CONCRETE FOR THE WORLD’S LONGEST TUNNEL – REQUIREMENTS, PRODUCTION AND TRANSPORT OF CONCRETE AND SHOTCRETE FOR THE GOTTHARD BASE TUNNEL

Jens Classen

ABSTRACT

The Gotthard Base Tunnel with its length of 57km will be the longest rail tunnel in the world when construction finishes in 2017. The Consortium TAT, together with its subcontractor Holcim/Sika, is in charge of production of approximately 1.5 million cubic meters of concrete and shotcrete for the two southern lots at Bodio and Faido. An overview is given over requirements, production and transport of concrete for the various working stations underground.

INTRODUCTION

The Consortium TAT was awarded both southern contracts totalling 30km of excavation and inner lining of running tunnels, crosspasses and the multifunctional station at Faido (for detailed project description see Paper: “The Gotthard Base Tunnel Project in Switzerland – Construction of the World’s Longest Railway Tunnel”).

While shotcrete, together with rock bolts, wire mesh and ring beams, serves as primary lining during excavation, concrete is used for the inner lining of the running tunnels and cross passages.

The caverns, crossovers, ventilation and rescue tunnels inside the multifunctional station in Faido will also be lined with shotcrete.

The excavation of long tunnels, such as the Gotthard Base Tunnel with its two tubes, produces a large amount of rock, which presents a valuable alternative for aggregate production. The excavated rock mass of the Gotthard amounts to 13.3 mio m³, 5 times the amount of the great Cheops pyramid in Egypt [1].

For a long time, the chip-like rock parts from TBM excavation were being thought of as not suitable for concrete production due to the high standards for aggregates. Instead, it was used for embankments or as landfill for disposal sites.

With regard to the large excavated amounts on one hand, and the need for concrete and shotcrete on the other, not using this resource was unacceptable to the client, the AlpTransit Gotthard Ltd.

PRODUCTION OF AGGREGATES

In 1993, the client launched a massive research programme in order to determine the necessary procedures and equipment to transform the excavated rock into suitable aggregates for the high-quality concrete with a 100-year lifetime. Included were universities, research institutes and the concrete industry. First results, though, were disappointing, showing low compressive strengths and water tightness, resulting mainly from the high mica content of the fine sand.

Further tests were executed in 1995, using for the first time excavated rock from the Gotthard project, namely the Piora exploration tunnel in Faido. Results were satisfactory, and in 1996 the client invited offering teams, consisting each of cement and additive manufacturers, to test and get authorized concrete and shotcrete recipes using aggregates from excavated rock.

The main criteria for the production of aggregates are:

- Los Angeles Index
- Content of petrographic unsuitable components
- Content of free phyllosilicates (mica)
- Sieve analysis and grading curves
- Gross density
- Water content

Especially the allowed content of 35% of free phyllosilicates in the sand fraction was until then unknown to the concrete industry, and experience was lacking.

To cover the need of 5 million tonnes of aggregate, the client awarded contracts to material recycling companies, which erected state-of-the-art material processing plants at each of the 5 working sites.
The main contractors are obliged to hand over the excavated material to the recycling contractor, the grain size limited to 150mm edge length.

All main contractors added one or more crushers to their production line to comply with these requirements. For example, the northern lots equipped their TBM’s with a crusher to keep damage from the conveyor belts, while TAT had a central crusher situated behind the rotary tip in Bodio. In Faido, the material was crushed in the central cavern of the multifunctional station, before being loaded onto a conveyor belt.

The excavated rock is then further crushed, washed and screened into five fractions within the processing plant, before being handed back to the main contractor’s batching plant via conveyor belts. There are three sand fractions, 0/1, 1/4, 4/8 and two gravel fractions, 8/16 and 16/22.

The main contractor has no direct control of the processing, nor has he any direct contractual relationship to the recycling contractor, and therefore relies completely on the quality control measures of the client.

**CONCRETE REQUIREMENTS**

The contractual requirements can be summarized as follows [2]:

- only authorized recipes from the concrete system suppliers
- all aggregates to be obtained from the processing plants
- production of concrete with high sulphate resistance
- all recipes must be functioning at high temperatures underground
- shotcrete recipes including steel fibres
- quality sufficient for a 100-year lifetime

As an example, Figure 1 shows the requirements for general shotcrete, and shotcrete with high sulphate resistance.

