Development and Underground Placing of Self Compacting Concrete

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1 Abstract

Self compacting concrete (SCC) for use in tunnelling has been tested in order to provide recommendation for minimum reinforcement and crack width limitation. Therefore, a tunnel according to German railroad restrictions of 24 m length was excavated by mining technology (see Figure 1).

Within this project SCC-mixtures were developed and tested in the laboratory, as well as at the construction site. Different concrete compositions using different cement types, as well as fly ashes as a filler have been applied. During the casting process - before and after pumping (120 m straight + 150 m vertical fall) - the time-dependent behaviour of fresh concrete was tested and samples were cast. Strength and dilation tests were carried out on samples stored underground (8°C/88 % r.h.) and according to standard (20°C/65 % r.h.). Furthermore early shrinkage tests and ultrasound tests were applied. The ongoing tests provide information concerning the interdependence between placing technologies and material performance.

Figure 1: View into the tunnel construction area.

2 Introduction

Self compacting concrete (SCC) belongs to the most promising developments of concrete construction in recent years. SCC can considerably improve the quality of constructions and due to its excellent properties new application fields can become accessible. Originally developed in Japan in the late 1980’s, this concrete with its excellent flowability is able to fill formwork self-dependent and self-aerating without any additional compaction energy just by the means of gravity [1, 2]. The excellent flowability enables a self-flowing of the concrete and the negotiation of barriers, such as reinforcement bars without blocking. Due to the self-levelling property smooth and planar surfaces will be formed. Nevertheless some difficulties arise regarding large scale production and placing of SCC since the concrete must demonstrate a good flowability without any segregation and bleeding.

Experience with SCC was gained in building construction and structural engineering. The high damage rate of inner walls of tunnels excavated by mining technology and cast with the classical compacted concrete was the reason for investigations new opportunities of quality improvement in modern tunnel constructions. The insufficient compaction quality e.g. in the ridge area and in the area of block spices and working spices belongs to the most frequent damage causes of tunnels cast with site-mixed concrete. Typical concerns of tunnel constructions such as geometry, thinness or in width varying elements near block outs, as well as poor accessibility argue in favour of self compacting concrete.

The aim of the research project is the theoretical and experimental investigation of the application of self compacting concrete in mining in 1:1 scale under consideration of concrete technological, conductional and statically aspects of tunnelling. Investigations on rheology, as well as in-situ measurements on the construction are in the focus of the project. Possible conveying and casting technologies have been investigated under consideration of the formwork aspects. In the project e.g. concrete dilation and temperature measurements in the wall area during the hardening process, as well as compressive strength development tests were implemented.

3 Underground testing field

The TU Bergakademie Freiberg is the only technical university in Germany who runs a working mine for the express purpose of teaching, research and education. The first level at 150 m underground is especially suited for the construction of a large-scale concrete test station due to its nearness to the mine shaft.

In order to cast the tunnel, the concrete produced in a ready mixed concrete plant was transported to the mine area in a ready mixed concrete truck, subsequently pumped about 50 m through a pipe to the mine shaft before falling 150 m through a hose down to the first level and to be transported from there approximately 100 m horizontal to the tunnel formwork using a second pump.

The properties of the fresh and hardened concrete were tested in the laboratory and in the ready mixed concrete plant in the development phase, as well as during the casting process aboveground and underground (before and after pumping). In order to gain experience with the installed transport technique the different base slab segments for the tunnel were cast first with SCC [3]. The pressure level in the pipe was mainly influenced by the pipe friction. The maximal pressure measured at the end of the vertical hose was approximately 12 bar (see Figure 2). In order to obtain an excellent flowability and to avoid segregation in the pipe and the hose the addition of chemical admixtures to the concrete, such as plasticizer and stabilizer, were necessary.

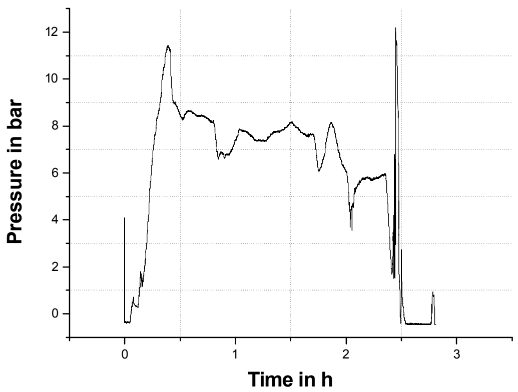


Figure 2: Pressure development at the lower end of vertical hose line.

