>
<td>40 s - 43 s</td>
</tr>
<tr>
<td>At 24 hours (with agitation)</td>
<td>39 s - 42 s</td>
</tr>
<tr>
<td>At 72 hours (with agitation)</td>
<td>41 s - 44 s</td>
</tr>
<tr>
<td>At one week (with agitation)</td>
<td>Impossible to measure</td>
</tr>
<tr>
<td>At two weeks (with agitation)</td>
<td>Impossible to measure</td>
</tr>
<tr>
<td>At one month (with agitation)</td>
<td>Impossible to measure</td>
</tr>
</tbody>
</table>

Test 2: Hardening process of liquid A captured inside mortar

This test shows that with a staged shutdown of the mortar pumps (a measure to
prevent clogging in the injection lines), component A alone also hardens. In this test,
the liquid component A was surrounded by freshly mixed components A & B as
shown in Figure 7.22. This simulates the situation of backfilling the annular gap with
only component A added to the previously injected two component mix.
Figure 7.22 Layout of the design of the hardening test.

The test showed that the presence of liquid A didn't prevent hardening of the two components. After 24 hours, the volume of component A was reduced due to the release of filtrate water. After 72 hours, the volume was further reduced with a thickened component A. After one week component A had the same hardness as components A & B.

With this test it was shown that component A hardens in the annular gap even without adding component B. Liquid B serves only as an accelerator resulting in quicker hardening and thus faster bedding of the tunnel tube in the surrounding soil.

Test 3: Evaluation of the influence of water on hardened two component mix

A nearly hardened block of two component mix was immersed in water to simulate almost real tunnel boring conditions. The surface of this block of backfill mix was soft on 1 to 2 mm. After a period of 24 hours the block was inspected. It was still hard and the first 1 to 2 mm of its surface were still soft. The same state was found 72 hours later.

After one week the immersed block was still hard but the surface became softened to a measured depth of 3 mm. This condition did not change after a further week of visual inspection.
Test 4: Comparison of the hardening process of the two component mix placed in air, water or liquid A.

Tests 2 and 3 showed that environments like air, water or component A have no influence on the hardening process of the backfill mix. The hardening process in all three cases has the same speed and results in the same development of strength.

7.2.5.2.2 Comparison of different formulas

Several formulas were developed with characteristic compositions of component A and different percentages of component B (Table 7.5). The objective to compare different mixes was to find a formula optimized for resistance against water washout and quick setting.

The component A is composed of the basic ingredients water, bentonite, cement and Condastab (stabilizer). Component B is the Condat accelerator additive Condacc.

Table 7.5 shows the configuration of five formulas for component A adapted to the permeable soil conditions of the project West Side CSO Portland.

Analysis of the results shown in Table 7.6 indicates that in terms of hardening formula # 5 furnishes the best results.

Mixes harden in the order 5 - 1 - 4 - 2 - 3. The less liquid B (accelerator) is injected the faster the hardening process, however with lower strength. Formula # 5 with 95% A and 5% B shows the best results in terms of hardening time.

Aging tests of component A were carried out. The table below shows no significant differences of all 5 formulas.
Table 7.5  Compositions of component A for backfill application in Portland in kilogram in direct comparison.

<table>
<thead>
<tr>
<th></th>
<th>Formula # 1</th>
<th>Formula # 2</th>
<th>Formula # 3</th>
<th>Formula # 4</th>
<th>Formula # 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>WATER</td>
<td>776 kg</td>
<td>801 kg</td>
<td>836 kg</td>
<td>811 kg</td>
<td>776 kg</td>
</tr>
<tr>
<td>BENTONITE</td>
<td>60 kg</td>
<td>48 kg</td>
<td>50 kg</td>
<td>55 kg</td>
<td>40 kg</td>
</tr>
<tr>
<td>CEMENT</td>
<td>300 kg</td>
<td>287 kg</td>
<td>250 kg</td>
<td>270 kg</td>
<td>320 kg</td>
</tr>
<tr>
<td>CONDASTAB</td>
<td>3 kg</td>
<td>2.9 kg</td>
<td>3 kg</td>
<td>3 kg</td>
<td>3 kg</td>
</tr>
<tr>
<td>Total</td>
<td>1139 kg</td>
<td>1138.9 kg</td>
<td>1139 kg</td>
<td>1139 kg</td>
<td>1139 kg</td>
</tr>
</tbody>
</table>

Table 7.6  Hardening times in seconds for the five formulas with varied proportions of component A and B.

<table>
<thead>
<tr>
<th>Formula #</th>
<th>90% A – 10% B</th>
<th>92% A – 8% B</th>
<th>94% A – 6% B</th>
<th>95% A – 5% B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>thick*</td>
<td>hard**</td>
<td>thick*</td>
<td>hard**</td>
</tr>
<tr>
<td>#1</td>
<td>15 s</td>
<td>40 s</td>
<td>12 s</td>
<td>33 s</td>
</tr>
<tr>
<td>#2</td>
<td>17 s</td>
<td>60 s</td>
<td>15 s</td>
<td>51 s</td>
</tr>
<tr>
<td>#3</td>
<td>19 s</td>
<td>60 s</td>
<td>15 s</td>
<td>44 s</td>
</tr>
<tr>
<td>#4</td>
<td>15 s</td>
<td>45 s</td>
<td>14 s</td>
<td>35 s</td>
</tr>
<tr>
<td>#5</td>
<td>12 s</td>
<td>30 s</td>
<td>11 s</td>
<td>25 s</td>
</tr>
</tbody>
</table>

* : Beginning of thickening (seconds)  ** : Beginning of hardening (seconds)

Table 7.7  Comparison of the density of component A dependent on the formula

<table>
<thead>
<tr>
<th>Formula</th>
<th>Density [kg/m³] of component A</th>
<th>After mixing</th>
<th>After 30 hours</th>
<th>After 72 hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>1.24</td>
<td>1.24</td>
<td>1.23</td>
<td></td>
</tr>
<tr>
<td>#2</td>
<td>1.22</td>
<td>1.22</td>
<td>1.21</td>
<td></td>
</tr>
<tr>
<td>#3</td>
<td>1.19</td>
<td>1.19</td>
<td>1.18</td>
<td></td>
</tr>
<tr>
<td>#4</td>
<td>1.24</td>
<td>1.22</td>
<td>1.21</td>
<td></td>
</tr>
<tr>
<td>#5</td>
<td>1.25</td>
<td>1.25</td>
<td>1.24</td>
<td></td>
</tr>
</tbody>
</table>
7.2.5.2.3 Requirements and testing results of two backfill mixes configured for the application in high permeable soils with presence of running water

One of the requirements for the application of backfill material in soil conditions with running water is a homogeneous, stable and low permeable mix that resists getting washed out from the annular gap.

Herrenknecht AG has performed tests in cooperation with Condat at their laboratories. The laboratory tests (see Table 7.2) evaluated two specifically configured formulas for the two component backfill mix. The formulas were adapted to the soil conditions as experienced in the project West Side CSO Portland.

The two formulas are

- Condat – Formula FHK 0464 A (without fly ash).
- Condat – Formula FHK 0464 B (with fly ash).

The composition of component A for both formulas is given in Table 7.8.

Formulas FHK 0464 A and FHK 0464 B are the best compromise with regards to density, viscosity, stability and mechanical properties compared to the other four formulas detailed in Table 7.5.

<table>
<thead>
<tr>
<th>Components (kg)</th>
<th>Condat – Formula FHK 0464 A</th>
<th>Condat – Formula FHK 0464 B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>776</td>
<td>776</td>
</tr>
<tr>
<td>Bentonite</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Cement</td>
<td>300</td>
<td>150</td>
</tr>
<tr>
<td>Fly ash</td>
<td>/</td>
<td>150</td>
</tr>
<tr>
<td>Stabilizer</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>
The materials used for the composition of component A are:

- Cement: VICAT cement – CEM II / BLL 32.5 R
- Fly Ash: was sent by the jobsite West Side CSO Portland (type of fly ash unknown)
- Bentonite: Cforage
- Stabilizer: Condastab
- Accelerator: Condacc

For both formulas eight typical characteristics of the backfill mix as listed below were assessed using the appropriate testing methods:

1. Grout density (component A)
2. Viscosity (component A)
3. Bleeding under atmospheric conditions (component A)
4. Bleeding under pressure (component A)
5. Stability under atmospheric conditions (component A)
6. Time of hardening (Two component mix)
7. Resistance against dilution by groundwater (Two component mix)
8. Mechanical properties (Two component mix)

1. Grout density, testing results for component A (without accelerator)

The grout density for both formulas FHK0464 A and FHK0464 B was tested. The density measurement serves as a control of the quality of the grout mix on site. The density of grout is an indication of the amount of water used in a grout mix. The density depends on the quantity of solid components like bentonite, cement and fly ash.

The test was done using a mud balance which is a beam balance consisting of a cup and a graduated arm carrying a sliding weight and is resting on a fulcrum. Component A was poured into the cup up to the attached mark and was balanced. The density was determined by reading the value on the scale of the mud balance. The density of the two formulas for component A are given in Table 7.9.
Table 7.9 Density of two formulas FHK 0464 A, FHK 0464 B (component A)

<table>
<thead>
<tr>
<th></th>
<th>Density [kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>FHK 0464 A</td>
<td>1.25</td>
</tr>
<tr>
<td>FHK 0464 B</td>
<td>1.24</td>
</tr>
</tbody>
</table>

The result shows that the density for the formula without fly ash (FHK 0464 A) shows a slightly higher density than the one using fly ash (FHK 0464 B) in the composition of component A.

2. Viscosity, test results for component A (without accelerator)

The tests are based on measuring the Fann viscosity with a Fann viscometer. Viscosity as property of fluids and slurries indicates their resistance to flow, defined as the ratio of shear stress to shear rate expressed as follows:

\[ \mu = \frac{\tau}{\gamma} \]  

(7.1)

where \( \tau \) = shear stress, \( \gamma \) = shear rate, \( \mu \) = viscosity.

The Fann viscometer has two speeds of rotation, 300 rpm and 600 rpm. The unit is centipoise (cp). After the moving cylinder is placed in the component A mixture, the values are logged at 300 rpm and 600 rpm. Then the viscosity and the yield point are calculated.

Figure 7.23 Test set up for measuring the Fann viscosity of formulas FHK 0464 A, FHK 0464 B
Figure 7.24 shows the measured values for viscosity and yield point of component A for both formulas.

![Fann Viscosities](image)

The test shows that both formulas for component A have the same viscosity behavior. Important is however that the viscosity after 72 hours for formula FHK 0464 B.
3. **Bleeding under atmospheric conditions, testing results for component A (without accelerator)**

Bleeding is the self-generated flow of mixing water or its emergence from freshly placed concrete or mortar as a result of consolidation. If the backfill mix is not consolidated it is possible that the shear strength is too low to counterbalance the buoyancy forces of the tunnel.

The bleeding under atmospheric conditions was tested with a wick-induced bleed test. The bleeding was measured after 6 hours and 72 hours with a graduated rule. The results are given in Figure 7.25.

![Figure 7.25 Bleeding under atmospheric pressure, testing of component A](image-url)
Figure 7.25 shows that no bleeding occurred after 6 hours for both formulas. After 72 hours formula F 0464 B with fly ash for component A showed reduced bleeding.

4. Bleeding under pressure, testing results for component A (without accelerator)

The bleeding under pressure was tested for both formulas with a Baroid filter press, a balance and a graduated rule.

Figure 7.26 Baroid filter press for the determination of bleeding under pressure

A cylinder was filled under pressure of 8 bars over 15 minutes. The remaining solids were deposited as a filter cake. The volume of filtrate was noted and the thickness of the filter cake was measured. The results are given in Figure 7.27.
Figure 7.27  Bleeding under pressure, testing of formulas FHK 0464 A, FHK 0464 B

<table>
<thead>
<tr>
<th></th>
<th>FHK 0464 A</th>
<th>FHK 0464 B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bleeding at 6 hours (%)</td>
<td>13</td>
<td>11.5</td>
</tr>
<tr>
<td>Cake thickness at 6 hours (mm)</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>Bleeding at 72 hours (%)</td>
<td>14</td>
<td>12</td>
</tr>
<tr>
<td>Cake thickness after 72 hours (mm)</td>
<td>8</td>
<td>6</td>
</tr>
</tbody>
</table>

Figure 7.27 illustrates bleeding under pressure. As already assessed in the previous test “bleeding under atmospheric conditions”, formula FHK 0464 B shows a better result although the difference is small. The results are summarized in Table 7.10.
Table 7.10 Comparison of the test results for the tests bleeding under atmospheric conditions and bleeding under pressure.

<table>
<thead>
<tr>
<th>Test #3</th>
<th>FHK 0464 A</th>
<th>FHK 0464 B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bleeding at 6 hours (%)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Bleeding at 72 hours (%)</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Test #4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bleeding at 6 hours (%)</td>
<td>13</td>
<td>11.5</td>
</tr>
<tr>
<td>Bleeding at 72 hours (%)</td>
<td>14</td>
<td>12</td>
</tr>
</tbody>
</table>

5. Stability under atmospheric conditions, testing results for component A (without accelerator)

The stability of the component A mix was tested using a sealed cylinder filled with component A. The liquidity was tested 72 hours later as per test 2. (viscosity). After 72 hours the component A was still liquid.

6. Time of hardening (setting), test results for two component mix (with accelerator)

Stiffening and setting of the two component backfill mix should not commence too early due to the risk of clogging in the lines during grouting but it should also not take too long, to avoid settlements. The setting behavior of the two component mix must be adjusted in such a way that the stiffness behind the shield suffices to accept the loads of the segmental lining and to stabilize its position.