<table>
<thead>
<tr>
<th>Concrete sort</th>
<th>SB1</th>
<th>SB2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Authorization</td>
<td>On site</td>
<td>Authorization</td>
</tr>
<tr>
<td>Compressive Strength Class</td>
<td>B 40/30</td>
<td>B 35/25</td>
</tr>
<tr>
<td>Early Strength</td>
<td>≥ 3 N/mm²</td>
<td>≥ 3 N/mm²</td>
</tr>
<tr>
<td>Depth of Penetration of Water</td>
<td>≤ 25 mm</td>
<td>≤ 30 mm</td>
</tr>
<tr>
<td>Chemical Resistance</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td>Water/Cement-Ratio</td>
<td>≤ 0.50</td>
<td>≤ 0.50</td>
</tr>
</tbody>
</table>

Fig. 1 Requirements for Shotcrete

For the consortium, there are additional requirements, especially concerning logistics [3]:

- different concrete recipes (SB1/SB2/OB1/OB2) at the same time from the same plant
- long open times due to long distances to the work sites
- different shotcrete recipes depending on hydraulic or pneumatic shotcrete application systems
- long pumping distances of more than 200m for shotcrete

From the above mentioned requirements, it is obvious that shotcrete production turned out to be more difficult than in-situ concrete production for the inner lining.

When production started in 2001, one sulphate-resistant recipe for shotcrete was available from the research and authorization phase (Fig. 2+3)

**Grading Curve**

<table>
<thead>
<tr>
<th>Gradation Curve</th>
<th>Dosage [%]</th>
<th>Dosage [kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand 0/3</td>
<td>5</td>
<td>90</td>
</tr>
<tr>
<td>Sand 0/4</td>
<td>50</td>
<td>830</td>
</tr>
<tr>
<td>Sand 4/8</td>
<td>45</td>
<td>755</td>
</tr>
<tr>
<td>Aggregates total</td>
<td>100</td>
<td>1'675</td>
</tr>
</tbody>
</table>

Fig. 2 Original Aggregates Grading Curve [2]

**Additives**

<table>
<thead>
<tr>
<th>Additives</th>
<th>Dosage [%]</th>
<th>Dosage [kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement (Fortico 5R)</td>
<td>-</td>
<td>450</td>
</tr>
<tr>
<td>ViscoCrete AT6 (FM)</td>
<td>1.4</td>
<td>6.30</td>
</tr>
<tr>
<td>SikaTard AT11 (VZ)</td>
<td>0.5</td>
<td>2.25</td>
</tr>
<tr>
<td>SikaPump AT 31</td>
<td>0.5</td>
<td>2.25</td>
</tr>
</tbody>
</table>

Fig. 3 Original Dosage of Additives [2]
This recipe had to be changed for the first time in 2001, due to the processing plant options. The sand fractions 0/3 and 0/4 were split into the new fractions 0/1 and 1/4. In addition, TAT started using two different shotcrete systems:

- pneumatic system using rotor pumps for shotcrete application in cross passages and other small excavations, as well as for the watertight membrane underground
- hydraulic system using piston pumps for the large scale application on the TBM’s and in the multifunctional station

These facts called for two different shotcrete recipes, one with a coarse grading curve for the rotor pumps, and another using a fine grading curve for the piston pumps (Fig. 4 – 7)

<table>
<thead>
<tr>
<th>Grading Curve „pneumatic“</th>
<th>Dosage [%] [kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand 0/1</td>
<td>15 257</td>
</tr>
<tr>
<td>Sand 1/4</td>
<td>40 684</td>
</tr>
<tr>
<td>Sand 4/8</td>
<td>45 770</td>
</tr>
<tr>
<td>Aggregates total</td>
<td>100 1711</td>
</tr>
</tbody>
</table>

Fig. 4 Grading Curve Pneumatic System [2]

