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Title

Structural fire protection with PP-fibre modified concrete in German road tunnels

1. INTRODUCTION

Experiences from the devastating fires in the transalpine tunnels (Mont Blanc Tunnel, Tauern Tunnel) and the Euro tunnel at the turn of the Millennium show that due to the rapidly increasing temperatures, the high temperature level and the long duration of a tunnel fire, there are significant damages to the structure.

Synthetic fibres are a well known concrete addition in building construction for quite some time. Here, they are particularly useful for the limitation of shrinking fractures of the concrete, the improvement of the early strength, but also for the improvement of the structural fire protection.

To ensure the structural fire protection only by using concrete and thus to avoid fire protection systems like fire-protection panels, several research projects and practical applications were carried out to evaluate the impact of adding PP-fibres to the concrete mixtures. The result was that the additional application of PP-fibres has a positive effect on the structural fire protection of the concrete.

For more than a decade PP-fibre modified concrete is being applied in Austrian road and train tunnels to ensure the structural fire protection. In Austria guidelines for the application of this building material already exist since then.

The aim of the research done by the Federal Highway Research Institute (BASt) was to fill the gap in the German regulations for the application of PP-fibre modified concrete. For this purpose several research projects were carried out (Kaundinya and Tauscher, 2008; Schmid et al., 2008; Blossfeld, 2009; Dehn et al., 2010). The projects showed the basis for the application of PP-fibre modified concrete under the considerations of the requirements of the regulations for Federal German road tunnels.

2. THEORETICAL BASICS

2.1 Fire curves

In order to explain the concrete spalling in case of fire and the correlations and function of the PP-fibres to reduce this spalling, it has to be outlined how the structural fire protection design is done for Federal German road tunnels. The design is based on a temperature-time curve, which illustrates the development of the fire. Throughout Europe, the so called “fire curves” are not consistent. A representation of the different fire curves is shown in figure 1.

The fire curve contained in the “Additional technical contract conditions and guidelines for engineering structures” (ZTV-ING) corresponds to:

- (1) Temperature increase to 1200°C within 5 minutes
- (2) A blazing fire phase at 1200°C of 25 minutes and
- (3) A cooling phase within 110 minutes

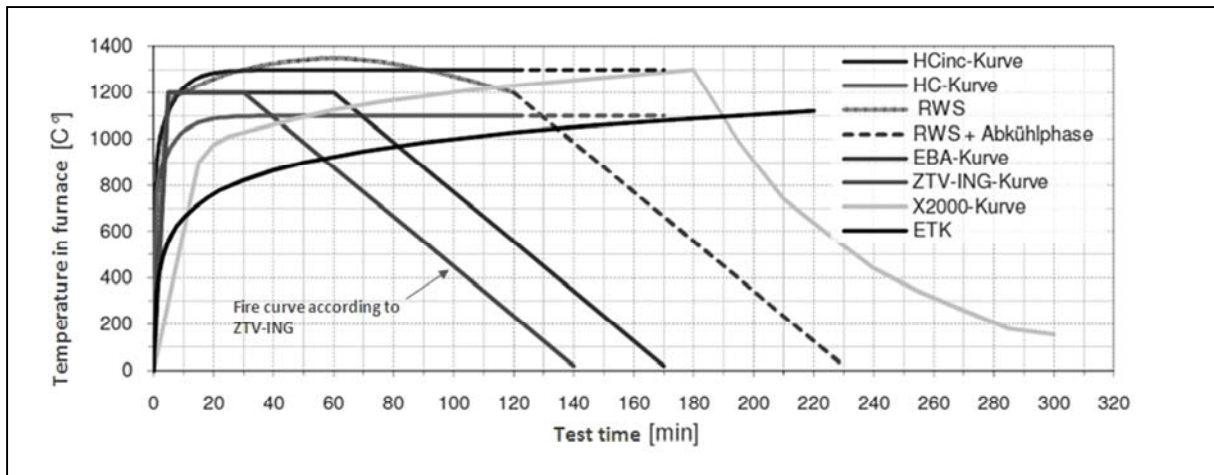


Figure 1: Typical fire scenarios for the assessment of tunnel parts (Dehn, 2009)

Particularly relevant for the extent of the explosive concrete spalling in case of a tunnel fire are the first few minutes. Here, a rapid increase of temperature takes place. The temperature penetration is in contrast to that determined by the duration of the fire (Dehn et al., 2006).