The two formulas FHK 0464 A and FHK 0464 B have been tested using a mixture of 90 % A and 10 % B (accelerator). The hardening (setting) time was determined by a Vicat Needle. The test measures when the hydrating cement develops a finite value of resistance to penetration by the Vicat Needle. The final setting time is the time when the needle does not sink visibly into the material.
Figure 7.28 Comparison of hardening times for both formulas with a mixing ratio of 90:10

<table>
<thead>
<tr>
<th></th>
<th>FHK 0464 A</th>
<th>FHK 0464 B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start of hardening</td>
<td>11</td>
<td>15</td>
</tr>
<tr>
<td>End of hardening</td>
<td>28</td>
<td>52</td>
</tr>
<tr>
<td>Start hardening at 72 hours</td>
<td>13</td>
<td>18</td>
</tr>
<tr>
<td>End hardening at 72 hours</td>
<td>56</td>
<td>68</td>
</tr>
</tbody>
</table>

The results show that the accelerator (sodium silicate) reacted with the cement. The time of hardening / setting varies with the quantity of cement.

The setting time of a grout mix can be adjusted within certain limits to a desired value. This can be achieved by selecting a particular cement and by the use of suitable accelerating or retarding admixtures.

7. Resistance against dilution by groundwater, testing results for two component mix (with accelerator)

An important goal in the development of two component mixes is to achieve resistance against dilution by groundwater resulting in a long term homogeneous,
stable ring of low permeability around the tunnel lining. The two component mix was tested for both formulas using two different mixing ratios (95% A – 5% B and 90% A – 10% B).

The test equipment comprised a device designed by Condat with a turbidimeter.

Figure 7.29 Test equipment for determining the water washout: Device from Condat with a turbidimeter

The mix was soaked with water with a device designed by Condat to measure the turbidity of the water.

Figure 7.30 illustrates the test results showing that the wash-out property is a function of two parameters

- cement quantity
- grout/sodium silicate ratio.

100% stands for clear water and 0% for opaque water.
8. Mechanical properties, testing results for two component mix (with accelerator)

The rate of hardening of backfill material due to hydration is the speed at which the two component mix develops strength. The backfill mix must develop sufficient strength (dependent on prevailing soil conditions) to ensure sufficient long term bond between the ground and the tunnel lining.

The unconfined compressive strength of the two component mix with a ratio of 90% A and 10% B was tested with cube specimens (40mm x 40mm x 40mm). The strength after 3 and 7 days was measured. The results are illustrated in Table 7.11.

The strength development of the two component mix is dependent on the type and amount of cement.
Table 7.11 Test results of unconfined compressive strength test of cube specimens with two component mix

<table>
<thead>
<tr>
<th></th>
<th>FHK 0464 A</th>
<th>FHK 0464 B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unconfined compressive</td>
<td>[kg/cm²]</td>
<td>[kg/cm²]</td>
</tr>
<tr>
<td>strength at 3 days</td>
<td>0.1</td>
<td>0.05</td>
</tr>
<tr>
<td>Unconfined compressive</td>
<td>[kg/cm²]</td>
<td>[kg/cm²]</td>
</tr>
<tr>
<td>strength at 7 days</td>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>

Summary of the test results

The test results for the two components are summarized in Table 7.12.

Several formulas were elaborated with the objective to find the best compromise regarding:

- Grout density. The density depends on the quantity of solid components such as bentonite, cement, fly ash.
- Viscosity (component A). The viscosity depends on the quantity of solid components such as bentonite, cement, fly ash and on the quality of the stabilizer.
- Bleeding under atmospheric conditions (component A). The bleeding (segregation) depends on the quantity of the bentonite.
- Bleeding under pressure (component A). The bleeding under pressure depends on the quantity of the bentonite. Bleeding can be reduced with fly ash as additive.
- Stability under atmospheric conditions (component A). The stability depends on the quantity and/or quality of the stabilizer.
- Mechanical properties (Two component mix). The mechanical properties (unconfined compressive strength) depend on the quantity and/or quality of cement and fly ash and also on the percentage of accelerator.
Table 7.12 Comparison of two component mix characteristics for application in highly permeable soils with presence of running water.

<table>
<thead>
<tr>
<th>Properties of stable mix, component A (without accelerator)</th>
<th>Unit</th>
<th>Condat – Formula FHK 0464 A</th>
<th>Condat – Formula FHK 0464 B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volumetric weight (density)</td>
<td>kg/m³</td>
<td>1.25</td>
<td>1.24</td>
</tr>
<tr>
<td>Bleeding at 6 h</td>
<td>%</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Bleeding at 72 h</td>
<td>%</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Filtrate</td>
<td>ml</td>
<td>55</td>
<td>46</td>
</tr>
<tr>
<td>Filtrate (Bleeding)</td>
<td>%</td>
<td>13</td>
<td>11.5</td>
</tr>
<tr>
<td>Cake thickness</td>
<td>Mm</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>Filtrate at 72 h</td>
<td>ml</td>
<td>56</td>
<td>48</td>
</tr>
<tr>
<td>Filtrate (Bleeding) at 72 h</td>
<td>%</td>
<td>14</td>
<td>12</td>
</tr>
<tr>
<td>Cake thickness at 72 h</td>
<td>Mm</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>Viscosity Fann AV (Apparent Viscosity)</td>
<td>cp</td>
<td>68.3</td>
<td>68</td>
</tr>
<tr>
<td>Viscosity Fann PV (Plastic Viscosity)</td>
<td>cp</td>
<td>18</td>
<td>19</td>
</tr>
<tr>
<td>Yield Point</td>
<td>Pa</td>
<td>65</td>
<td>66</td>
</tr>
<tr>
<td>Viscosity Fann AV at 72 h</td>
<td>cp</td>
<td>79.2</td>
<td>93.2</td>
</tr>
<tr>
<td>Viscosity Fann PV at 72 h</td>
<td>cp</td>
<td>14.8</td>
<td>23.5</td>
</tr>
<tr>
<td>Yield Point after 72 h</td>
<td>Pa</td>
<td>62</td>
<td>67</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Water washing-out (with Condacc)</th>
<th>Condat – Formula FHK 0464 A</th>
<th>Condat – Formula FHK 0464 B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixing with sodium silicate 95A/5B</td>
<td>%</td>
<td>47</td>
</tr>
<tr>
<td>Mixing with sodium silicate 90A/10B</td>
<td>%</td>
<td>84</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Property of two component mix (with Condacc)</th>
<th>Condat – Formula FHK 0464 A</th>
<th>Condat – Formula FHK 0464 B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time start hardening (Vicat needle)</td>
<td>sec</td>
<td>11</td>
</tr>
<tr>
<td>Time end hardening (Vicat needle)</td>
<td>sec</td>
<td>28</td>
</tr>
<tr>
<td>Time start hardening (Vicat needle) at 72 h</td>
<td>sec</td>
<td>13</td>
</tr>
<tr>
<td>Time end hardening (Vicat needle) at 72 h</td>
<td>sec</td>
<td>56</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Unconfined Compressive Strength</th>
<th>Condat – Formula FHK 0464 A</th>
<th>Condat – Formula FHK 0464 B</th>
</tr>
</thead>
<tbody>
<tr>
<td>On cube 40x40x40 at 3 days</td>
<td>kg/cm²</td>
<td>0.1</td>
</tr>
<tr>
<td>On cube 40x40x40 at 7 days</td>
<td>kg/cm²</td>
<td>6</td>
</tr>
<tr>
<td>On cube 40x40x40 at 28 days</td>
<td>kg/cm²</td>
<td>/</td>
</tr>
</tbody>
</table>
7.2.6 Examination of washout resistance of two component backfill material for annular gap grouting

The annular gap between the outside of a segment ring and the soil, as an effect of TBM excavation is a structural risk with regards to bedding of the segments and surface settlements. Therefore, backfilling of the tail void is mandatory. Materials are injected via injection lines monitoring pressure and volume.

Damages to the segmental lining resulting from incomplete grouting of the annular gap can be caused by washed out backfill material in geologies with groundwater flow. Purpose of the annular gap backfilling is generally the stabilization of the tunnel ring in the surrounding soil, the preservation of the natural state of stresses in the surrounding soil in order to keep settlements limited and the sealing of the segments and the shield tail seals against groundwater ingress (water-tightness).

7.2.6.1 Washout resistance test for two component backfill material, “running water” tests

Based on the test results discussed in the previous chapter a test rig was designed and built to test the washout resistance of two component backfill material in the annular gap.

The following objectives were pursued with the “running water” tests in order to reflect on-site requirements:

- Prevention of backfill wash-out with backfill material adapted to permeable soil conditions and running water
- Achievement of pressure resistance within a short time. (Examination of strength properties with cubes 150mm x 150mm x 150mm after 3, 7 and 28 days)
- Testing of the functionality of the new injector type (steel case), see Figure 7.19
- Behavior during restart of pumping after long standstill (clogging of the injector?)
- Visual examination of the mixing ratio by using Ultra White Cement for component A and graphite powder (4 μm) for component B.

7.2.6.1.1 Test set-up and test material

For technical reasons the annulus was simulated by means of a steel vessel, i.e. it did not have the same curvature as the segment ring.

The setup consisted of the following components (see Figure 7.31):

- Pressure vessel for washout tests with running water:
  - Length of 600 mm
  - 300 mm diameter.
  - Port for water, pressure gauge and pressure regulating valve
  - Port for 2-component backfill mix
  - Pressure vessel 300 mm diameter with lateral openings for simulation of water flow.
- Mixing section (ID= 30 mm)
- Suspension line (ID= 30 mm) for component A
- Injection hose (ID= 6 mm) for component B
- Two pumps for components A and B
- A mixer for blending of component A.

The material for the test comprised a test soil with a grain size distribution curve similar to the soil found on the project Westside CSO Portland characterized by a permeable gravel alluvium as shown in Figure 7.32.
Figure 7.31 Test rig for two component injection tests

Figure 7.32 Grain size distribution curve “Gravel Alluvium”, project West Side CSO Portland (Red curve corresponds to the used test soil).
A two component backfill material based on the Condat products Condastab and Condacc was tested using a mixing ratio of 93% component A : 7% of component B for best possible compliance with the geological and hydrological conditions encountered in the West Side CSO Portland project (high permeability, flowing ground water).

The washout resistance tests in running water have been realized with two component material from Condat consisting of the following mixture:

Table 7.13 Two component mixture adapted to permeable soils with running water

<table>
<thead>
<tr>
<th>Component A</th>
<th>Quantity [kg]</th>
<th>Component B</th>
<th>Quantity [kg]</th>
<th>Quantity for 1 chamber filling (42l):</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>742</td>
<td>CONDACC</td>
<td>89</td>
<td>Volume [l]</td>
</tr>
<tr>
<td>Bentonite</td>
<td>46</td>
<td>Water</td>
<td>7</td>
<td>Weight [kg]</td>
</tr>
<tr>
<td>Cement</td>
<td>482</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CONDASTAB</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total weight Material A</td>
<td>1 274</td>
<td>Total weight Material B</td>
<td>96</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Volume [l]</td>
<td>Weight [kg]</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>31.3</td>
<td>31.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.8</td>
<td>2.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.6</td>
<td>20.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.2</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>38.9 l</td>
<td>54.1 kg</td>
<td></td>
</tr>
<tr>
<td>TOTAL VOLUME A + B</td>
<td>±1 m³</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>42 l</td>
<td>58.2 kg</td>
<td></td>
</tr>
</tbody>
</table>

The mixing of the two components was carried out for a 42 l batch. For the component A-mix various properties have been determined and are described in the following section.
7.2.6.1.2 Test set-up and course of testing

Before each washout test started, laboratory tests at Herrenknecht AG were used to determine the properties of the backfill component A.

Laboratory Tests

The following properties of component A, for application in permeable soils with running water, have been ascertained with various laboratory tests:

- Liquid flow limit of component A with ball harp (DIN 4126). Figure 7.33 a).
- Density of component A with mud balance. Figure 7.33 b).
- Viscosity of component A with Marsh funnel (EN445). Figure 7.33 c).
- Settling ratio of component A with measuring device. Figure 7.33 d).

Figure 7.33 Testing devices for the determination of properties of component A suspension. a) Ball harp  b) Mud balance  c) Marsh funnel  d) Measuring device.

The liquid flow limit of component A characterizes its consistency. The consistency of the mortar could be best described as mortar flow behavior and mortar
structure. Whether the mortar has a yield point and, should this be the case, which yield stress is necessary to overcome the yield point as well as the corresponding viscosity is important for the evaluation.

The measurement of the density is used to control the quality of component A. With an adjustment of the density, buoyancy effects can be balanced.

The viscosity is a useful value to characterize the consistency of the grout and to control the grout penetration. The viscosity generally gives information about the flow properties of the backfill component.

With information about setting ratio, the stability under atmospheric conditions can be determined. An objective is to avoid a release of water and the segregation of mixtures during injection. An eventual segregation would have a negative affect on strength and durability of the backfill.

After each of the 11 test runs to be described in this chapter, the two component mix was filled into concrete test cube moulds (150 mm x 150 mm x 150 mm) to determine the unconfined compressive strength (UCS) of the hardened backfill material after 3, 7 and 28 days. UCS tests were performed in the laboratory of company “Schöck Bauteile GmbH”, Baden-Baden.

Course of practical testing and test equipment

Washout resistance tests of two component backfill material were carried out at Herrenknecht AG in Schwanau between the 7th of March 2005 until the 18th of March 2005.

A test rig consisting of a steel tube and pipework for material transport and injection was designed and built. See Figure 7.34.
Figure 7.34 Test equipment for two components washout resistance tests.
a) B-component supply, b) A-component supply, c) injector position, d) water supply.

