THE APPLICATION OF SHOTCRETE IN THE NATM

(Operating equipment, payment provisions and practical example)

W. Mayrhauser

1. Introduction

The NATM is a double shell building method consisting of the shotcrete outer arch (reinforced by welded wire fabric and steel rib sections) and the systematically anchored rock carrying ring. The rock carrying ring is the primary supporting element and thus of the greatest importance. These two shells - the shotcrete outer arch and the rock carrying ring - have to be dimensioned in such a manner that the ground reaches a permanent equilibrium. To ascertain this, extensive measuring is required. These measurements are a fundamental criterion of the NATM and consist of:

a) Roof consolidation bolts
b) Convergency measurements
c) Extensometer measurements
d) Measuring anchors

These measurements are taken continuously in the course of the advance on site.

There are several fundamental means of stabilization and support in the NATM, but hereinafter we shall only speak about shotcrete.

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1/ Arlberg Tunnel Consortium, Arlberg, Austria
Shotcrete and its predecessor, Gunite, in particular, are much older than the NATM and their development was substantially pushed in the U.S.A. and Switzerland. This applies not only to the development of shotcrete, but as well to the construction of appropriate shotcrete machinery.

The advantages of shotcrete for the NATM lie primarily in its good applicability in sealing exposed cavities as fast as possible and thereby avoid detrimental loosenings around the rim of the cavity; besides, it provides immediate protection for the crews.

In the rock conditions encountered at the Tauern tunnel and, to an even greater extent, at the Arlberg West tunnel there was, however, a critical rigidity of the shotcrete outer arch. If said critical point was surpassed, shear fractures were the result. This rigidity of the shotcrete outer arch could be avoided by a methodical placement of contraction slots (fault slots) which kept the shotcrete shell from being destroyed.

Hereinafter, I shall briefly explain the excavation method used at the Arlberg West tunnel and in the same connection the operational equipment used for applying shotcrete.

2. **Work sequence - operational equipment**

The rock is loosened on the basis of the requirements specified in the technical conditions of the tender. Since poorer types of rock were predominant, we chose the system of top heading and bench driving before construction started.
The tunnel section of about $105 \text{ m}^2$ which is to be excavated, is divided into 7 partial excavations, depending on the excavation and the supporting sequence.

a) Top heading

b) Bench I, left and right

c) Bench II, left and right

d) Excavation of the invert and concrete left and right.

After blasting and mucking one of the sectional depths of round and depending on the behaviour of the face, a face protection or safety shotcrete is applied at once. For these concrete spraying after the shotcrete method, which have to be carried out at great speed, two independent shotcrete installations are installed. Both are equipped with feeding silos ($6 - 9 \text{ m}^3$ capacity each). From these silos, 2 conveyor belts feed 6 each shotcrete machines of the GM 57 type. The powdery quicksetting accelerator is added at the conveyor belts via an automatic dosing device. One of the installations is at the roof section for the top heading, the second at the invert for the bench excavation.

When driving in poorer rock with a great water inflow, the quick setting of the sprayed concrete is of primary importance. But this must not be achieved by overdosing the accelerator, since this would reduce the strength of the shotcrete beyond admissible limits. This means that great demands have to be made on the shotcrete additive. The necessary tests were conducted by us before construction was started.
### Chart I

**Cements:**

<table>
<thead>
<tr>
<th>Spec. surface (Blaine)</th>
<th>Cement A</th>
<th>Cement B</th>
<th>Cement C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PZ 275(H)</td>
<td>PZ 275(H)</td>
<td>PZ 275(H)</td>
</tr>
<tr>
<td>Begin of setting</td>
<td>3420</td>
<td>3970</td>
<td>3630</td>
</tr>
<tr>
<td>End of setting</td>
<td>2,55 min.</td>
<td>2,10 min.</td>
<td>2,30 min.</td>
</tr>
<tr>
<td></td>
<td>3,50 min.</td>
<td>2,40 min.</td>
<td>3,20 min.</td>
</tr>
</tbody>
</table>

**Crushing/flexural strength**

(W/Z = 0,70)

| 1 d | 72/22 | 141/36 | 106/33 |
| 7 d | 241/39 | 396/63 | 298/44 |
| 28 d| 407/75 | 499/79 | 462/78 |