2.2 Explosive concrete spalling

The cause of explosive concrete spalling due to fire impact can be found both in thermo-mechanical and thermo-hydrological processes. It's possible to distinguish three different damage mechanisms which overlay during the fire impact (Schneider and Kordina, 2003; Paliga, 2004):

- (1) Due to the different thermal expansion coefficients of the concrete components, tensile stresses perpendicular to the component surface occur at the contact zone between aggregate and mortar matrix. An exceeding of the maximum stress leads to concrete spalling at larger aggregate particles.
- (2) Due to the fire impact water vapour pressure builds up perpendicular to the surface. This leads to concrete spalling.
- (3) As a result of the temperature drop in the tunnel construction in the first minutes of a fire, tensile stress parallel to the components surface occurs. This leads to concrete spalling at a depth of 1.5 to 2 cm.

The tendency to explosive concrete spalling is supported by (Kusterle and Lindlbauer, 2004; Paliga, 2004):

- A high moisture content of the concrete,
- A low permeability of the concrete,
- A prevention of the cross section to expand,
- A prevention of balancing the water vapour pressure by a rapid temperature increase and
- High compressive stresses parallel to the surface from an external load.

2.3 Mode of action of PP-fibres in concrete

To reduce the explosive concrete spalling due to a fire impact PP-fibres are added to the concrete mixture. The PP-fibres behave chemically neutral in the concrete. They are neither affected by acid nor by solvent and they are alkali-resistant. The PP-fibres melt at about 170°C and are thermally decomposed at about 330°C.

With the normally used doses PP-fibres have no influence on the properties of the hardened concrete. The workability of the fresh concrete is however significantly influenced by the addition of PP-fibres. The large number of individual fibres in a usual dosage and geometry of PP-fibres leads to a significantly higher water and plasticiser demand

The increased level of the fire protection of PP-fibre modified concrete is substantially created by the increasing of the gas permeability of the concrete. Even at temperatures below 100°C, the permeability increases due to the finely porous contact zone between fibre and concrete. Between 200°C and 300°C, the cavities of the molten PP-fibres determine the gas permeability of the concrete (Kalifa et al., 2001; Kusterle and Lindlbauer, 2004). It has been experimentally demonstrated by Kalifa et al. (2001) that at 170°C the fibres are melting in the concrete. The PP-fibres are absorbed from the surrounding cement paste at about 180°C. At a temperature of about 400°C finely dispersed micro cracks occur in the mortar matrix of PP-fibre modified concrete. They lead to a further increase of the gas permeability.

To get a consistently networked pore system of fibre cavities, contact zones surrounding the aggregate and cavities as a result of micro-cracks a sufficient length and dosage of the PP-fibres is needed (Kalifa et al., 2001; Kusterle and Lindlbauer, 2004).

3. VERIFICATION AND VALIDATION OF THE INFLUENCE OF PP-FIBRES ON THE STRUCTURAL FIRE PROTECTION

In order to verify the influence of PP-fibres in the concrete on the fire and spalling behaviour according to the regulations for Federal German road tunnels a research project at the Leipzig Institute for Materials Research and Testing (MFPA Leipzig) was carried out (Dehn et al.; 2010). It was investigated which PP-fibre content and geometry has to be applied in the concrete to prevent major explosive concrete spalling. Also, it was important to find out whether and if so what impact the galvanized mesh reinforcement has on the fire and spalling behaviour of a cut-and-cover tunnel.

To identify the impact and effectiveness of PP-fibre modified concrete, in general, fire tests are performed. In these tests specimens are flame-treated in a furnace to a specified time-temperature curve. The tests are evaluated with regard to the defined criteria.

As part of the project, fire tests were conducted by the researcher focusing on the specific requirements of the tunnel concrete pursuant to ZTV-ING which are significantly diverging from the Austrian regulations. To evaluate the fire protection properties of the PP-fibres concrete with and without fibres was investigated. Furthermore the specimen's load was

varied. The tests were performed on representative specimens for the cut-and-cover technique and the mining technique.

Table 1: Limits of the concrete composition for the relevant exposition class XF2 according to ZTV-ING

	Mining technique	Cut-and-cover technique
Maximum water-cement ratio	0.50	0.50
Minimum compressive strength class	C30/37	C30/37
Minimum cement content [kg/m ³]	320	320
Minimum cement content in Recognition of concrete additives [kg/m ³]	270	Recognition permitted

The evaluation criteria for fire tests used were the permissible average and maximum concrete spalling depth and the compliance with the maximum temperature of the bearing reinforcement of 300°C according to ZTV-ING.

For tunnels constructed with the cut-and-cover technique and the mining technique the fire tests demonstrated (see Table 2) that a dosage of 2 kg/m³ of PP-fibres with a diameter of 0.018 mm and a length of 6 mm ensures a significant improvement to the structural fire protection.