The annular gap is represented by a steel tube (Ø300 mm, length of 600 mm). It simulates an annular gap when excavating permeable sands below running groundwater. Pressure gauges and flow meters are installed to monitor essential pressures and flows.

The 300 mm diameter steel tube is half filled with permeable sand as illustrated in Figure 7.35.
To be able to monitor the conditions of the tests at any time, a data logger was installed. For the supply lines A and B, pressures and flows were measured. The pressure in the steel vessel was also monitored. Data was recorded at 1 second intervals.

Eleven different tests were undertaken with this setup, namely:

1. Preliminary experimental run
2. Functionality of the injector type and rate of mixing of components
3. Depressurized vessel, constant water flow, discharge valve closed
4. Depressurized vessel, constant water flow, discharge valve opened
5. Pressurized vessel (4 bar), constant water flow, 4 bar at constriction-hose valve with 4 bar
6. Pressurized vessel (4 bar), water filled vessel, constant water flow
7. Pressurized vessel (4 bar), water filled vessel, constant water flow, constriction-hose valve 4 bar
8. Pressurized vessel (4 bar), constant water flow
9. Water filled vessel and opening of constriction-hose valve
10. New injector type and injection of two components into pressurized vessel with constant water flow
11. Injection of components under a constant flow of water.
Each of the tests is described in the following section "experimental runs".

Experimental runs

Test 1 – Preliminary experimental run

The preliminary test was necessary to check the set-up and to identify relationships between flow rate, pressure and adjustment of the frequency settings of the pump invertors.

First of all the pump curves for the two component supply lines were examined. Systematically the frequencies for the optimum pressure-flow combinations were determined. Water was used instead of grout components. Pressure and flow rate were constantly measured. As soon as the equilibrium was reached the corresponding values were recorded. The results are illustrated in Figure 7.36.

Figure 7.36 Preliminary experimental run
Both pumps were adjusted to achieve an A to B ratio of 93% to 7%. The pump for component A was tuned to an average flow of 4.9 l/min; pump B was tuned to an average flow rate of 0.38 l/min. Tests revealed that the flow in both lines could be kept stable without readjustments of the pumps.

**Test 2 – Functionality of injector type and rate of mixing of components**

The second test was used to test the functionality of the steel injector and to visually inspect the mixing rate of both components.

During the test the vessel was pressurized but no water flow was simulated.

Figure 7.37 shows the operational data of this test run using an Ultra White cement for the component A mix and a graphite powder (4 μm) added to component B. The white cement and graphite powder are used for a better visualization of the homogenous mixing of A and B.

Figure 7.37 Functionality of injector type and rate of mixing of components
The data in Figure 7.37 illustrate the injection of both components. It can be seen from this diagram that at the end of the injection process, the flow of component B is switched off a few seconds earlier than component A to avoid a clogging in the mixing section. With the delayed cut-off of component A the mixing section is flushed with component A. This avoids component B remaining in the line consequently avoiding blockages as a result of hardening grout.

The functionality of the new injector design was verified. The grout showed a homogenous mix (see Figure 7.37) and no marble-effect indicating poor mixing.

*Test 3 – Depressurized vessel, constant water flow, discharge valve closed*

For this third test, the components were mixed in two 42 l batches as per mix proposed by Condat. The formula (see Table 7.13) is adjusted to permeable soils with running water conditions.

First of all the flow properties of component A were tested as described in chapter 7.2.6.1.2. Laboratory tests. A summary of the properties like density, liquid flow limit, viscosity and settling behavior is presented in Table 7.14 following the description of the 11 tests.

Before commencing the test concrete test cube moulds (150mm x 150mm x 150mm) were prepared for UCS tests on samples of the two component backfill mix after 3, 7 and 28 days.

The test tube was filled half with gravel alluvium. A constant water flow through the depressurized vessel was generated with the discharge valve closed.
Initially a constant flow of average 4.5 l/min was established, pump for component A was started and then, after a short delay, pump B was started to deliver accelerator. Shortly after the start the pressure in the chamber increased steadily up to a maximum of 4 bar. The pressure increase and the injection of component A & B stopped the water flow.

The injected backfill mix was gel-like and intruded into the gravel alluvium forming a filter cake. Because the discharge vessel was closed and the injected material formed a waterproofing layer, the vessel remained half filled with water until it was opened.
Figure 7.39 Depressurized vessel, constant water flow, discharge valve closed

After the test a cube mould N° 1 was filled with the injected material to determine the UCS after three days. The results are listed in Table 7.14.

Test 4—Vessel not pressurized, constant water flow, discharge valve opened

This fourth test was almost identical to test number 3 with the exception that the discharge valve was kept open. A continuous water flow through the vessel was established. The two components were then injected into the constant water flow until grout mix poured out of the discharge valve at the top of the vessel indicating that the tank was completely filled with grout. The excess material had a significant gel-like consistency.

Three sample cubes were filled with the two component mix. Test cubes N° 2/1 (UCS after 3 days) and N° 2/2 (UCS after 7 days) were filled with the material released from the discharge valve, sample N° 2/3 (UCS after 28 days) was taken from the tube.

Figure 7.40 shows that the two components have been injected into the “annular gap” with a constant water flow of about 4.6 l/min present. The water flow was maintained throughout the time the material was injected into the chamber.
Test 5 – Pressurized vessel (4 bar), constant water flow, 4 bar at constriction-hose valve

All tests were run with the same composition and properties of component A. The vessel for was half filled with gravel alluvium.

The constriction-hose valve was adjusted to a pressure of 4 bar. The vessel was completely filled with water maintaining a constant water flow. Next the pressure in the vessel was increased to 4.6 bar. The two components were injected into the simulated annular gap leading to pressure increase in the vessel of up 6 bar that could not be controlled by means of the setup (see Figure 7.41). The test was stopped when the mix poured out of the discharge valve. The flow of component B was cut off and the mixing section was flushed with component A. The vessel was completely filled with the two component material. The inspection of the backfill mix showed a hardened material. The injector was neither blocked nor opened.
Four test cubes were filled with backfill material for later UCS tests. Two cubes were filled with material from the discharge valve: No 3/1 (UCS after 3 days), 3/2 (UCS after 7 days). On the remaining two cube samples No 3/3 and 3/4 the UCS after 28 days were determined.

Figure 7.41 Pressurized vessel (4 bar), constant water flow, 4 bar at constriction-hose valve
**Test 6 – Pressurized vessel (4 bar), water filled vessel, constant water flow**

For tests 6 and 7 new components A and B were mixed as per the mix recommended by Condat, adjusted to resist washout in running water conditions. The properties of the component A mix were determined in accordance with chapter 7.2.6.1.2.

Because the operational data for test 6 were registered faulty, it is not possible to illustrate the test run in form of a diagram. The test was run with an adjusted constant water flow. Then the vessel was pressurized to 4 bar maintaining a water flow of 4 to 5 l/min. The two components were then injected into the vessel and the pumps were stopped when mix poured from the outlet.

The material at the surface of the sand was liquid. Probe No 4 was taken from the vessel to determine the unconfined compressive strength of the two component mix after 28 days.

**Test 7 – Pressurized vessel (4 bar), constant water flow, constriction-hose valve 4 bar**

The constriction-hose valve was adjusted to 4 bar. Then a constant water flow of 4.5 to 5 l/s was established through the vessel until the complete tank was filled with water. This was recognized by water flowing out of the discharge valve. The vessel was pressurized with 4 bar when the two component injection started. The water flow stopped shortly after the two components had been injected and the pressure in the vessel increased to 14.5 bar. The component injection was continued until the mix poured out of the discharge valve.

The two components formed a thin and relatively liquid, layer as illustrated in Figure 7.42.

Two cube specimens were taken, No 5/1 from the discharge valve to test the UCS after 7 days and No 5/2 from the vessel to test the strength after 28 days.
Figure 7.42 Pressurized vessel (4 bar), constant water flow, constriction-hose valve 4 bar

Test 7 - Constant water flow, pressure in vessel of 4 bar
9th of March 2005, Hammenleicht AG

Test 8 - Pressurized vessel (4 bar), constant water flow

For Tests 8 and 9 a new batch of component A was mixed. Test 8 is characterized by the generation of a constant water flow until the vessel was pressurized with 4 bar. Then the two component mix was injected into the pressurized and water filled vessel. To inspect the content, the vessel was opened. The two component mix penetrated into the sand and formed a filter cake.

One test cube (N° 6/1) was filled with material extracted from the vessel. Here the UCS after 28 days was determined. Figure 7.43 shows the graphical interpretation of this test run.
Figure 7.43  Pressurized vessel (4 bar), constant water flow

Test 9 – Water filled vessel and opening of constriction- hose valve

After a constant water flow was adjusted, the constriction-hose valve was closed to fill the vessel completely with water. Afterwards the constriction-hose valve was opened maintaining a constant water flow. The two components were injected until the backfill mix poured from discharge valve.

Three test cubes were filled. Sample N° 7/1 (UCS after 3 days) was taken from the discharge valve, N° 7/2 (UCS after 7 days) as well as N° 7/3 (UCS after 28 days) were taken from the vessel.

The material that had poured from the discharge valve quickly reached a gel-like consistency and started hardening. The rest of the 42 l vessel was filled with backfill material.
Test 10 – Application of an injector with a rubber sealing ring and injection of two components into a pressurized vessel with constant water flow

For test 10 a new base mix for component A was prepared according to Table 7.13. For this test run the experimental set-up was modified in the way that the constriction-hose valve was assembled on the top of the vessel (see Figure 7.45) to keep the vessel at a pressure of up to 5 bar.

The injector used for this test (Figure 7.46) is characterized by a rubber sealing ring around the openings for the B-component.
Figure 7.45 Set-up with constriction-hose valve assembled on the top of the vessel

Figure 7.46 Injector with rubber sealing ring
By adjusting the flow of pump B the injector was function-tested. The injector was set to an opening pressure of 0.5 bar.

A constant water flow was generated to fill the vessel with water and to pressurize it to 5 bar. Then the two components were injected until the vessel was completely filled with the mix until material poured out of the constriction-hose valve.

Two samples, No 8/1 and 8/2 (UCS after 28 days) were taken from the constriction-hose valve. Further three samples were taken from the chamber after being pressurized to 4 bar for three hours.

- 8/3 (UCS after 3 days)
- 8/4 (UCS after 7 days)
- 8/5 (UCS after 28 days).

Figure 7.47 depicts the recorded data for this test run.

Figure 7.47 New injector type and injection of two components into a pressurized vessel under constant water flow
The material taken from the chamber after it was pressurized for 3 hours showed good strength.

The tested injector design is believed not to be suitable for a long-term application. When the pump for component B was turned off, the flow didn’t immediately stop as seen with the first injector tested, because the sealing ring was pre-stressed to only 0.5 bar. Result was that component B accumulated around the sealing ring which is believed to lead to line blockages during long term applications.

Test 11 – Depressurized test. Injection of components into a constant water flow

For the last experimental data record is available. This test was under atmospheric pressure with the two components injected into a constant water flow of 5 l/min.

After the test run the vessel was kept closed maintaining a constant water flow.

After two and a half days the vessel was opened for inspection. The material was very hard and could only be removed from the vessel using a crowbar. Figure 7.48 shows the material shortly after removing the cover from the tank.

Figure 7.48 Hardened material that was kept in the vessel for about 2.5 days with a constant water flow at times
Summary of test results (see Appendix D)

The test results of the 11 washout tests as well as the result of the mechanical property tests for the component A mix and the strength tests for the final backfill mix are summarized in Table 7.14.

Table 7.14 Résumé of mechanical properties of component A mix and cube strengths of the two component mix

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Properties of comp. A</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Density (mix balance)</td>
<td>g/cm³</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.3</td>
<td>1.3</td>
<td>1.3</td>
<td>1.3</td>
<td>1.3</td>
<td>1.3</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>2 Liquid flow (Void %)</td>
<td>mm²</td>
<td>7.53</td>
<td>7.53</td>
<td>7.53</td>
<td>4.63</td>
<td>4.63</td>
<td>4.63</td>
<td>4.63</td>
<td>6.66</td>
<td>6.66</td>
<td>6.66</td>
<td>6.66</td>
</tr>
<tr>
<td>3 Marsh Viscosity (marsh funnel)</td>
<td>sec</td>
<td>42</td>
<td>42</td>
<td>42</td>
<td>26</td>
<td>26</td>
<td>26</td>
<td>26</td>
<td>43</td>
<td>43</td>
<td>43</td>
<td>41</td>
</tr>
<tr>
<td>4 Setting rate</td>
<td>sec/m²</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>20</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Properties comp. A&amp;B-Mix</th>
<th>Units</th>
<th>Probe</th>
<th>Probe</th>
<th>Probe</th>
<th>Probe</th>
<th>Probe</th>
<th>Probe</th>
<th>Probe</th>
<th>Probe</th>
<th>Probe</th>
<th>Probe</th>
<th>Probe</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Cube strength</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3days</td>
<td>mm³</td>
<td>111</td>
<td>111</td>
<td>111</td>
<td>111</td>
<td>111</td>
<td>111</td>
<td>111</td>
<td>111</td>
<td>111</td>
<td>111</td>
<td>111</td>
</tr>
<tr>
<td>7days</td>
<td>mm³</td>
<td>111</td>
<td>111</td>
<td>111</td>
<td>111</td>
<td>111</td>
<td>111</td>
<td>111</td>
<td>111</td>
<td>111</td>
<td>111</td>
<td>111</td>
</tr>
<tr>
<td>28days</td>
<td>mm³</td>
<td>111</td>
<td>111</td>
<td>111</td>
<td>111</td>
<td>111</td>
<td>111</td>
<td>111</td>
<td>111</td>
<td>111</td>
<td>111</td>
<td>111</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mix Design</th>
<th>kg</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Water</td>
<td>242</td>
<td>242</td>
<td>242</td>
<td>242</td>
<td>242</td>
<td>242</td>
<td>242</td>
<td>242</td>
<td>242</td>
<td>242</td>
<td>242</td>
</tr>
<tr>
<td>B</td>
<td>Bentonite</td>
<td>242</td>
<td>242</td>
<td>242</td>
<td>242</td>
<td>242</td>
<td>242</td>
<td>242</td>
<td>242</td>
<td>242</td>
<td>242</td>
<td>242</td>
</tr>
<tr>
<td>B</td>
<td>Coarse</td>
<td>242</td>
<td>242</td>
<td>242</td>
<td>242</td>
<td>242</td>
<td>242</td>
<td>242</td>
<td>242</td>
<td>242</td>
<td>242</td>
<td>242</td>
</tr>
<tr>
<td>B</td>
<td>Clinker</td>
<td>242</td>
<td>242</td>
<td>242</td>
<td>242</td>
<td>242</td>
<td>242</td>
<td>242</td>
<td>242</td>
<td>242</td>
<td>242</td>
<td>242</td>
</tr>
<tr>
<td>B</td>
<td>Water</td>
<td>242</td>
<td>242</td>
<td>242</td>
<td>242</td>
<td>242</td>
<td>242</td>
<td>242</td>
<td>242</td>
<td>242</td>
<td>242</td>
<td>242</td>
</tr>
</tbody>
</table>

A test certificate of Schöck is attached to appendix D showing the unconfined compressive strength of the air-dried test samples.
7.2.6.1.3 General Result of the washout-resistance tests “running water” tests for two component backfill material

All 11 tests show significant results with regards to the injection of two component backfill material under running water conditions. Not all tests runs ended with a completely filled chamber but in each test, the material intruded into the sand and formed a filter cake and sealed the soil against water ingress.