**Water abstraction**

(Heidelberg method)

### Chart II

**Preliminary tests cement to additive**

<table>
<thead>
<tr>
<th>additive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement A</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Required dosage (%) in the lab</th>
<th>3,5</th>
<th>2,0</th>
<th>4,0</th>
<th>2,0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beginning of setting (in sec.)</td>
<td>120</td>
<td>75</td>
<td>125</td>
<td>75</td>
</tr>
<tr>
<td>End of setting (sec.)</td>
<td>210</td>
<td>105</td>
<td>180</td>
<td>185</td>
</tr>
<tr>
<td>5 hours</td>
<td>54/3</td>
<td>54/3</td>
<td>56/3</td>
<td>52/3</td>
</tr>
</tbody>
</table>

**Pressure/flexural tensile stress**

<table>
<thead>
<tr>
<th>kg/cm²</th>
<th>7 d</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>170/40</td>
</tr>
</tbody>
</table>

**Decrease in strength**

| 7 d in % | 38 | 45 | 39 | 41 |

**Constancy in volume**

(boiling test)

| yes | yes | yes | yes |
Cement B

Required dosage (%) in the lab  4.0  3.0  3.5  4.0

Beginning of setting (in sec.)  120  145  140  120

End of setting (in sec.)  225  260  225  175

5 hours  49/3  40/2  44/2  42/2

Pressure/flexural tensile stress
kg/cm²  7 d  158/52  148/36  141/50  141/37

Decrease in strength
7 d in %  37  41  44  44

Constancy of volume
(boiling test)

It is particularly important to select the additive quality according to the chosen cements; we attached the greatest importance to increased setting speeds and the lowest possible decrease in strength after 28 days, as compared to shotcrete without additives.

3. Shotcrete requirements according to the tender conditions

The shotcrete has to meet the following requirements:

3.1 Shotcrete used for safety at the face and as a preliminary tunnel lining, while offering sufficiently short setting times and a 1-day strength of at least 40 kg/cm², has to reach a minimum compression resistance of 220 kg/cm².

3.2 Besides the "tuning-in" of additive to cement, the optimum granulometric proportions have to be observed.

3.3 For the structural shotcrete, the maximum size aggregate will be 16 mm.
3.4 The production of a quality shotcrete will have to be proved on site by shotcrete specimens from the moment the shotcrete work is started.

We had to prove to the client that our shotcrete met the above quality requirements before construction started.

In addition, the following is required during construction:

3.5 Before applying the shotcrete, the cut surfaces have to be cleaned carefully.

3.6 For the rock grades to be excavated, there are prescribed thicknesses of shotcrete which vary according to the type of rock (Figures 1 - 7). At the request of the client, the overall thickness applied will have to be confirmed by drilling a hole.

3.7 To prove the strength, and at the request of the client, cores will have to be drilled.

In theory, payment provisions are based on square meters of shotcrete in the prescribed thickness for each type of rock grade.

Depending on the type of rock, thicknesses vary between 3 and 25 cm (Figures 1 - 7).
FIG. 1

ALTERNATIVES

ANCHORS AND WELDED WIRE FABRIC IN SECTION WITHOUT WATERPROOFING

SHOTCRETE IN SECTION WITH WATERPROOFING

ROOF

WALL

33°

33°

2.30

2.00

WITHOUT WATERPROOFING

WITH WATERPROOFING

SECTION A-A

ROCK GRADE I
FIG. 2

Grouted expanding anchors or resin bolts.
- Welded wire fabric AQ 38 (1.78 kg/m²)
- Waterproofing substrate
- Waterproofing membrane
- Inner arch B 225 or B 300

SECTION B-B

ROCK GRADE II
FIG. 3

SECTION C-C

ROCK GRADE III

- Grouted anchors
- Welded wire fabric AQ 50 (3.08 kg/m²)
- Shotcrete $f_p = 220$ kg/cm²
- Waterproofing substrate
- Waterproofing membranes
- Inner arch B 225 or B 300

ROCK GRADE III
FIG. 4

SECTION D-D

ROCK GRADE IV
FIG. 5

SECTION E-E

ROCK GRADE V
FIG. 6

SECTION F-F

ROCK GRADE VI

Grouted anchors
4mm tunneling steel planks
Steel girders Thô 27
Shotcrete $f_p = 220 \text{ kg/cm}^2$
Welded wire fabric AQ 50
Waterproofing substrate
Waterproofing membrane
Inner arch B 225 or B 300
FIG. 7