4 Investigations on concrete

In this research project different cements were incorporated. Depending on the materials favoured by the industry, at each casting time different ashes have been used in the concrete mixtures.

Therefore, the concrete mixtures were developed and tested in the laboratory using a 50 l batch before testing and optimizing the concrete mixture in the ready mixed concrete plant using 1 - 2 m³. During the casting of the tunnel concrete tests have been carried out on material taken from aboveground before pumping and from underground after pumping.

The materials and mixture composition utilized for the tunnel are shown in Table 1. Table 2 shows the fresh concrete tests with parameters and requirements according to standards and guidelines [4]. Investigations carried out on hardened concrete, as well as sample sizes and testing times are given below in Table 3.

Table 1: Materials and mixture compositions.

Material	Labelling	Content	w/c
Portland cement	CEM I 42,5 R	300 kg/m³ (SFA 1 and SFA 3)	0.57
Portland composite cement (slag + limestone)	CEM II/B-M(S-LL)32,5 R	350 kg/m³ (SFA 3)	0.47
Fly ash (hard coal)	SFA 1 or SFA 3	227 kg/m³(CEM I); 177 kg/m³ (CEM II/B-M)	
Sand	0-2 mm	50 % (of total aggregates)	
Gravel	2-8 mm	25 % (of total aggregates)	
Gravel	8-16 mm	25 % (of total aggregates)	
Plasticizer	FM	Variation as necessary	
Stabilizer	St	Variation as necessary	

Table 2: Fresh concrete tests and parameters.

Test	Parameter and requirement
Slump	t_{500} = 5 - 7 s; r_1; r_2; r_m > 65 cm
J-Ring	r_1; r_2; r_m > 65 cm; no blocking (difference of concrete height inside and outside the ring < 5 mm)
L-Box	$h_2/h_1 > 0.88$
Funnel time	t = 10 - 20 s

Table 3: Properties tested on hardened concrete.

Test	Sample [cm³]	Testing time	Concrete	Storage
Bending strength	4 x 4 x 16 8 x 8 x 25	1 d, 2 d, 7 d, 28 d, 90 d	from aboveground and underground	each according to DIN* and TNL**
Compressive strength	4 x 4 x 16 8 x 8 x 25 10 x 10 x 10 15 x 15 x 15	10 h, 12 h, 14 h, as well as 1 d, 2 d, 7 d, 28 d, 90 d		

* Storage under standard conditions according to DIN 1045 (20°C and 65 % relative humidity)

** Storage at the tunnel site (8°C and 88 % relative humidity).

5 Results

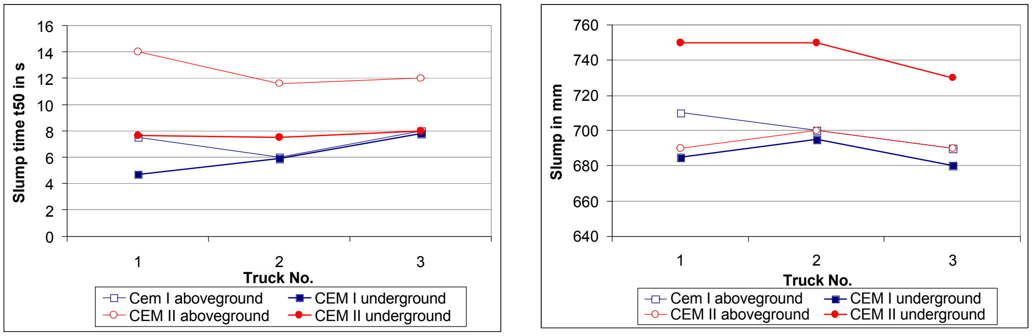
5.1 Consistency

The consistency of the SCC mixture is important in order to have a smooth casting process and after hardening to have a concrete of high quality. Following the consistency changes due to the casting process of the two tunnel segments (measurements aboveground and underground) are recorded (3a and 3b).

It can be seen in Figure 3a, that the concrete mixture cast with cement CEM I 42,5 R did flow faster than the concrete mixture cast with cement CEM II/B-M (S-LL) 32,5 R, whereby the CEM I-mixture almost achieved the requirements for the t50 flow time of 3-5 seconds. Even if the concrete mixtures met the requirements in laboratory tests or even ones in the ready mixed concrete plant tests at a 1.5 m³ batch; in the ready mixed concrete plant the accuracy required – e.g. regarding added water or chemical admixtures - cannot be achieved due to the mixing techniques and procedures e.g. The fact is to attribute e.g. to the manual aggregate moisture determination, to the scale time which is too short for the flow of viscose admixtures, and to the remaining water in the trucks after cleaning. While the flow times of the CEM I-concrete tested aboveground and underground tended to be identical, the CEM II/B-M-concrete was clearly slower in aboveground measurements before pumping compared to the underground measurements at the testing site after pumping.