Washout resistance and mixing behavior of two component backfill material:

The washout resistance of the two component backfill material could be verified with each of the accomplished tests (test 2 to test 11) as illustrated in chapter 7.2.6.1.2 experimental runs.

Also the injector types (Figure 7.46 and Figure 7.49) used for the tests showed good results with regards to homogeneous mixing of the two components. The sealing ring fitted around the injection openings as shown in Figure 7.46 is pre-stressed to 0.5 bar. The arrangement does however not stop the flow of accelerator instantly once the pump is switched off. Blockages are the consequence. The design is therefore not suitable for on site application. The injector illustrated in Figure 7.49 in comparison is characterized by a robust design as described in the following section.

Durability of used injector type:

Experience was gained on one undocumented test run because an operating error caused by operating personnel lead to a blockage in the mixing section. During the course of testing first the pump for the component A was switched off instead of first switching off the flow of component B in order to flush the line with component A to keep it free from clogging. On TBMs this operating error can be avoided by presetting of pumps and flow rates. This error was however helpful in order to test the injector type under extreme conditions. After the blockage in the mixing section occurred the injector was disassembled. No damage or clogging of the material at the outlet of the injector was visible. Thus this injector can be regarded as tough and was
therefore recommended for the application in the two component low pressure grouting systems.

Figure 7.49 Tough injector after mixing line got completely blocked

Further the strength of the two component backfill mix was tested with a hand test and cube samples of the two component mix where taken to test the strength after 2, 7 and 28 days.

**Strength properties:**

The two components were prepared according to the mix given in Table 7.13 with a mixing ratio of 93 % component A to 7 % accelerator which was a sodium silicate. Immediately after mixing, the two components showed a gel-like consistence.

Thus, in permeable loose soil conditions an optimized mix of base component A and accelerator (component B) improves the stabilization of the tunnel ring in the surrounding soil matrix.

The washout resistance for permeable soil conditions have been proved with the series of tests described above. The adjustment of the two components to permeable soil conditions lead to satisfactory result.

The UCS of the tested samples range from 1 to 3 MPa and are in the predefined limits (see Table 7.2).
The test results show that the requirements as listed as objectives in chapter 7.2.6.1 could be achieved. The backfill of the annular gap with two components is a viable alternative for filling the tail void especially in permeable soil conditions.

7.2.7 Two component backfilling material and influence on convergences in the annular gap

In this section the influence of convergence in the annular gap with two component backfill material will be investigated with experiences gained during construction of the railway tunnel on the project Brescia (Project description, see Appendix B).

The question was, if convergence in the tail void can be kept to a minimum with the use of two component dynamic grouting materials.

Convergence measurements performed in the past years on different sites were based on either invar wires or classical theodolite observations. Application of invar wires are impossible along the back-up trailer because of obstructions by the back up equipment and the work in progress. Classical theodolite observations are only possible with disproportionately high effort. VMT developed a more efficient convergence measurement system called RCMS.

In tunnelling a just built segment ring is exposed to various loads, for example when the ring leaves the tailskin, during primary and secondary grouting of the annular gap, while exposed to the weight of the last back-up trailer and other potential long term effects. Engineers are mostly concerned about the initial deformations of a ring, built under the influence of thrust during TBM advance and subsequent load changes.

To analyze possible movements in the ring due to the annular gap grouting with two component backfill material, a more efficient measurement system was designed by VMT, that models the ring in the measurement cross section, in the case
of the project Brescia, 6 + 1 segments, by a girder with rigid and moveable bearings with 7 joints. The bars are presumed to be rigid and have a constant length.

For the test design of this thesis the ring convergence measuring system was installed on a defined test section.

The RCMS can be used immediately after a ring is erected as well as for completed tunnels. In the context of this work the deformation just after ring erection was of interest, with backfill just completed.

The RCMS determines the relative deformation of one segment ring by means of a series of inclinometers as illustrated in Figure 7.50.

Figure 7.50 Position of inclinometers and crown prism (courtesy of VMT)
For the project Brescia with 6 +1 segments altogether 6 inclinometers have been provided.

The basic idea is the assumption that any deformed ring could be considered as a chain of rigid bodies linked by joints. Deformations could take place only along longitudinal joints, to be treated as articulations (courtesy of VMT).

The deformation of the entire ring will be determined by collecting tilt changes of the inclinometers. The obtained coordinates of the articulations will permit the calculation of any convergence line. Convergence accrues from the differences between any two arbitrarily chosen time instances (so-called epochs).

With the help of inclusion and measurements to one or more reference prism(s), absolute movements can be observed and contribute to the convergence measurement analysis.

For the project Brescia one tunnel ring (ring number 58) was selected and equipped with the RCMS. The very first record (one set of inclinometer readings) was defined as zero measurement. To start the evaluation the 2D co-ordinates of the articulations are required. With each additional series of inclinometer readings (epoch) the changes of the inclinations were measured and the same evaluation as with the zero epoch were repeated.

The comparison with the spatial distances of the zero epoch yielded small differences, which permitted conclusions about the stability of the ring and also of the lining in its vicinity. The accuracy of the results increases with the number of measurements.

The set of displayed dashed lines in Figure 7.51 are the maximum available convergence lines, with the three diagonals being of prime interest, and among them the near vertical line S1-S4 being the most important.
One requirement within this research was to monitor the absolute displacement of the ring, to determine convergences in the annular gap, either a settlement of the crown and/or a lift of the invert, respectively a proof of absence or insignificance.

Based on inclinometer measurements only the relative ring deformations can be determined, i.e. changes with time of the form of the observed ring, relative to a presumed initial form at a specific time instance of reference.

For the determination of absolute displacements, e.g. potential settlements of the crown, or lift of the invert, or tunnel lift-up, one or more prisms can be installed in addition to the inclinometers. Segment reference prisms can conveniently be placed closely to the crown of the ring under observation, as shown in Figure 7.50.

In one tunnel ring of the project Brescia (Project description, see Appendix B) one reference prism was installed in the tunnel crown. The segment reference prism
could be observed by the servo-theodolite of the TBM Guidance System SLS-T. For
the integration into the Guidance System, a software adaptation was necessary.
Measurements and data recording of the segment reference prism were performed
automatically, after a preliminary system calibration. Subsequently, one can split the
vertical convergences into two separate components “crown settlement” and “invert
lift”. Should it happen that both components exhibit the same sign, then a tunnel lift-
up is detected.

The software for the RCMS serves for recording inclinometer measurements.
- Output of inclinometer readings with a resolution of 1/1000°
- Each sensor individually activated/deactivated by a controller
- Single and permanent measurements are possible
- Recording of measurements in a database
- Recording of all data in log-files
- Export to e.g. MS Excel.

For the data evaluation and visualization the program requires the geometry of
the ring type (co-ordinates of the articulation points) and the database of the
measurements of the monitored ring, in this case ring 58.

In the following Table 7.15 the main components of the RCMS are described.
Figure 7.52 shows a schematic of the RCMS and its main components.
Table 7.15 Main components and characteristics of the RCMS

<table>
<thead>
<tr>
<th>Main components</th>
<th>Figure</th>
<th>Characteristics</th>
</tr>
</thead>
</table>
| Inclinometers                    | ![Inclinometers](image) | The quantity depends on the ring configuration.  
- System housing of aluminum  
- Adaptable rotation angle to accommodate different sensor inclinations  
- Galvanic separation of the sensors from their housing  
- Analogue/digital conversion. |
| Controller Unit with integrated touch screen | ![Controller Unit](image) | - Noa-touch screen  
- Switchgear, made of steel plates, painted (20x20x10 cm)  
- Power connection 220 V AC  
- Power supply for the inclinometers  
- Digital data transfer from the inclinometers  
- Data transfer to the system-PC. |
| Software                         | ![Software](image) | - Each sensor can individually be activated or deactivated  
- Single measurements and continuous measurements are possible  
- Recording of measurements into a database  
- Recording of all data into log-files  
- Export to standard PC-Software, e.g. MS Excel is possible  
- Visualization of calculated data  
- History of all data sets (chronological). |
The tunnel lining of the Brescia project consists of \(6+1\) reinforced concrete segments. The annular gap between the outside of the segment and the excavated soil is backfilled with two component grout along the 5,400 m long bored tunnel section. The backfill material consists of a mixture of cement, bentonite, water and retarder for component A and a sodium silicate for component B. One main advantage of this backfill material is a better and quicker stabilization of the tunnel ring in the surrounding soil.

Tunnelling with the 9.15 m diameter EPB-Shield started at the end of November 2005. The geology along the tunnel alignment is tuff, silty, clayey and gravely soils. The overburden is within the range of 10 to 25 meters. The machine is designed for a face operating pressure of 3 bar.

The test section comprised the section from ring 58 to ring 75 corresponding to a section of 26 meters over a period of 11 days.
The steps for the analysis of the RCMS data are:
1. Selection of the ring to be equipped with the RCMS
2. Installation of the inclinometers, prism and controller unit
3. Activation of the inclinometers by the controller and automatic recording of data of prism and inclinometers
4. Definition of reference data record (zero measurement)
5. Automatic recording of data from prism and inclinometers

Steps 1 to 3: For the measurement and data recording an inclinometer was installed on each of the six segments of the selected ring but not the key. One permanent prism was installed in the crown to be able to determine the absolute displacements. After the controller unit was fixed, the convergence lines were defined.

Step 4: The reference data record (zero measurement) was defined before the recorded data from the RCMS database was recorded. The zero measurement was data set number 1 of 279 dated February 3, 2006, 18:53:15 pm.

The RCMS recorded data between February 3, 2006 and February 13, 2006.

Step 5: The analysis of the data from the permanent prism shows no displacements: no settlement of the crown, no lift of the invert or even a lift-up of the entire tunnel tube. The absolute vertical displacements of the crown prism are shown in Figure 7.53.

Figure 7.53 illustrates that over a period of 7 days the segment reference prism moved from +1.6 mm to -2.6 mm.

With the information gathered from the tilt changes of the inclinometers along the 26 meters of the test section over a time period of about 7 days the deformations of the entire ring from the zero measurement to the last measurement (data set 279) could be determined. The obtained coordinates of the articulations permitted the calculation of the interesting convergence lines as depicted in Figure 7.54.
Figure 7.53 Visualization of absolute vertical displacements on a defined test section in Brescia from Ring 58 to Ring 75.
The analysis of the data in Figure 7.54 shows only minor convergences and consequently a very stable form of the segment ring in the measured section.

The largest convergence referred to the zero measurement amounts to 5 mm for the convergence line S4 - S6. With 5 mm the convergences are within the limit of the expected degree of accuracy. For an overall accuracy estimation one could refer to the attachment “Brescia_RCMS_accuracy_estimation.xls” (see Appendix G).

A comparison of the reported maximum 5 mm convergence to accuracy of the RCMS may be deemed:

- significant
- within the expected degree of accuracy
- harmless as to the stability of the segmental lining.
Comparing the observed very small vertical displacements of only 2 mm to 3 mm (see figure 7.53) of the crown prism with the finally detected vertical convergence of +1.8 mm the following conclusions can be drawn for project Brescia:

- that the crown had settled by about −2.6 mm
- that the (almost) vertical convergence line S1 - S4 had increased for about +1.8 mm, leading to an apparent invert settling of 4.4 mm.

The measuring results and the performed studies indicate that convergences in the annular gap can be kept to a minimum by using two component grouting material. However, it cannot be necessarily gathered from these results that they are exclusively based on the effect of the two component grout. In order to prove this effect a test series with standard grout would have been necessary under the same tunneling conditions.

The experiment showed by means of the RCMS that the ring shape and the injection of the annular gap with two component grout could be kept stable during the measuring period.

7.3 Two component high pressure annular gap backfilling

In parallel to the low pressure system (max. 16 bar) the development of an high pressure injector was also considered which could be used to inject accelerator at a maximum of 120 bar to achieve an even more homogenous backfill material. This requires however modifications to the grout injection pipe cross section and the injection pumps.