<table>
<thead>
<tr>
<th>Recipe Design „pneumatic“</th>
<th>Dosage [%] [kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement Fortico5R</td>
<td>- 425</td>
</tr>
<tr>
<td>Sika ViscoCrete AT8</td>
<td>1.2 5.10</td>
</tr>
<tr>
<td>SikaTard AT11 (VZ)</td>
<td>0.5 2.13</td>
</tr>
<tr>
<td>SikaPump</td>
<td>- -</td>
</tr>
</tbody>
</table>

Fig. 5 Recipe Design Pneumatic System [2]

<table>
<thead>
<tr>
<th>Grading Curve „hydraulic“</th>
<th>Dosage [%] [kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand 0/1</td>
<td>33 550</td>
</tr>
<tr>
<td>Sand 1/4</td>
<td>27 450</td>
</tr>
<tr>
<td>Sand 4/8</td>
<td>40 667</td>
</tr>
<tr>
<td>Aggregates total</td>
<td>100 1667</td>
</tr>
</tbody>
</table>

Fig. 6 Grading Curve Hydraulic System [2]

The concrete recipe for the in-situ concrete, as it is used today, is shown in figures 8 and 9.

<table>
<thead>
<tr>
<th>Grading Curve In-Situ Concrete</th>
<th>Dosage [%] [kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand 0/1</td>
<td>25 449</td>
</tr>
<tr>
<td>Sand 1/4</td>
<td>18 323</td>
</tr>
<tr>
<td>Sand 4/8</td>
<td>10 180</td>
</tr>
<tr>
<td>Gravel 8/16</td>
<td>21 377</td>
</tr>
<tr>
<td>Gravel 16/22</td>
<td>26 467</td>
</tr>
<tr>
<td>Aggregates total</td>
<td>100 1796</td>
</tr>
</tbody>
</table>

Fig. 8 Grading Curve In-Situ Concrete

<table>
<thead>
<tr>
<th>Recipe Design In-Situ Concrete</th>
<th>Dosage [%] [kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement Fortico5R</td>
<td>- 375</td>
</tr>
<tr>
<td>Sika ViscoCrete AT507</td>
<td>1.2 4.50</td>
</tr>
<tr>
<td>Water/Cement-Ratio</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Fig. 9 Recipe Design In-Situ Concrete

**CONCRETE PRODUCTION**

In 2001, the concrete production contract was awarded to the joint venture of Holcim-Sika. The contract worth 180 million SFR (or 240 mio NZ$) includes:

- Installation and operation of a batching plant in Bodio
- Operation of the existing batching plant in Faido
- Operation of the cement-handling facilities in Bodio and Faido
- Production of 1 million cubic meters of in-situ concrete for the inner lining
- Production of 250'000m³ of sprayed concrete (shotcrete) for primary rock support and inner
lining of caverns, crossovers, rescue and ventilation tunnels
- All necessary testing, authorization procedures and quality controls including all necessary equipment

The existing batching plant in Faido was taken over from the pre-contractor, who had excavated the access tunnel. It was originally equipped with a 1,5m³ mixer that was later enlarged to 2,25m³, due to the intensified need for shotcrete in the fault zones of the multifunctional station (MFS).

The newly erected batching plant in Bodio has the following features:
- two plants each equipped with a 3m³ mixer
- 2 x 6 silos for aggregates, capable of holding a maximum of 800m³
- 6 cement silos, each holding 130m³
- 1 microsilica silo of 50m³
- 8 tanks for additives, each holding 4'000litres
- separate dosage systems for cement, water and additives
- dosage system for steel fibres
- heating system for aggregates and water

A further requirement is a loading and mixing time of 3 minutes for a 3m³ batch, giving one plant a capacity of 60m³/h, and a total of 120m³/h for the entire plant. Both batching plants in Bodio and Faido are operated by Holcim/Sika on a 24hour/7days a week basis.

**CONCRETE TRANSPORT**

During the excavation of the MFS in Faido, the site operated separately from the main installation site in Bodio, and was supplied with concrete from the existing batching plant. Until the end of the excavation works in 2007, it produced approximately 200'000 m³ of shotcrete, while in-situ concrete was rarely used.

Mixer trucks transported the shotcrete to the various working sites inside the MFS via the 2,7km long access tunnel. At peak times, seven working spots had to be provided.