SECTION G-G

OVERBURDEN SECTION

Grouted anchors
4mm tunnelling steel planks
Steel girders Thd 21
Shotcrete $f'_c = 220 \text{ kg/cm}^2$
Welded wire fabric AQ 50 (3.08 kg/m$^2$)
Waterproofing substrate
Waterproofing membrane
Inner arch B 225 or B 300
With these demands on the thickness and quality of the shotcrete there have been no problems with payment provisions between contractor and owner. It is a simple matter: The owner has to pay for the specified thickness of the required concrete quality.

**Chart III**

**Shotcrete quality control**

<table>
<thead>
<tr>
<th>Specific gravity</th>
<th>Carrot strength kg/cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kg/m³</td>
</tr>
<tr>
<td>Shotcrete with-</td>
<td></td>
</tr>
<tr>
<td>out additive</td>
<td>2300</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Shotcrete</td>
<td></td>
</tr>
<tr>
<td>with additive</td>
<td>2365</td>
</tr>
<tr>
<td>5%</td>
<td>183</td>
</tr>
</tbody>
</table>

The specific gravity of 2300 kg/m³ and the favourable compression resistance of 374 kg/cm² of the shotcrete without additive show the good granulometric composition and the satisfactory cement dosage of the shotcrete. Besides, the decrease in strength of 38% is within the normal range.

In this solution of payment provisions it surely is the risk of the contractor to include an adequate excess profile for the respective thicknesses when handing in his offer. Experience shows that such an excess profile will have to be more generous for thinner shotcrete layers than for thicker ones.
If the required shotcrete strength should not be reached in certain cases, the agreement foresees that the inferior strength may be compensated by thicker layers of concrete. In such a case, the following computation is applied:

\[ dl = \left( \frac{F}{m} - 1 \right) d \]

- \( F \) = required strength \( \text{kg/cm}^2 \)
- \( d \) = theoretical thickness of the shotcrete lining \( \text{cm} \)
- \( m \) = measured strength \( \text{kg/cm}^2 \)
- \( dl \) = additional thickness required in \( \text{cm} \)

**Practical example**

Shotcrete thickness called for = 20 cm

Required shotcrete strength = 220 kg/cm\(^2\)

Proven shotcrete strength = 200 kg/cm\(^2\)

therefore:

\[ dl = \left( \frac{220 \text{ kg/cm}^2}{180 \text{ kg/cm}^2} - 1 \right) 20 \text{ cm} \]

\[ = (1.22 - 1) 20 \text{ cm} \]

\[ = (0.22) 20 \text{ cm} = 4.4 \text{ cm} \]

This means that in this specific case, where locally only 180 kg/cm\(^2\) strength were achieved with a requested shotcrete layer thickness of 20 cm, an additional provable thickness of 4.4 cm is required.

This type of computation, however, will only rarely have to be done in practice since the called for values regarding strength
and quality can always be achieved. Besides, this type of computation has its limits insofar as the intrados of the shotcrete outer arch may extend 5 cm at the utmost into the theoretical inner arch. The contractor is therefore well advised to foresee excess dimensions in height and width in keeping with the local rock conditions.

Thus, only the theoretical surface of specified thickness is paid for. Beyond that, there is a single case where additional shotcrete may be paid for, namely in the case of geological post fracturing. However, only quantities exceeding 60 cm of the theoretical excavation profile will be paid.

I hope that my presentation managed to give you an idea regarding the payment provisions for shotcrete in an Austrian road tunnel project. But, let me add that this type of settling accounts will in any case favour the owner.

4. Practical example NATM

Arlberg West road tunnel

Description of the excavation

4.1 Top heading (Figure 8)

The excavation of the top heading is composed of the following work sequences: Drilling the face; the length of round is conveniently adapted to the distances of the steel ribs and is usually 1.2 m.
After drilling, loading and blasting the top heading face, mucking is done with 2 or 3 Cat. 966 front end loaders. In tandem operation, they muck the spoil to the haulage track at the bottom.