7.3.1 Design and function of the high pressure backfill system

This system works with significantly higher pressures (approx. 120 bar) than the low pressure injection system with maximum pressures of up to 16 bar.
It comprises an outer line through which the base mix (component A) is pumped and a smaller co-axial line for the accelerator (component B). Both injection lines are hose pipes which allow a more flexible arrangement.

The injection lines run from the pumps located in the rear part of the tailskin to the annular gap. At the end of the interior injection hose a high pressure nozzle (injector) is mounted. The injector has a working pressure of 100 bar and does not require any kind of silicone sealing rings or other mobile parts to close the outlet. From the pump, the smaller of the two hoses leads through hollow hydraulic cylinder. The hose is fixed in such a way that it moves with the retraction and extension of the cylinder. Behind the hydraulic unit both injection lines run co-axial.

Figure 7.55 Hydraulic unit, high pressure system

When the backfill process starts, the hydraulic cylinder extends and moves the inner hose towards the annular gap.

First, the pump for component A will be switched on. With a delay of about 60 seconds, the accelerator (component B) is injected with high pressure. Due to the high pressure, a strong jet is generated at the injector outlet. Since three of four openings are arranged around the injector, the jet stabilizes and keeps the injector in a horizontal position. See Figure 7.56. The two components can thus be well mixed.
Figure 7.56 High pressure injector

The high working pressure ensures a “self-cleaning effect”, because the fast flowing or spraying out of the material avoids an accumulation of the base mix at the injector.

When the injection process is complete, first the accelerator pump (for component B) is switched off. The injector is retracted 100 mm before it is cleaned by the continuing flow of component A around it. Afterwards also the base mix (component A) is switched off.

Figure 7.57 illustrates the retraction of the accelerator hose in the outer hose. The base mix of component A will be pumped through the pipe displayed in red color. The blue colored part represents the hollow piston rod of the cylinder which is connected to the accelerator hose colored in brown.
7.3.2 Experiences with the high pressure backfill system

A Herrenknecht Mixshield used for construction of a 4,050 m long tunnel section for the south lot of the project SMART (Storm Water and Road Tunnel) Kuala Lumpur, was equipped for the first time with the high pressure backfill system. The high pressure backfill system was installed parallel to the conventional single component grouting system as specified by the contractor who had experience with a similar system on a Japanese TBM for the CTRL (Channel Tunnel Rail Link) Project in London.

The high pressure backfill system works with operating pressures up to 120 bar. A major disadvantage of this grouting method is the cost factor. The costs are about 10 times higher than the low pressure system due to the fact that all parts exposed to high working pressures including the pumps have to be designed larger and tougher than for the low pressure system. This results in higher initial and running costs.
7.4 Premix variant for annular gap backfilling

The third dynamic two component annular gap backfill system, the premix variant will be discussed in this chapter. The design and function as well as the development steps of this premix grouting variant are explained.

7.4.1 Design and function of the premix variant

This injection system is completely different from the previously described systems with low and high pressure injection. The premix variant is used for the first time for the project Eastside LRT Los Angeles (Project description, Appendix B). Interchangeability of the pipes and an integrated flushing system for the two component lines were specified.

With this backfill method the components are pre-mixed on the TBM back-up. From there the two component mix will be pumped through a single pipe towards the end of the tailskin. Two injection lines run parallel. In the tailskin, a two further pipes run between the injection lines that are used for flushing/cleaning of the system (Figure 7.58, (1)). Each injection line (Figure 7.58, (2)) is connected with one flushing pipe. The mortar line will be connected at an angle to the pipe. See Figure 7.58.

Figure 7.58 Connection between grouting and flushing line

1 flushing/cleaning system
2 injection line
The injection pipe conducts the backfill mix towards the annular gap. In both flushing lines a movable hollow rod is installed with a gate valve mounted to a hydraulic cylinder allowing axial movement of the assembly.

The gate valve at both ends has the same diameter as the flushing line. The middle section of the gate valve is tapered. At the front part of the gate valve in direction of the annular gap, a notch is milled with an opening for water. Above the notch an inflatable seal is mounted.

When the rod moves towards the segment ring, the valve closes the pipe shortly behind the inlet of the injection line. In extended position the valve closes the grout supply line. In retracted position the valve closes the pipe before the injection of grout and opens a part of the pipe which leads into the annular gap.

When the injection process is started, the valve is hydraulically retracted opening the tail pipe. Via the injection line the mixed backfill material is pumped into the annular gap.

Upon completion of the injection, base mix will be pumped for a short time through the pipes to avoid remaining mixed backfill material in the pipes to prevent hardening. When the remaining two component mix is completely pressed out of the line, the valve extends again and closes the supply to the annular gap. To clean the pipes, water will be flushed through the hollow rod holding the gate valve. The openings in the valve provide a connection between flushing and injection lines with water flowing in the grout line. The water cleans both lines from grout.

7.4.2 Development steps of the premix variant

The first modification relates to the concept of the cleaning system. With the variant described in the chapter “design of the premix variant” the two hydraulic cylinders necessary for the movement of the valve would have to be small and slim.

Design and customer requirements require that hydraulic cylinders should be installed. In addition the tubular valve rod should be replaced by a more robust and
larger version in order to withstand conditions of high forces of pressure and tensile loads. As a result, the rod (see Figure 7.59, (3)) was later machined from round steel instead of pipe. This variant still has two parallel injection lines (see Figure 7.59, (2)) connected to the flushing line at the end of the tailskin. In addition to the traditional mortar supply, the flushing line has a further bore attached next to the mortar supply, adapting also the valve gate. On both ends the piston has about the same diameter as the conduit of pipes. In the middle section it is strongly tapered leading to a clearance between the ends. Furthermore the inflatble rubber seal / O-ring seal combination was replaced by grease lubrication.

Figure 7.59 Modified pipe system

If the valve gate moves to the rear during the injection process, the second opening is closed. Simultaneously the gate valve separates the flushing line shortly before the mortar supply. The two component mix can thus be injected into the annular gap via the remaining flushing line.

Once the backfill is complete, injection is stopped, the valve gate moves forward and closes the line against the annular gap. The valve clearance is positioned to cover both openings of the flushing and injection line establishing a closed circuit for cleaning the system with water.
The initial design of the premix system comprised the lines for the annular gap backfill, both connecting rods and the supply lines for the brush seals. Consequently, space in the system was limited. The “interfering” grease lines were removed from the original grouting system. Installation space gained was used to increase the clearance between the hydraulic cylinders from 70 mm to about 120 mm. Thus both flushing lines could be positioned between both connecting rods. The improved utilization of space facilitates thicker hence more stable walls. This avoids structural weakening of the tailskin by the system. During the design of this premix two component backfill system, priority was given to the interchangeability of all parts.
CHAPTER 8
COMPARISON BETWEEN EXISTING SINGLE COMPONENT GROUTING SYSTEMS AND DYNAMIC GROUTING SYSTEMS

This chapter deals with the comparison of the existing grouting systems where conventional mortar is injected through mortar lines with an oval cross section and the dynamic low pressure grouting system where two components are used as backfill material.

8.1 Calculation of injection volume, flow rate and power

For both grouting systems, the conventional backfilling system with traditional mortar and the low pressure two component grouting system, the flow rates, pipe friction losses and the required pumping capacity will be compared by calculation.

8.1.1 Determination of flow rates using the two component low pressure system

The calculations are based on data from the project Metro Line 1 Naples (Project description, see Appendix B). The mixing ratio of the two components comprises 10% accelerator and 90% base mix consisting of water, cement, bentonite and a stabilizer.

The required injection volume $V_{RS}$ is calculated as follows:

$$V_{RS} = \frac{\pi}{4} \cdot (D_R^2 - D_A^2) \cdot B$$  \hspace{1cm} (8.1)

Based on formula (8.1) following injection volume results:

$$V_{RS} = 3.86 m^3$$  \hspace{1cm} (8.2)
The volume of grouting material per injection line is obtained by dividing the injection volume by the number of injection lines:

\[ V_L = \frac{V}{n} \]  

(8.3)

\[ V_L = 0.965\,m^3 \]  

(8.4)

With the given mixing ratio of 10% accelerator and 90% base mortar and the calculated volume of the injection material per injection line with formula (8.3) following values of accelerator and base mix result:

\[ V_{Komp.A} = 0.8685\,m^3 \]  

(8.5)

\[ V_{Komp.B} = 0.0965\,m^3 \]  

(8.6)

Component A (base backfill material) will be supplied during the entire injection time \( t \). With the following equations it is possible to determine the volume flow in both injection lines:

\[ \dot{V}_{Komp.A} = \frac{V_{Komp.A}}{t} \]  

(8.7)

\[ \dot{V}_{Komp.B} = \frac{V_{Komp.A}}{(t - 2\,\text{min})} \]  

(8.8)

With equations (8.3) and (8.4) the volume flow in both lines of component A and B results:

\[ \dot{V}_{Komp.A} = 0.0578\,m^3/\text{min} \]  

(8.9)

\[ \dot{V}_{Komp.B} = 0.0074\,m^3/\text{min} \]  

(8.10)

In order to be able to calculate the flow rates, the free cross sections of the injection lines must be first determined. For component B, the entire hose cross section is available while for the base backfill material (component A) only a part of
the cross section is available for the material transport because the injection line incorporates the injection hose for component B (accelerator):

\[ A_{Komp,A} = \frac{\pi}{4} \cdot (D_1^2 - D_2^2) \]  \hspace{1cm} (8.11)

\[ A_{Komp,B} = \frac{\pi}{4} \cdot D_3^2 \]  \hspace{1cm} (8.12)

With the dimensions given on the jobsite (Table 8.1) for the outer injection line and the accelerator hose, values for the free cross sections are to be calculated with the equations (8.11) and (8.12):

\[ A_{Komp,A} = 628.32 \text{mm}^2 \]  \hspace{1cm} (8.13)

\[ A_{Komp,B} = 50.27 \text{mm}^2 \]  \hspace{1cm} (8.14)

With the already calculated values for the cross-sectional area and volume flows as well as the following equation the flow rate can be determined:

\[ v = \frac{\dot{V}}{A} \]  \hspace{1cm} (8.15)

It has to be taken into regard, that the accelerator line is positioned at the last 1,240 mm in the injection line for component A. That is the reason why two flow rates result for the base mix (component A) line.

The first flow rate \( v_{A1} \) represents the area, in which the accelerator line runs coaxial. The second flow rate \( v_{A2} \) represents the area, in which the entire cross section is available:

\[ v_{A1} = 1.53 \text{m/s} \]  \hspace{1cm} (8.16)

\[ v_{A2} = 1.36 \text{m/s} \]  \hspace{1cm} (8.17)

\[ v_{Komp,B} = 2.45 \text{m/s} \]  \hspace{1cm} (8.18)
Table 8.1 Technical data, EPB-Shield Metro Line 1 Naples

<table>
<thead>
<tr>
<th>Name</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter cutting wheel</td>
<td>$D_h$</td>
<td>mm</td>
</tr>
<tr>
<td>Outside diameter segment ring</td>
<td>$D_A$</td>
<td>mm</td>
</tr>
<tr>
<td>Segment Length</td>
<td>$B$</td>
<td>mm</td>
</tr>
<tr>
<td>Diameter of injection line comp. A</td>
<td>$D_1$</td>
<td>mm</td>
</tr>
<tr>
<td>Outside diameter hose (for comp. B)</td>
<td>$D_2$</td>
<td>mm</td>
</tr>
<tr>
<td>Inside diameter hose (for comp. B)</td>
<td>$D_3$</td>
<td>mm</td>
</tr>
<tr>
<td>Number of injection lines</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>Advance Speed</td>
<td>V</td>
<td>mm/min</td>
</tr>
<tr>
<td>Injection time</td>
<td>T</td>
<td>min</td>
</tr>
</tbody>
</table>

8.1.2 Determination of flow rates using the conventional grouting system with single component grout

The dimensions of the grouting line can be taken from Figure 8.1.

Figure 8.1 Grout injection line

Likewise four injection lines are foreseen. The injection volume is determined according to equation (8.1). Result of equation (8.2) is the injection volume per injection line:

$$V_L = 0.965 m^3$$  \hspace{1cm} (8.19)
The injection time $t$ amounts to 15 minutes. The volume flow rate is determined by the following equation:

$$V_M^* = \frac{V_L}{t}$$  \hspace{1cm} (8.20)

By putting in verified values for the injection time $t$ ($t = 15$ minutes) and the volume of backfill material $V_L$ from (8.19) following volume flow results:

$$V_M^* = 0.0643 \, m^3/min$$  \hspace{1cm} (8.21)

To reach a possible low overall height, the injection line is oval as illustrated in Figure 8.1. The calculation of the cross section of the injection line is done according to following equation:

$$A_m = (\pi \cdot R_m^2) + (H_m \cdot B_m)$$  \hspace{1cm} (8.22)

With $R$ as radius, $H$ as height and $B$ as width of the injection line. With (8.22) the cross section of flow can be determined:

$$A_m = 2056.6 \, mm^2$$  \hspace{1cm} (8.23)

With the help of equation (8.20) and the determined flow of the injection volume and the cross section of the line, the flow rate of the conventional grouting system can be calculated as follows:

$$v_M = 0.52 \, m/s$$  \hspace{1cm} (8.24)
8.1.3 Calculation of the pipe friction loss and required pumping capacity of the two component low pressure system

The pressures related in Table 8.2 are based on the geological conditions of the project Metro Line 1 Naples (Project description, see Appendix B).