In the Bodio section, the concrete transport is all rail-bound. In-situ concrete trains consist of 4 closed mixer cars with a capacity of 12m³ each. The train is pushed by a 35ton locomotive to the various sites underground. These trains are used to transport the invert concrete to the TBM’s, and the inner lining concrete to the worms.

Shotcrete trains usually consist of one to three cars, depending on their destination and on the prevailing geological conditions.

When a train arrives on one of the two tracks underneath the batching plant, the covers of the mixers are lifted and swerved sideways automatically by small cranes, that also put them back into place when the cars are fully loaded.

Four buckets, which can travel along the whole length of a concrete train, take up the 3m³ batches from the mixers, filling up the mixer cars without moving the train.
The batching plant has a capacity of 120m³/hour. With two tracks underneath the plant, two trains can be filled simultaneously within an hour, including lifting and placing of the covers.

To date, the plant has produced more than 900'000m³ of concrete and shotcrete, the maximum output for one day has been 1’200m³.

During the transport up to 20km inside the tunnel, the drums are continuously turned one at a time, using a cascade system operated by the loco driver. This measure ensures constant concrete consistency upon arrival at the working sites.

**SHOTCRETE APPLICATION**

1. **MFS Faido**

During the drill-and-blast excavation of the MFS at Faido, the shotcrete was applied by self-propelled Aliva AL 500 shotcreting systems. The shotcrete was retarded for 5 hours, giving the mixer trucks enough time to drive down the steep access tunnel, plus some waiting time inside the MFS.

The shotcrete was mainly used as primary support in layers of 10cm, with a maximum thickness of 60cm.

2. **TBM's Bodio**

The shotcrete application installations on the TBM are divided into two sections, the so-called L1 zone approximately 5 to 10 m behind the cutter head, and the L2 zone 40 to 60m back.

In good rock conditions, shotcrete is only applied in the L2 zone, sealing the rock surface and covering the wire mesh and rock bolts. A fine layer of shotcrete is added to create a smooth surface for the watertight membrane.

The shotcrete installations in L2 consists of one or two shotcrete nozzles that can move longitudinally on a drum-like trolley, which itself can also move longitudinally on the main frame of the TBM. Thus, a 10m section of tunnel can be covered without moving the TBM itself, giving some flexibility to the shotcrete logistics.

The nozzles cover 270° of circumference, leaving out the invert, where the in-situ concrete slab is cast shortly after.

For the Bodio drives, no great amount of shotcrete was foreseen in the L1 zone. Therefore, a nozzle was mounted on the drill rig carriage. To move the nozzle, both drill rigs had to be moved circular in order to cover approximately 180° of tunnel surface.

Since the TBM found unstable rock conditions almost from the beginning, it was soon obvious that this nozzle was unsuitable for the necessary extensive shotcrete application, especially for filling the large overbreaks. The re-design of the L1 zone during the winter break of 2004/2005 was especially dedicated to this problem.
Company ROWA of Switzerland was awarded the design, manufacture and installation of the L1 modifications including:

- new, less vibrating centre platform to allow for moving installations longitudinally
- new shotcrete robot to cover 270° and to enable large overbreaks to be filled quickly and safely
- new, self-propelled ring beam transporter which serves also to move the shotcrete robot longitudinally
- new movable working platforms on either side of the centre platform to allow for easy access to all working areas

The new shotcrete robot proved to be very flexible, with almost no interruptions in the concrete flow, due to the less vibrating platform it is travelling on.

With the above mentioned improvements, only the invert in the L1 zone had to be sprayed by hand.

The shotcrete is pumped to both installations over a distance of up to 200m by two Schwing BPN 300 piston pumps that operate separately, so both working zones can be supplied separately. The accelerator pumps are electronically connected to the concrete pumps. Dosage of the Sigunit AT 25 accelerator is between 4.5% in the L2 zone, and 5.5% to 7.5% in the L1 zone. The accelerator is stored in four 1’000litre tanks that are filled up regularly by the shotcrete train.