The slump spread (see Figure 3b) of the CEM I-mixture was recorded higher in the aboveground test compared to the underground test – whereby the CEM II/B-M-mixture did show an improved spread underground after pumping.

These results can be explained by the following: The materials employed (e.g. cement and fly ash) behave differently in this casting process. Due to pumping a kind of further mixing power is introduced into the concrete – which might be especially efficient for mixes with lower w/c-ratios or higher cement contents. Also, the lower content of stabilizer compared to the CEM I concrete was probably not suitable enough for stabilizing throughout the whole casting process. The influence of the pumping forces and the resulting additional mixing effect on the action of the chemical admixtures as well as on the time between aboveground and underground tests (about 15 min. more reaction time) was approximately the same for both concretes.



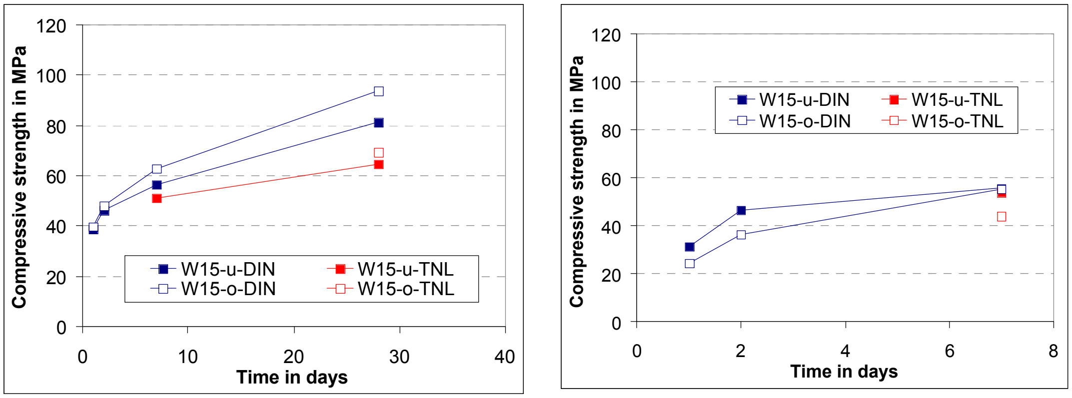
a) Slump time b) Slump spread

Figure 3: Results of consistency tests by using the slump cone.

5.2 Strength

Figure 4a and 4b show the results of the compressive strength tests carried out on samples cast with concrete from aboveground (meaning the empty symbols) and cast with concrete from underground (meaning the filled symbols). Also, different storage conditions where applied: blue curves for storage according to DIN-standard and red curves for storage at the tunnel site. While the CEM I concrete samples show higher compressive strength values when cast aboveground, CEM II/B-M concrete samples show higher values when cast with underground concrete.

Samples of both concrete mixtures show higher strength values when stored under standard conditions (DIN). The higher temperature (20°C) in the laboratory has more effect than the higher relative humidity in the tunnel – at least at early testing times.



a) CEM I 42,5 R concrete samples b) CEM II/B-M concrete samples

Figure 4: Results of compressive strength tests on cubes of 15 cm³.

5.3 Shrinkage

The development of the early shrinkage determined in the laboratory by means of Schleibinger shrinkage channels [5] is shown in Figure 5. The shrinkage started about 0.5 – 3.5 h after filling the channels, which was approximately 2 h after concrete production in the ready mixed concrete plant. The shrinkage of the concrete mixture with CEM I started 1-2 hours earlier compared to the one of the CEM II/B-M-concrete. It becomes apparent, too, that the shrinkage process of concrete samples from aboveground started at the same time or even later than the one for the underground samples, nevertheless the total early shrinkage of the aboveground concrete is higher.

The CEM I-mixture shows more shrinkage (approximately 50 to 150 µm/mm) compared to the CEM II/B-M-mixture which might be attributed to the slightly higher total clinker content. The total shrinkage values measured with the small channels (length: 25 cm) are between -300 µm/m and -750 µm/m.

5.4 Concrete temperature development

Looking at the temperature curves taken from the concrete tested in the laboratory (see Figure 6) it becomes apparent that the temperature of the concrete in the large channel reached higher values of 22.7°C compared to 21.4°C in the small channel. The concrete temperature levels to room temperature after approximately 24 hours.