Table 8.2  Technical data of the two component system

<table>
<thead>
<tr>
<th>Name</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure in accelerator line</td>
<td>p_B</td>
<td>8</td>
</tr>
<tr>
<td>Pressure in injection line A</td>
<td>p_A</td>
<td>3</td>
</tr>
<tr>
<td>Assumed viscosity accelerator</td>
<td>η_B</td>
<td>140</td>
</tr>
<tr>
<td>Assumed viscosity component A</td>
<td>η_A</td>
<td>68.3</td>
</tr>
<tr>
<td>Density accelerator</td>
<td>ρ_B</td>
<td>1350</td>
</tr>
<tr>
<td>Density component A</td>
<td>ρ_A</td>
<td>1220</td>
</tr>
<tr>
<td>Diameter of the outer injection line</td>
<td>D_1</td>
<td>30</td>
</tr>
<tr>
<td>Outer diameter of the hose</td>
<td>D_2</td>
<td>10</td>
</tr>
<tr>
<td>Inside diameter of the hose</td>
<td>D_3</td>
<td>8</td>
</tr>
<tr>
<td>Total length of injection lines</td>
<td>L</td>
<td>13070</td>
</tr>
</tbody>
</table>

An earth pressure of 2.5 bar is presumed based on the information taken from the Geotechnical Baseline Report (GBR) of the project Metro Line 1 Naples (Drawing number 8F0001N1E0526, GBR Napoli, 16.01.2002, Herrenknecht AG). To inject backfill material through the tailskin, the working pressure must be higher.

The pressure in the accelerator is calculated as follows. Because the accelerator hose is installed within the component A injection line, its ambient pressure is equally to the working pressure of the outer injection line. The injector (nozzle) at the end of the accelerator line opens at a defined pressure of 5 bar. Thus, a pressure of 8 bar (excess pressure of 5 bar plus 2.5 bar earth pressure) has to be used in the accelerator line to open the nozzle.
To calculate eventual flow losses and pumping capacities, the type or nature of flow and the Reynolds’ number must first be determined. Where there is no circular cross section available a hydraulic equivalent diameter must be calculated:

\[ d_{hyd} = 2 \cdot s \]  \hspace{1cm} (8.25)
\[ d_{hyd} = 20mm \]  \hspace{1cm} (8.26)

This diameter is only required for the area where both injection lines run coaxial. For the other areas the hydraulic diameter is equal to the diameter of the pipe.

Furthermore the kinematic viscosity has to be determined as follows:

\[ \nu = \frac{\eta}{\rho} \]  \hspace{1cm} (8.27)

The following values for the kinematic viscosities of component A and B (accelerator) were calculated:

\[ \nu_A = 5.6 \cdot 10^{-5} \frac{m^2}{s} \]  \hspace{1cm} (8.28)
\[ \nu_B = 1.04 \cdot 10^{-4} \frac{m^2}{s} \]  \hspace{1cm} (8.29)

With the values of (8.27) and (8.25) the Reynolds’ number can be determined:

\[ Re = \frac{u \cdot d_{hyd}}{\nu} = \frac{u \cdot d}{\nu} \]  \hspace{1cm} (8.30)

Due to the partial coaxial direction of lines, two Reynolds’ numbers result for the base mortar (component A) and one for the accelerator (component B):

\[ Re_{A1} = 546.43 \]  \hspace{1cm} (8.31)
\[ Re_{A2} = 730.1 \]  \hspace{1cm} (8.32)
\[ Re_B = 188.46 \]  \hspace{1cm} (8.33)
If Re < 2300, then a laminar flow is present and a determination of the pressure losses can now be done (http://de.wikipedia.org/wiki/Reynolds-Zahl). The pressure losses can be divided into friction losses in pipes and losses in the mounting parts. The friction losses in pipes result from the friction of the flowing fluid at the tube wall and are calculated as follows:

$$\Delta p_v = \frac{64}{Re} \cdot \frac{L}{D} \cdot \frac{\rho}{2} \cdot \bar{u}^2 = \lambda \cdot \frac{L}{D} \cdot \frac{\rho}{2} \cdot u^2$$  \hspace{1cm} (8.34)

With equation (8.34) the following values are determined for ring sections and/or pipes:

$$\Delta p_{a1} = 10369.3 Pa$$  \hspace{1cm} (8.35)

$$\Delta p_{a2} = 39000 Pa$$  \hspace{1cm} (8.36)

$$\Delta p_{a3} = 2034658.3 Pa$$  \hspace{1cm} (8.37)

Additionally, four bends in the pipeline have been allowed for calculation for the purposes, two 45° and two 90°:

$$\alpha_1 = 90°, \quad \alpha_2 = 90°, \quad \alpha_3 = 45°, \quad \alpha_4 = 45°$$  \hspace{1cm} (8.38)

The pressure losses in these mounting parts are generally caused by secondary flows and bubbling. With details about the angle and indications in the literature, the loss coefficients of the curves can be determined:

$$\zeta_{90°} = 0.1, \quad \zeta_{45°} = 0.59, \quad \zeta_{90°} = 0.059$$  \hspace{1cm} (8.39)

With these values, the losses in the mounting parts of the curves can be determined as follows:

$$\Delta p_{\gamma} = \zeta \cdot \frac{\rho}{2} \cdot u^2$$  \hspace{1cm} (8.40)
The calculated values for these losses are:

\[ \Delta p_{VA} = 394.15 Pa \]  
\[ \Delta p_{VB} = 1288.4 Pa \]  

(8.41)  
(8.42)

All pressure losses must be considered in order to determine the required pumping capacity. The total pressure losses \( \Delta p_{Vges} \) are determined by adding the individual losses. For the accelerator and the base mortar following total pressure losses are obtained:

\[ \Delta p_{Vges} = 50033.44 Pa \]  
\[ \Delta p_{Vges} = 2035946.7 Pa \]  

(8.43)  
(8.44)

Equation (8.45) is applicable to determine the pumping capacity:

\[ P_{th} = \Delta p_{pump} \cdot Q_{th} \]  

(8.45)

Thereby the theoretical displacement volume flow corresponds with the in (8.20) determined flow rate. Further, the difference of pressure \( \Delta p_{pump} \) between pump inlet and outlet should be known:

\[ \Delta p_{pump} = \Delta p_{Vges} + p_i \]  

(8.46)

The difference in pressure \( \Delta p_{pump} \) is determined for the injection lines A and B. With equation (8.46) following values are obtained:

\[ P_{thA} = 337.2 W \]  
\[ P_{thB} = 349.77 W \]  

(8.47)  
(8.48)

Minimum total installed power to supply the calculated quantities of backfilling material is the sum of the above values:

\[ P_{Vges} = 686.9 W \]  

(8.49)
Four injection lines are installed at the circumference of the TBM with a power of 2.7 kW.

8.1.4 Determination of the pipe losses and the required pumping capacity with the conventional grouting system

Table 8.3 Technical data of the grouting system

<table>
<thead>
<tr>
<th>Name</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure in the grouting line</td>
<td>$p_i$</td>
<td>bar</td>
</tr>
<tr>
<td>Flow rate</td>
<td>$U$</td>
<td>m/s</td>
</tr>
<tr>
<td>Assumed grout density</td>
<td>$\rho_M$</td>
<td>kg/m³</td>
</tr>
<tr>
<td>Kinematic viscosity</td>
<td>$\nu_M$</td>
<td>m²/s</td>
</tr>
<tr>
<td>Dynamic viscosity</td>
<td>$\eta_M$</td>
<td>Pas</td>
</tr>
<tr>
<td>Length of grouting line</td>
<td>$L$</td>
<td>mm</td>
</tr>
</tbody>
</table>

Also with the conventional grouting system first the Reynolds’ number can be determined with equation (8.30):

$$Re_M = 4.3$$  \hspace{1cm} (8.50)

Due to the slow flow rate, the Reynolds’ number is small. Here it is again important that this value is smaller than 2300 (http://de.wikipedia.org/wiki/Reynolds-Zahl), because otherwise a turbulent flow would be present.

With the conventional grouting system only one injection line is present. Thus it is possible to determine at this stage the friction losses in the pipe with equation (8.34):

$$\Delta p_{iM} = 1058270 Pa$$  \hspace{1cm} (8.51)
Since with the two component injection four installed pipe bends have been considered, they are also included in this calculation. The loss coefficients are therefore the same as the calculation of chapter 8.1.3:

\[ \zeta_{90'} = 0.1, \quad \zeta_{45'} = 0.59 \cdot \zeta_{90'} = 0.059 \]  \hspace{1cm} (8.52)

If the losses of the mounting parts are determined according to equation (8.34), the following pressure losses must be considered:

\[ \Delta P_{VM1} = 85.9 \text{ Pa} \]  \hspace{1cm} (8.53)

With a working pressure of 3 bar, the required pumping capacity is calculated as:

\[ P_{im} = 1453.4 \text{ W} \]  \hspace{1cm} (8.54)

This power is necessary to use one injection line. For the four installed injection lines a total power of 5.8 kW results.

8.1.5 Evaluation of the calculated values

The comparison of the calculated values for both injection systems shows that the pressure loss in the accelerator line of the two component low pressure system is relatively high with approximately 20.3 bar. The conventional grouting system shows a much lower loss of 10.5 bar because of the lower flow rate of the mortar.

The higher the flow rate, the higher the friction losses in the pipe system.

Nevertheless, almost double theoretical power is required for the conventional grouting system compared to the two component low pressure system. This is because the largest portion of the pressure loss with the two component low pressure system is allotted to the accelerator line with relatively high pressures and flow rates. The required quantity of accelerator is about 1 m³. Because the injection time is equal for
both systems, the volume flow of the accelerator is smaller as with the conventional grouting system.

The calculation shows that the two component low pressure system has a lower installed power requirement.

With the two component injection only the accelerator shows material properties analogous to a Newtonian Fluid. These fluids have, in spite of changing flow rates and shear stresses, the same viscosity with which pressure losses can be calculated. Both the grouting mortar of the conventional system and the base mortar of the two component system cannot be included with these fluids. They are Bingham fluids, characterized by a so called liquid limit (http://de.wikipedia.org/wiki/Nicht-Newtonsches_Fluid).

If a shear stress is admitted to a Bingham fluid, it behaves as a solid body until the liquid limit is reached, after which, it starts to flow. The more these materials are stressed e.g. by shear forces, the more free-flowing they become. This material behavior is known as viscous. This means that it is not possible to determine a viscosity value which characterizes the flow properties under all conditions. Instead, an apparent viscosity must be determined with the help of flow charts. Based upon a determined shear stress and/or velocity.

The values used in the calculation for the two component grouting system are provided by Condat as mentioned in chapter 7.2.3 The viscosity value of the “normal” (conventional) grouting mortar is average and based on indications in the literature (Buchenau et al. 2005, p. 147), where the viscosity of mortar is given with 6-18 Pas. This value varies widely and is dependent upon the composition of the mortar. The higher the viscosity of the mortar, the higher the losses in the lines would be. With the application of more viscous materials, higher installed pumping power is required to achieve the same TBM advance speeds.
8.2 Economical comparison of the existing single component grouting system and dynamic grouting system

Further to the technical comparison of the single component grouting system and the low pressure dynamic two component grouting system regarding flow rates, pipe losses and required pumping capacity, an economic comparison is also made as a basis for an investment decision with regard to the choice of operating system.

The following comparison of the economic efficiency has been made on the provision of detailed knowledge of the mode and design of the available injection systems.

Table 8.4 shows that equipment for the two component grouting system, which includes, for example, tanks for backfill material, pumps and installation materials such as hoses and pipes etc, is 36% lower than the single component grouting system. Overall, the two component system is 41% lower than the single component grouting system.
Table 8.4 Cost comparison for two component low pressure and single component grouting systems in tabular form

<table>
<thead>
<tr>
<th>Item Description</th>
<th>Cost Percent</th>
<th>General</th>
<th>Project</th>
<th>General</th>
<th>Project</th>
<th>Total</th>
<th>Cost Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>General</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Project</td>
<td></td>
<td>Y</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diameter</td>
<td>6.0cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grouting</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 1 pc Meter mixing tank</td>
<td>22%</td>
<td></td>
<td></td>
<td>0%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 1 pc Thick Wall Pump JSR12</td>
<td>43%</td>
<td></td>
<td></td>
<td>4%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 4 pc. Raising pipes standard</td>
<td>1%</td>
<td></td>
<td></td>
<td>15%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 4 pc. Pressure cells</td>
<td>3%</td>
<td></td>
<td></td>
<td>7%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 4 pc. Tank for pressure cell</td>
<td>1%</td>
<td></td>
<td></td>
<td>8%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 4 pc. Coupling</td>
<td>1%</td>
<td></td>
<td></td>
<td>8%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 4 pc. Suction pipe</td>
<td>1%</td>
<td></td>
<td></td>
<td>1%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 4 pc. Seal valve (SNDC)</td>
<td>1%</td>
<td></td>
<td></td>
<td>1%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 Other positions grouting</td>
<td>1%</td>
<td></td>
<td></td>
<td>6%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 Installation material, hoses/pipes</td>
<td>6%</td>
<td></td>
<td></td>
<td>36%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total installation</td>
<td>66%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydraulics grouting</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11 1 pc Motor 44kW</td>
<td>2%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12 1 pc coupling, Pumping room, Drills</td>
<td>0%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13 1 pc. Hydraulics pump with solenoid</td>
<td>3%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14 2 pc Carnot black-dahle</td>
<td>2%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 Filter, Monomerics, ball valves</td>
<td>1%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16 Installation material, hoses/pipes</td>
<td>2%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total hydraulics grouting</td>
<td>9%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17 Electric installation</td>
<td>3%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18 Design and installation hours</td>
<td>6%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19 Cost Meter per m²</td>
<td>0.06%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>100%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
CHAPTER 9
APPLICATION OF DYNAMIC GROUTING SYSTEM TO ACTUAL CONSTRUCTIONS

This chapter deals with the use of the two component annular gap filling technology in practical operation.