Table 2: Results of fire tests for cut-and-cover tunnels

Specimen		OB 1	OB 2
PP-fibre content	[kg/m ³]	--	2,0
Horizontal loading		yes	yes
Mass loss	[% by wt]	11,00	4,66
Maximum value of the concrete spalling depth	[mm]	-156	-66
Average value of concrete spalling depth	[mm]	-61	-29

Furthermore it could be demonstrated that with this geometry and dosage of PP-fibres the maximum temperature of the bearing reinforcement is under the limit of 300°C according to ZTV-ING.

For the cut-and-cover technique fire tests were conducted on scaled frame corners. These fire tests indicated that the galvanized mesh reinforcement in the ceiling cannot prevent major concrete spalling due to a fire for a long time.

Additionally a feasibility study was carried out to ascertain that a concrete with a consistency class F4 according to DIN 1045-2, as it is required for the mining technique to ensure pumpability and compressibility by exterior vibrator, can be accurately made. However, it was also investigated that these concretes are very sensitive to changes in the dosages of the constituent materials.

4. PILOT PROJECT CUT-AND-COVER TECHNIQUE - TUNNEL BAUTZEN

4.1 Boundary conditions

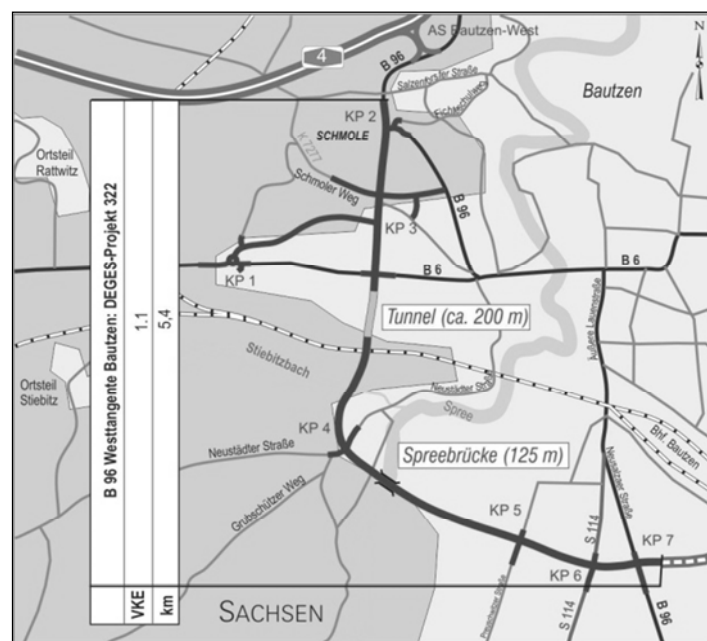


Figure 2: Area map Tunnel Bautzen

As part of the construction of the B 96 in Bautzen (Saxony) a tunnel construction in the area of the crossing with the B 6 (Figure 2) became necessary. The tunnel is 200 m long. On both portals it is followed by 100 m long reinforced concrete through structures. The structure build with the cut-and-cover technique is a rectangular frame with a clear width of 9.50 m. The thickness of the walls is 80 cm. The frame bars have a thickness of 60 cm. The corners of the frame are haunched in. The length of the individual blocks is 10 m. The cross-section is shown in Figure 3.