The haulage is performed by a Schoma diesel locomotive (240 HP) and 6 Muhlhauser muck cars (each of 15 m$^3$ carrying capacity). While mucking the top heading, access to the two benches is blocked and work on the benches ranks second, or the operation has to be planned beforehand to prevent the mucking of the top heading from interfering substantially with the bench excavation.

Depending on the rock characteristics of the top heading face, a protective shotcrete coat is applied immediately after mucking. After completion of the shotcreting, the profile is checked and surveyed by means of a template adjusted with the aid of a laser-beam. Thereafter, the steel ribs, subdivided into 5 separate sections, are installed.

The steel arch is assembled at the bottom of the top heading while the profile is surveyed, placed at the face with a front end loader and anchored to the rock with 6 expanding anchors. Simultaneously with the steel ribs, the welded wire fabric is also applied in the segment of the latest advance. Anchorholes are then drilled and the rock bolts are installed (type SN, $\phi$ 16, 6-9 m long). Besides applying the rib sections and subsequent shotcreting the latest round,
contraction slots are left open at the overlapping of the steel rib sections. The shotcrete may also be applied before drilling the anchor-holes.

4.2 Bench I (Figure 9)

Bench I is excavated alternately on the left and right to secure the side walls before opening the entire cross-section. Mucking and haulage routes have to be adapted to changing work conditions.

There are the following work sequences:

Excavation (drilling, blasting — in part ripping the material), profile checking, lengthening the steel rib by one segment, installing the welded wire fabric, anchoring and shotcreting. The length of round in excavating the benches is at most 3,00 m.

4.3 Bench II (Figure 10)

Excavation and support are effected as with bench I.

4.4 Invert Excavation (Figure 11)

Invert excavation is done almost exclusively by machines (excavators of the OK RH 9 type). The strongly pressing rock calls for very little blasting. On the contrary, often friable, torn parts or fairly large mylonitic fault zones have to be removed with the muck. Excavation work
is also done alternately left and right, as in the benches. After excavation and clean-up, the invert is covered with concrete (Figure 12).

4.5 Securing - Anchoring

Hereinafter, I'll give further details of anchoring. The various types of anchor used are apparent from the enclosed chart. The most difficult operational step in effecting an SN-anchoring is the placing of mortar into the borehole, whereby the viscosity of the mortar plays a decisive role. If the mortar is too viscous, it will easily flow out of upward inclined boreholes. We countered this at the Arlberg by placing - as an additional safety device - a collar at the anchor head when driving it into the borehole, thereby sealing the borehole until the rock bolt is completely driven in and thus guaranteeing one hundred per cent grouting of the anchor bar along its entire length.

If the mortar is too stiff, a part of it will set in the pug mill, or the filling hoses will be permanently clogged. In principle, the mortar for SN-anchor is placed - with small pressure tanks - from the back of the borehole, and the growing mortar column pushes the extruder hose out of the borehole.

In addition, we place synthetic resin cartridges, consisting of two components and an accelerator, into the rock of
SHOTCROTE FOR GROUND SUPPORT
the borehole (adhesive length), before filling it with mortar. In the strongly water-bearing rock, this has the advantage that due to the instant hardening of the synthetic resin, the anchor can also be post-tensioned instantly when necessary.

5. **Comparison regarding safety**

In conclusion, we have to state that the New Austrian Tunneling Method is a safe construction method. There is, however, a single drawback - we mentioned it initially: It calls for a highly-qualified team of engineers trained in rock mechanics, and the crew has to command considerable technical knowledge, too.

Provided all these conditions are met, the NATM is one of the safest and most economical methods for building underground cavities. Safety is particularly increased by the continuous measurements and their interpretation.

Coming to a close, I would like to quote Prof. Lad. von Rabcewicz who said:

"The infinite variety in geological and mineralogical aspects of the complex building material "rock" confront the engineer with new and interesting tasks, over and over again. Therefore, a method of tunneling must never remain stationary, but necessarily continues to develop if it is to master changing tasks satisfactorily and if it is to be up to the latest findings in rock mechanics. These postulates contradict the habit of patenting each new idea right away, since any wording of a patent specification puts fetters on the inventor, hindering any further development. The development of the NATM is by no means completed, and this
method will constantly be improved, on the one hand in mastering new tasks, on the other thanks to the development of the stabilizing means."