Figure 9.1 Application of the two component grouting system to current TBM projects (based on end of year 2005)

<table>
<thead>
<tr>
<th>Low pressure variant</th>
<th>High pressure variant</th>
<th>Premix variant</th>
</tr>
</thead>
<tbody>
<tr>
<td>West Side CSO Portland, U.S. (2x Mix)</td>
<td>SMART Tunnel Kuala Lumpur, Malaysia (1x Mix)</td>
<td>East Side LRT Los Angeles, US (1x EPB)</td>
</tr>
<tr>
<td>Metro Line 1 Naples, Italy (2x EPB)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Circle Line 852, Singapore (2x EPB)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brescia, Italy (1x EPB)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Circle Line 855, Singapore (2x EPB, 2x Mix)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Circle Line 856, Singapore (3x EPB)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Durban Harbour Tunnel, South Africa (1x Mix)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Istanbul Metro Otogar, Turkey (1x EPB)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sao Paulo Metro Line 4, Brazil (1x EPB)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Guangzhou Metro Line 5, China (1x EPB)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Copenhagen Energy Tunnel, Denmark (1x EPB)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
9.1 Low pressure dynamic grouting variant

At the time of writing the thesis, the only projects in actual operation are Westside CSO Portland, Metro Line 1 Naples and Circle Line 852 in Singapore. Thus it is only possible to describe the application of the low pressure dynamic grouting variant.

**Westside CSO Tunnel Portland.**

Two Mixshields of 5.05 m and 5.14 m diameter have been used for tunnel lengths of 1,350 m and 4,350 m respectively.

The geology along both tunnel drives was gravel alluvium, a soil of high permeability.

The two Mixshields have been equipped with both, DN50 mm lines for the conventional grouting with single component grout and DN30 mm lines for two component annular gap grouting. Before starting tunneling, tests at Herrenknecht AG have been done with two component products from Condat and Mapei as described in Chapter 7.2.3.

The joint venture, Impregilo/Healy, decided to use the stabilizer and the accelerator from Mapei SpA.

Experience during the start of excavation was made with lateral infiltration of backfill material into the tailskin. This was possibly caused by the position of the wire brushes on the ring (gap or joint between the rings) and a partial setting of the backfill mix related with a high injection pressure.

Further testing at site parallel to the start of the TBM drive failed to demonstrate satisfactory results. It was therefore decided to grout the annular gap with conventional single component grout through the parallel installed oval injection openings.
Metro Line 1 Naples

Two EPB-Shields 6.74 m diameter that are in operation for Metro Line 1 in Naples will each drive a tunnel length of approx. 4,340 m through clay and tuff. Both machines are identical, equipped with four injection groups each comprising two lines, one for conventional grouting and one for two component injection. The arrangement of the groups A1 to A4 and of the injection lines 1 to 8 is shown in Figure 9.2.

Figure 9.2 Arrangement of the injection groups and lines for annular gap backfilling (Lines 2, 3, 6 & 7 for two components with DN30 and lines 1, 4, 5 & 8 for conventional grouting with DN50)

For both machines the operational data of the complete tunnel section have been analyzed to show how the backfilling of the annular gap with a dynamic grouting system performed. Data relating to the grout and accelerator flow in lines 2, 3, 6 and 7 has been considered.

The average mixing ratio of components A and B in the injection lines has been determined.
Table 9.1 Average mixing ratio in two component injection lines 2, 3, 6 & 7 for EPB-Shield N° 1.

<table>
<thead>
<tr>
<th>Ring N°</th>
<th>ØFlow Comp. A Line 2 [%]</th>
<th>ØFlow Comp. B Line 2 [%]</th>
<th>ØFlow Comp. A Line 3 [%]</th>
<th>ØFlow Comp. B Line 3 [%]</th>
<th>ØFlow Comp. A Line 6 [%]</th>
<th>ØFlow Comp. B Line 6 [%]</th>
<th>ØFlow Comp. A Line 7 [%]</th>
<th>ØFlow Comp. B Line 7 [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>15-914</td>
<td>95</td>
<td>5</td>
<td>94</td>
<td>6</td>
<td>96</td>
<td>4</td>
<td>95</td>
<td>5</td>
</tr>
</tbody>
</table>

The mixing ratio was continually adapted to the soil conditions. For lines 2 and 7, the ratio was preset to 95% A : 5% B, for line 3 to 94% A : 6% B and for line 6 to 96% A : 4% B.

Figure 9.3 illustrates the two component grouting along the first tunnel section of EPB Shield N° 1 from ring 15 to 914.

Figure 9.3 Flow in l/h for two component injection through lines 2, 3, 6 and 7 for rings 15 to 914 (courtesy of Herrenknecht AG, operational data S-238, 16.01.2006).
The interpretation of the diagram shows that the two components have been permanently injected as planned through all two component lines 2, 3, 6 and 7 (groups A1, A2, A3 and A4).

For EPB-Shield N° 2 the same analysis of operational data has been undertaken for the first section. Table 9.2 shows the average mixing ratio of component A & B for a section of about 1,015 m.

Table 9.2 Average mixing ratio in two component injection lines 2, 3, 6 & 7 for EPB-Shield N° 2.

<table>
<thead>
<tr>
<th>Ring N°</th>
<th>( \Phi )Flow Comp. A Line 2 [%]</th>
<th>( \Phi )Flow Comp. B Line 2 [%]</th>
<th>( \Phi )Flow Comp. A Line 3 [%]</th>
<th>( \Phi )Flow Comp. B Line 3 [%]</th>
<th>( \Phi )Flow Comp. A Line 6 [%]</th>
<th>( \Phi )Flow Comp. B Line 6 [%]</th>
<th>( \Phi )Flow Comp. A Line 7 [%]</th>
<th>( \Phi )Flow Comp. B Line 7 [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-879</td>
<td>94</td>
<td>6</td>
<td>95</td>
<td>5</td>
<td>100</td>
<td>0</td>
<td>95</td>
<td>5</td>
</tr>
</tbody>
</table>

Figure 9.4 illustrates the two component grouting along the first tunnel section of EPB Shield N° 2 from ring 10 to 879.
Figure 9.4 Flow in l/h for two component injection through lines 2, 3, 6 and 7 for rings 10 to 879 (courtesy of Herrenknecht AG, operational data S-239, 16.01.2006)

The analysis shows that the dynamic grouting system worked well along this tunnel section.

The full data analysis of the two component grouting for EPB-Shields Nos. 1 and 2 for project Metro Line 1 Naples are included in Appendix E.

The accelerator injection nozzles, active in lines 2, 3 and 7, were designed as shown in Figure 7.17. This nozzle type performed adequately for between 5 to 10 days, equivalent to approx. 45 to 90 rings before it had to be replaced. An inspection carried out after 37 advances revealed that the silicone sealing rings were loose or damaged. The steel bars that have been welded as a modification in order to protect the nozzle from loosing the rings remained in place but some welded points were lost, possibly because of trying to remove several blockages by the use of pressures higher 16 bar.
Circle Line 852, Singapore

Grouting the tail void with the two component low pressure system with max. 16 bar was also foreseen for the two EPB-Shields 6.60 m diameter that have been in use for the excavation of two approx 1,870 m long Metro tunnels for the Circle Line 852 in Singapore. The machines faced geological formations such as marine clay, old alluvium, sand and weathered granite.

The EPB-Shields were similarly equipped to the TBMs for Naples and Portland with four DN30 mm lines for injection of the two components and four oval grout lines DN50 mm for the injection of conventional single component grout.

Figure 9.5 Arrangement of the injection groups and lines for annular gap backfilling (Lines 1, 4, 5 & 8 for two components with DN30 and lines 2, 3, 6 & 7 for conventional grouting with DN50)

The two TBMs started excavation by the end of December 2004 and end of March 2005 respectively. The dynamic two component grouting system was active from the beginning of the tunnel drives. Component A consisting of Cement, bentonite, plasticizer and water was mixed with Component B with a ratio of 92-93% A to 7-8% B. Component B is an accelerator.

Based on experience made on site, the circular injection lines 1, 4, 5 and 8 that were specially installed for the backfilling of the two components haven’t been used. These lines (DN30 mm) were considered to be too small for incorporating the injector
(Ø20 mm). Instead, the parallel installed common DN50 mm oval lines for conventional grouting with single component grout have been used to lead the injector for component B inside the injection line for component A.

The two component backfilling system was active from ring N° 1 onwards for all tunnel sections. The two component mixture has been injected through all four oval injection lines 2, 3, 6 and 7. Figure 9.6 and Figure 9.7 illustrate the flow in liters per minute of the two component backfill material through the four active lines of TBM Nos. 1 and 2.

The full data analysis regarding the two component grouting for TBM Nos. 1 and 2 for project Circle Line 852 Singapore are included in Appendix F.

With this project, the function of the steel case injector type as described in chapter 7.2.4.3 was verified by its installation in all four lines through which the two component mix was successfully injected.

Figure 9.6  TBM N° 1: Flow in l/min for two component injection through lines 2, 3, 6 and 7 for rings 1 to 453 (courtesy of Herrenknecht AG, operational data S-262, 16.11.2005).
9.2 High pressure dynamic grouting variant

The high pressure dynamic grouting system was installed parallel to the conventional grouting system on one Mixshield for the SMART Tunnel project in Kuala Lumpur.

SMART Tunnel Project Kuala Lumpur, Malaysia

The Storm Water Management And Road Tunnel (SMART) Project in Kuala Lumpur is one of the first examples to show that the tunnels can take over more complex service functions. It will be operated both as a storm water retention and bypass channel to divert floodwater around and away from the city center and as a double-deck toll road facility for cars.

Two Mixshields 13.21 m diameter will tunnel a total length of 9.4 km. The project is divided into two lots (northern section with 5.4 km, southern section with 4.05 km). The TBM for the southern section is operated by the local joint venture
MMC-Gamuda the MMC Engineering Group Berhad and Gamuda Berhad. The geology consists of partially full face rock sections, compact and fresh marble with karst sections. The ground water level along this section is about 0.7 to 2.2 m below surface.

A dynamic two component high pressure system (max. 120 bar) was installed for backfilling the annular gap of the Mixshield according to design and function as described in chapter 7.3. There are eight annular grout lines which are evenly distributed on the tail shield circumference, each with its own grout pump.

Figure 9.8 Arrangement of the injection lines for annular gap backfilling, grout lines 1 to 8.

Four of these lines have been used with the remaining four as spares. A backfill mix for normal grouting with traditional mortar was used which showed good results with a proper backfilling of the annular gap and setting of the grout.
9.3 Premix dynamic grouting variant

The Eastside LRT Project in Los Angeles is the first Herrenknecht AG project where the premix grouting variant is used.

Eastside LRT Project Los Angeles, U.S.

The Los Angeles County Metropolitan Transportation Authority is constructing a 9.65 km dual-track light rail system in the East Side Corridor, connecting downtown Los Angeles with communities in East Los Angeles.

Two EPB-Shields 6.51 m diameter will be used to tunnel each a section of approx 2.1 km through Alluvium. The TBM's are provided with a two component backfilling system as described in chapter 7.4. The grout is made of two parts, type A solution and type B solution. Type A is made of cement, fly ash, bentonite, retarder and water. This mix can stay active for weeks. Component A is batched on the surface and pumped along the tunnel in a pipe to a storage tank placed on the TBM back-up. Type B is also pumped along the tunnel to a storage tank on the TBM back-up. Both solutions are pumped individually from the respective tanks to a mixing head that is located just before the point where the grout is pumped through the pipes installed in the tail shield. There, the solutions are mixed. The backfilling is a volume controlled injection.

Experience of the practicality of this premix variant is not available at this stage because the TBM's have not been delivered at the time of writing this thesis.
CHAPTER 10
DISCUSSION OF TEST RESULTS

Within this thesis a critical analysis was carried out regarding the development of an effective dynamic grouting system for backfilling the annular gap in heterogeneous and complex geological conditions.

The scope of the thesis focuses on the theoretical and experimental investigation of the two component annular gap backfilling system. In addition, analysis of this system has been carried out in practice to allow for a qualitative and quantitative assessment of the two component system.

The results of this work permit statements with respect to:

1. Testing method and test equipment for assessment of two component backfill material.
2. Material properties of two component annular gap backfill material.
3. Critical analyses of present grouting technology, design and arrangement of the grouting system.
4. Qualitative assessment of the dynamic grouting systems with investigations in practice.

1. Testing method and test equipment for assessment of two component backfill material

For the assessment of two component backfill material, a number of tests have been devised and conducted on both laboratory and field samples.

The primary purpose of the annular gap backfilling is the minimization of surface settlements. It is therefore essential to develop or to have testing methods that will allow the assessment of the grout behavior prior to use. These testing methods can be used as general guidance for testing tail void backfilling material. An overview
of the possible testing methods and equipment is listed in Table 7.2 and described in chapter 7.2.5.1.

2. Material properties of two component annular gap backfill material

Effective tail void grouting is a critical aspect of tunneling, using pressurized TBM's with segmental lining systems. Grouting simultaneously with the advance process through pipes installed along the tailskin can significantly reduce the settlement over tunnels in soft ground. To meet the project specific requirements and to find the best suitable mix composition, an adapted two component grout mix has been tested with the most appropriate testing equipment.

To handle the two component backfilling process in permeable soil conditions as tested within the frame of the thesis, new mixing formulae and tests for comparison have been created in order to find the best composition to avoid grout washout in the annular void and to provide rapid short term strength to hold the ring in place during the excavation process. If the mix of backfill material is not carefully selected to obtain the appropriate rheology, then there can be problems with floatation of the tunnel ring and consequent damage to the complete lining with possible adverse impact on the long term stability of the tunnel.