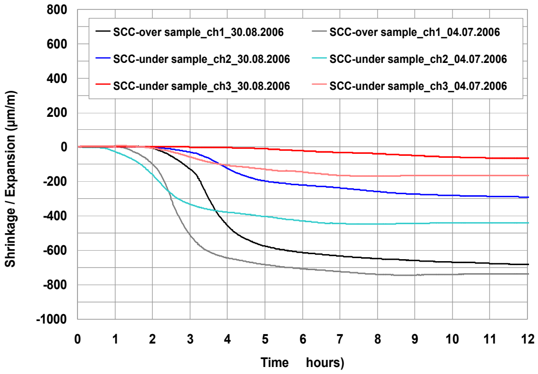


Figure 5: Results of early shrinkage tests in the laboratory; CEM I: 07/04/2006 (pale curves); CEM II/B-M: 08/30/2006.

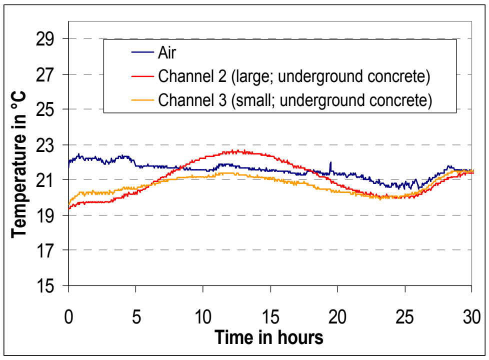


Figure 6: Temperature development during the early phase of hydration in the laboratory.

6 Discussion of results

6.1 Consistency and strength

A correlation between the consistency tests and the compressive strength tests became apparent. Concrete with the improved consistency values does show enhanced compressive strength results after DIN-storage, as well as tunnel storage (TNL). That means for the CEM I-concrete higher compressive strength values were recorded if the samples were cast with concrete from aboveground compared to the concrete cast underground. Furthermore, the CEM II/B-M-concrete samples developed improved strength if cast with concrete from underground after pumping compared to the aboveground samples.

6.2 Shrinkage and temperature

During the shrinkage process between 1 and 4 hours, as can be seen in the shrinkage channel curves (see Figure 5), the measured temperature rise (see Figure 6) is marginal, since the evaporation heat is taken from the concrete and overlaying the hydration heat. After the shrinkage levels at a pretty stable value after approximately 4 hours the temperature rises clearly and reaches the maximum.

6.3 Laboratory and tunnel tests

The concrete temperature measured in the tunnel was highest during the first half day with more than 45°C. The higher temperature compared to the laboratory test is attributed to the concrete mass, the element thickness and the resulting slow heat flow.

In tests of the tunnel concrete length changes of approximately -500 µm/m were measured which range in the area of the laboratory measurements. Nevertheless these shrinkage values were measured in the tunnel after approximately 28 days. After this time the temperature of the tunnel concrete reaches the air temperature of the mine and following the temperature induced expansion of the concrete did not overlay the shrinkage anymore.

7 Conclusions

The aim of this project was the development of a SCC for casting tunnels underground. During the casting and hardening process tests on fresh and hardened concrete based on different mixtures were carried out using concrete from aboveground before pumping and underground after pumping forces e.g. where inserted. The hardened concrete samples were stored under standard conditions in the laboratory as well as at the tunnel site in the mine before testing at different ages.

The following results can be summarized:

The concrete transportation and casting process has influence on the stability of the concrete consistency. The intensity of the influence depends on material and mixture parameters. While the CEM II-concrete-slump spread increased due to the transportation and pumping process the CEM I-concrete quality was almost stable even after pumping.

A correlation between consistency, determined as slump spread, and strength was observed for both concrete mixtures whereas the CEM I-concrete from aboveground and the CEM II-concrete from underground did demonstrated higher slump spread and thus higher strength.

Tunnel concrete shrinkage values determined in the laboratory and on the tunnel in the mine did range in the same magnitude.

The shrinkage of the concrete in the tunnel became apparent earliest after approximately 28 days – that means one month later compared to the laboratory test. The temperature strain due to the higher temperature ($\Delta T \cong 20°C$) of that mass concrete element compared to the laboratory sample did overlay the shrinkage measurement.

The production and casting process of SCC for mass elements and also for casting underground, e.g. tunnels, implicates general problems. The SCC-mixture quality is sensitive to marginal changes in mixing composition. The mixing technique in normal ready mixed concrete plants does not allow throughout the whole process the accuracy required . Furthermore, pumping and other forces can influence the fresh and hardened concrete quality and are therefore to be taken into account.

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