The shotcrete is transported to the pumps by short conveyor belts. The shotcrete itself has an open time of 12hours to guarantee maximum flexibility. Usually the pipes are always full of concrete and emptied only for longer breaks.

3. Cross Passages Bodio

In Bodio, the cross passages were also excavated by drill-and-blast methods. In total, 51 cross passages had to be lined with shotcrete as a primary support. Due to the small cross section and the limited space inside the running tunnel, only a small shotcreting unit using a pneumatic system could be used. This pumping unit was served by a train of one mixer car, pushed by a 25ton locomotive.

4. Reprofiling Works

On the inner lining installations, the so-called worms, shotcrete is only applied in small amounts to smoothen the surface as preparation for the sealing works. Due to the narrow space, application is by hand, using a pneumatic system with a rotor pump.

Due to convergences and uplift of up to 50cm in some fault zones, the primary support and the in-situ concrete slabs had to be demolished over a length of approximately 300m in each tunnel. With regard to the extent of these works, two re-profiling carriages were installed to carry out demolition and reconstruction of the outer shell and the invert slabs. Shotcreting was carried out either by hand in narrow spaces or, where possible, by an Aliva 503 pneumatic spraying system.
IN-SITU CONCRETE PLACING

1. Inner Lining of Running Tunnels

In-situ concrete placing is carried out in 3 areas: casting of the invert slab on the TBM and in the cross passages, and installation of the inner lining on the concrete installations, the worms. For detailed information of these installations including transport, pumping and placing of concrete see paper: “The Gotthard Base Tunnel Project in Switzerland – Construction of the World’s Longest Railway Tunnel” by the same author.

Today, the worms have arrived in the Faido MFS, and are being refurbished to take on the next 12km of inner lining in the Faido section.

While the inner lining thickness in Bodio was 25cm, it will vary in Faido between 30 and 35cm, due to the higher overburden and squeezing rock conditions.

2. Invert Concrete Slab (TBM)

The in-situ concrete invert slab is cast on the TBM for various reasons:

- concrete slab serves as base for rail tracks, including side rails for the TBM trailer construction
- main drainage and wastewater pipes can be placed and used for TBM wastewater
- an enclosed and therefore fireproof compressed air pipe can be placed to serve the rescue containers on the TBM and the trailing installations

The TBM’s started off by using a heavy shutter system of 10m length. Concrete was supplied by conveyor belts directly from the concrete mixer cars.

During Christmas break 2003, the conveyor belts were replaced by rail-bound Schwing BP1800.
concrete pumps, and a new lightweight shutter system was developed and ordered.

A couple of months later, the new system was installed on the TBM, and the concrete pumps were fixed on the trailer construction for easier cleaning and maintenance.

The system proved very successful, finally giving the chance to pour 3 slabs in 24 hours to follow the TBM's progress without being on the critical path.

The same system is still in use for the Faido to Sedrun section. A stationary mixer has been added to the piston pump, in order to homogenize the concrete after more than 20 km of travel inside the running tunnel. The mixer is also equipped with a dosage system to enable mixing additives, should the concrete quality deteriorate during transport.

3. Inner Lining of Cross Passages

The invert slab of the cross passages is immediately cast after the excavation. Before the worms arrive, the slab is used to place preliminary doors, ventilators, transformers and other equipment used for the ventilation system.

The inner lining is cast by the worm crews behind their installations. A single shutter of 10 m length is used to pour 3 sections to finish the cross passage lining.

Today, 50 of 51 cross passages are lined in the Bodio section, while the excavation in the Faido lot has just started.

SUMMARY

The production of aggregates from excavated rock has been found difficult, but nevertheless possible. Adjustments have to be made whenever rock conditions change. Especially the high mica content proved to be the cause of many problems, which led to difficulties in the application of shotcrete.

In the early stages of the excavation, the TBM installations had to be modified. The shotcrete application only started going smoothly, when a new flexible robot for the L1 zone was installed.

The invert concrete slab production only took up the pace after being completely replaced by a lighter solution, and after changing from a belt conveyor transport to a pump solution.

The inner lining using the ‘worms’ proved to be a perfect solution in these site conditions. They leave behind a smooth, fracture-less concrete shell, designed to last for at least 100 years.
REFERENCES