Generally, the material properties of the backfill material need to be adjusted to provide effective support to the lining and prevent it from moving during excavation. In particular, the specific material properties must prevent or limit buoyancy due to the fluid pressures exerted by the grout itself and the surface settlement. Therefore, the material properties should also meet the requirement of being pumpable to the point of placement without segregation or bleeding to assure sufficient bond between the surrounding ground and the tunnel lining.

Within the limits of this thesis, it has been verified that the properties of the two component backfill material can be easily adapted to the requirements of tunnelling in heterogeneous and complex geological conditions. It was shown that the grout mix tested in respect of washout resistance did not suffer any segregation during pumping and also was able to develop sufficient strength within the preset time.
In comparison to the traditional sand based mortar grouts, the problem is to achieve a grout that is easily pumpable, has a very long effective setting time and yet is capable of holding the ring in place as soon as it is placed into the annular gap around the segment ring. The physical properties of available grouts today regarding hardening times are summarized in Figure 10.1.

Figure 10.1 Physical properties of grouts in terms of hardening time

![Diagram showing hardening times of grouts]

- **Single component grouts**
  - **Mortars** (gravel, silica, cement and additives)
  - **Inert grouts** (fine sand, silica and fly-ash)
  - **Hours**

- **Two component grouts**
  - (water, bentonite, cement, stabilizer and hardener)
  - **Weeks**
  - **Minutes**

It was shown, that the advantage of the two component grouts, in comparison to the single component grouts, is that the chemical grouts harden in a matter of minutes.

3. **Critical analyses of present grouting technology, design and arrangement of the system**

With a critical analyses of the current grouting technologies carried out in Chapters 7 and 8, the advantages and disadvantages of backfilling the annular gap are demonstrated, as well as comparing the functioning and structure of the developed two component systems.

The existing grouting system with single component grouts is compared with the dynamic two component low pressure grouting system. The result of this
examination shows that the two component low pressure system has clear advantages regarding power requirements. Almost twice as much theoretical power is needed for the conventional single component grouting system compared to the two component low pressure system. Moreover, the qualitative comparison of the two systems in total has shown that the low pressure two component system is about 40% cheaper than the existing single component system where the usual basic components of backfill grout are binders (cement), sand and water.

As far as the economic aspects are concerned, project specific requirements must also be integrated in the preferred choice of grouting system to be employed.

4. Qualitative assessment of the dynamic grouting system with investigations in practice

In the practical investigations, experience with the two component low pressure grouting system as well as the modifications to the systems are put together.

An extensive laboratory and field investigation was carried out with the development of a new injector for addition of component B to the base mix flow of component A. The modification and final development is shown with the example of the projects Metro Line 1 Naples and the West Side CSO Portland.

In addition, the low pressure two component system was modified to change the injector in conditions where high groundwater pressures are encountered.

The developed testing methods and equipment in the thesis allow for a reliable assessment of backfill properties with regard to exposed soil conditions. One main focus of this thesis was to find a mixing ratio of backfill material for permeable loose soil conditions.

To conclude from the investigations carried out within this research, a mixing ratio of component A and B of 90-93% A and 7-10% B for coarse grained soils with higher permeability can be regarded as being suitable.

With the given ratio, a grout washout in the annular gap or lateral infiltration along the shield towards the tunnel face can be avoided by generating a stable backfill mix with a relatively quick setting time and early strength development.
Figure 10.2 summarizes in a tabular form the major findings of this thesis research regarding the grouting of the annular gap with dynamic two component grouting material in TBM.

Figure 10.2 Appropriate solutions with dynamic grouting material to meet the engineering requirements.

<table>
<thead>
<tr>
<th>Outcome of the development of the dynamic two component grouting system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply and engineering requirements of two component grout</td>
</tr>
<tr>
<td>- Early strength development to stabilize the bond between geology and tunnel lining in order to reduce settlement</td>
</tr>
<tr>
<td>- Gel and hardening time can be set to meet specific project requirements</td>
</tr>
<tr>
<td>- Quick stiffening: fast, secure and uniform support of tunnel lining</td>
</tr>
<tr>
<td>- Pumpable to the point of injection without segregation or bleeding</td>
</tr>
<tr>
<td>- Backfill resistant against segregation and water washout</td>
</tr>
<tr>
<td>- Long term durability: strength remains stable over a long period of time</td>
</tr>
</tbody>
</table>

The three dynamic grouting system (low pressure, high pressure and premix variants) developed in this thesis have also been evaluated and discussed from a perspective of application of these systems to actual tunnel construction.

The low pressure variant is regarded to be the most favorable dynamic backfill system, not only because of its economical advantage, but also because it presents a reliable method for the application in loose soil conditions below the groundwater table. Potential clogging of the injection lines can to a great extent be avoided with
this backfill method, making possible for a more efficient tunnel boring process. In addition, the workability of the two component backfill material is favored because it is independent from TBM stoppage periods or the TBM advance speed.

The early strength development of the annular backfill material shows that it would be advantageous to stabilize the bond between the excavated surface and the tunnel lining in order to prevent a displacement of the rings when they are stressed by TBM back-up loads.
CHAPTER 11
CONCLUSIONS AND RECOMMENDATIONS

This chapter of the thesis presents the conclusions of the research carried out regarding the grouting of the annular gap with dynamic grouting material. Comments for practice for future tunnelling projects with regards to specific soil and project conditions, which contribute to a better assessment of the annular gap backfill material, are also given, as well as recommendations for further investigations.

11.1 Conclusions of the thesis

The review and assessment of the current practices used in annular gap backfilling has revealed valuable information about their shortcomings. These have been examined in detail and then used as a basis to develop the main objectives of this thesis effort, as summarized below:

- Good pumpability of two component grout mixtures with different composition of mediums and consistencies.
- Recommendation of a grout mixture for application in coarse soil conditions.
- Comparison of different grout mixtures for washout resistance.
- Investigation of the consistency of the grouting material during restart of the pump after a defined temporary downtime.
- Avoidance of convergence in the annular gap.
- Proper backfilling of the annular gap.

For soft ground tunnel boring operations with Earth Pressure Balance Shields or Mixshields in favorable geological conditions, production rates in the range of 15 to 35 m per day can be achieved where cycle times for one segment ring can be reduced to approximately one hour. Because conventional annular gap grouts general-
ly remain fully fluid for several hours with parallel high production rates, floating of
the segments can occur in the fluid grouts, resulting in severe ring damage. The applica-
tion of the two component grouts has been found to have a positive effect to
mitigate the above conditions.

Based on the research conducted in this thesis, it has been concluded that the
technical and economic effectiveness of filling the annular gap with a two component
grout is higher than by the traditional grouting methods. A shorter setting time targets
filling the annular gap and minimizes the potential for the backfilling mix to be
diluted or segregated by groundwater. Finally, settlement is minimized whilst holding
the segment rings in place during shield tunneling.

The annular gap backfilling through the tailskin presents the safest solution to
fill the annulus between the outside diameter of the tunnel lining and the excavated
ground directly when it occurs. The tunnel lining needs a stable and durable bedding
to avoid deformations during loading. An improved grouting achieved with the
dynamic two component backfilling system leads to higher water tightness of the
tunnel tube.

If the tunnel is excavated in concrete aggressive soils, the outer shell of the
backfilling material presents an additional isolation of the actual tunnel tube. The low,
optimal pumpability of the single component grouts has also been a problem area in
backfill grouting. Since the single component grouts are relatively viscous, it can only
be pumped through larger cross section injection holes. Moreover it is necessary to
adapt the radii of the pipe bends to the flow conditions of the single component
mortar. This means that relatively large radii need to be provided.

In order to eliminate this disadvantage in design, developments have been
made in the context of the thesis for the two component annular backfilling system.

In summary, the backfilling material should be constituted as follows:

- Reaching as a minimum the strength of the surrounding soil,
- High impermeability to water,
- No contamination of the groundwater,
- No segregation during transport,
• Easily pumpable over long distances
• Complete filling of the annular gap.

Within the framework of this thesis, it has been demonstrated that the process engineering of mechanized tunneling can be further developed in so far as the grouting process with two component annular gap backfilling material which can be adapted towards a settlement controlled TBM advance.

On the basis of the knowledge gained from annular gap grouting in permeable to highly permeable soils, the application of two component backfilling material can also be recommended in heterogeneous loose soil conditions.

The tests undertaken can be directly transferred into field practice such that that additional modifications and adaptations of the backfilling medium can take place on site to match the actual soil conditions without any downtime of the excavation process.

11.2 Comments for practice

The successful backfilling of the annular gap is of primary importance for the success of a settlement controlled shield tunneling operation.

Requirements cited in Chapter 2 for grouting the annular gap with dynamic two component grouting material are listed in Figure 11.1.
Figure 11.1 Requirements for a suitable composition of backfill material

<table>
<thead>
<tr>
<th>1. Knowledge about</th>
</tr>
</thead>
<tbody>
<tr>
<td>- The characteristics of the subsoil (geotechnical and hydrological conditions)</td>
</tr>
<tr>
<td>- Specific project conditions</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2. Predefinition of engineering requirements like</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Prevention of settlements and buoyancy</td>
</tr>
<tr>
<td>- Proper and complete backfilling of the annular gap</td>
</tr>
<tr>
<td>- Quick hardening and thus early support</td>
</tr>
<tr>
<td>- Demand on water tightness</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3. Demand on supply requirements like</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Mixing, transportation and injection of the grout</td>
</tr>
<tr>
<td>- No segregation or bleeding during pumping to the point of placing</td>
</tr>
<tr>
<td>- Homogeneously mixing of both components A&amp;B at the end of the tailskin</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>4. Testing of predefined properties of the two component mix according to the characteristics of the subsoil like</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Liquid flow limit</td>
</tr>
<tr>
<td>- Density</td>
</tr>
<tr>
<td>- Viscosity</td>
</tr>
<tr>
<td>- Bleeding</td>
</tr>
<tr>
<td>- Stability of base component A</td>
</tr>
<tr>
<td>- Settling ratio</td>
</tr>
<tr>
<td>- Resistance against dilution</td>
</tr>
</tbody>
</table>
Laboratory and field testing with two components are recommended in advance of project start. The laboratory tests can be performed either in facilities of the supplier of the base products for the two component backfill material, at universities or in company owned facilities. Field testing can be carried out with the equipment specially designed in this thesis for the washout tests or with another design of test set up.

For further adaptation or adjustment of two component backfill mix to the prevailing soil conditions, tests can also be conducted, if required, simultaneously with tunnel excavation.

Requirements referring to the grouting process during TBM operation are listed in Figure 11.2.

Figure 11.2 Requirements on grouting process during TBM operation

1. Grout composition according to Engineering and supply requirements.

2. Grout equipment on TBM and surface adapted to the planned capacity of TBM advancement taking peak performances into account also Supply of sufficient backfill material.

3. Controlled backfill process and avoidance of downtimes due to blocked injection lines by flushing the injection lines with Component A after the injection process. (Preset control that flow of component B stops 60s earlier than flow of component A).

Where the grout composition according to the requirements listed in Figure 11.1 and the grouting process during TBM operation according to the requirements listed in Figure 11.2 is fulfilled, then a successful TBM advance process is possible.
11.3 Recommendations for Future Work

Based on the results of the laboratory and field investigations performed in this thesis with regards to grouting the annular gap with two component backfill material, the following areas are recommended for additional research.

Further detailed investigations and field measurements are needed to determine how much the convergence in the annular gap can be reduced or avoided with the two component annular gap backfilling system in soft ground tunneling. Future investigations referring to possible convergences in the annular gap can include a wireless sensor technique whereas the sensors are pumped together with the two component backfill material into the annular gap. If the position of an injected sensor and the distribution of the backfill material with the sensors in the annular gap can be determined, then the question can be clarified whether and how much the ground surrounds the tailskin and therefore contributes to the support of the ground and the settlement behavior.

Another interesting aspect for closer inspection would be the application of dynamic grouting material in hard rock tunneling with segmental lining construction where high deformations may result due to high overburden and stresses in the rock. There appears to be great potential for flexible lining and backfilling systems that permit control of convergence of the excavated space.

The suitability of the application of two component grouting in aggressive and contaminated soils would also be of interest in connection with the question if aggressive and contaminated soils have an influence on the strength development, the tightness and durability of the backfill material.

Of further interest would also be to evaluate if the use of two component grouting systems would be applicable for tunnel drives with an extremely downgrade alignment in order to avoid that backfill material from flowing towards the tunnel face with the negative aspect to get stuck on the shield and causing obstructions to the TBM advancement by hardened and clogged material.
Future research concerning annular gap grouting should also aim in the direction of a backfill mix that serves as additional sealing of the tunnel lining. This mix can be composed of a grout and extruded concrete being injected into the annular gap by a sliding formwork behind the TBM shield.

The two component grouting system and its interaction between soil and tunnel lining still needs substantial further research and development, in particular with regard to the long-term durability of the two component backfill material to satisfy the design requirements for long-term durability of 100 year lifetime.


Herrenknecht AG, internal information.


Herrenknecht GmbH/ Philipp Holzmann AG. Fließverhalten und
Druckverhältnisse ausgewählter Mörtelrezepturen im simulierten Ringraum,
1997.

Berechnungsmethoden für Tunnelauskleidungen mit Tübingen und deren
verfahrenstechnische Voraussetzungen. Vorträge der Baugrundtagung
SELECTED BIBLIOGRAPHY


EM 1110-1-3500: Chapter 2, Chemical Grout Materials, 31 Jan 95, pp. 2-1 -2-10.

ETAC Brochure.


Metrosur 2, Contract 1 from Leganes, 24.03.03, pp. 7-13.


TAC Brochures in Japanese.