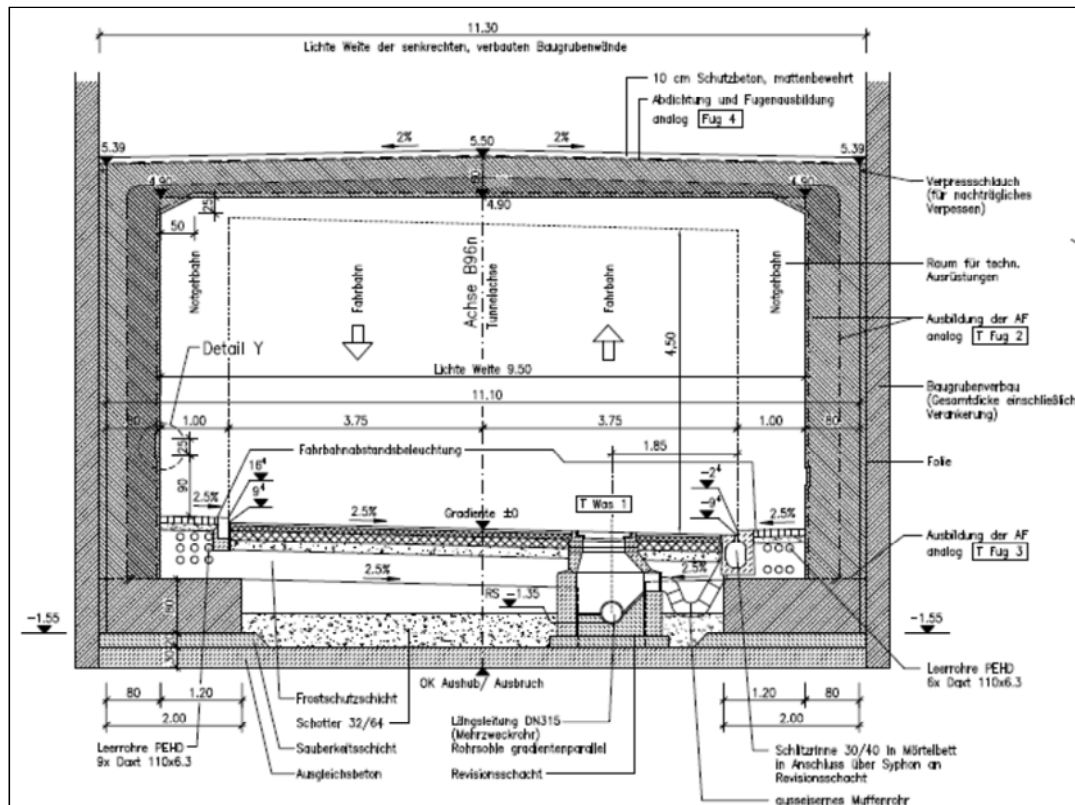


Figure 3: Cross section Tunnel Bautzen

The fundament of the tunnel construction was made in granodiorite. The excavation pit ranges up to 7 m deep into the rock. The excavation support was done exclusively with shotcrete. The following Table 3 shows the various contract sections necessary for the construction of the tunnel.

Table 3: Chronology of the construction of the tunnel Bautzen

tunnel excavation	11/2010 – 09/2011
tunnel shell	09/2011 – 03/2013
Operating Hardware	12/2012 – 10/2013
completion road construction	04/2013 – 10/2013

4.2 Production of PP-fibre modified concrete

4.2.1 Tender

In order to validate the results of the research projects, the concrete technology issues were considered in the tender documentation of the tunnel Bautzen. In addition, the construction was accompanied by an external consultant.

In compliance with the concrete technology specifications stated in the ZTV-ING (e.g. maximum water-cement ratio = 0.5) the order was to design a concrete that contains a dosage of 2 kg/m³ of PP-fibres with a diameter of 0.016 to 0.020 mm and a length of 6 mm.

To take account of a sufficient dosage it is specified in the tender documentation that the recovery rate at the wash-out tests according to the regulations of the Austrian Society for Construction Technology (ÖBV) comply with stricter limit values than those set from the ÖBV (ÖBV, 2013).

In order to raise the awareness of the ready-mixed concrete manufacturers in the area around the construction site for the specific requirements and examinations for the execution of a PP-fibre modified concrete an information event was held.

4.2.2 Production

According to the ZTV-ING the entry areas of tunnels have to be assigned to exposure class XF2 and XD2 (according to DIN 1045-2). Since the tunnel Bautzen is only 200 m long these assignments were set for the entire tunnel.

As already described, the rheological properties such as viscosity and fluidity change upon the addition of PP-fibres to the concrete. Furthermore, the risk of bleeding of the concrete increases.

The target value for the consistency according to DIN EN 12350-5 was 480 +/- 20 mm at the construction of tunnel Bautzen. It was necessary to reach the value in compliance with the specified maximum water-cement ratio of 0.5 by choosing a superplasticizer based on modified acrylates.

Table 4: Concrete composition Tunnel Bautzen

Compressive strength class	C35/45
CEM III/A 42,5 N	350 kg/m ³
Limestone powder	50 kg/m ³
Water-cement ratio	0.49
Plasticizer	based on modified acrylates
Aggregate	Distribution AB 16, Round grain, quartzitic
PP-fibres (l = 6 mm; d = 0.018 mm)	2.0 kg/m ³

To test the practicality of the designed PP-fibre modified concrete sample concretings were carried out. Two sample walls were concreted that were provided with the actual

reinforcement and bodies corresponding to the future operational technology (Figure 4). The dimensions of the walls were 3.5 x 3.0 x 0.8 m³.

In order to do the concreting in the most realistic manner the concrete was made and delivered by the ready-mixed concrete manufacturer which delivered the tunnel construction site in further course. Furthermore, the concrete was pumped in the formwork and compacted with internal vibrators. The work was carried out by the future site personnel. The experiences with the execution of the PP-fibre modified concrete collected during the sample concreting were stipulated in the quality assurance plan.

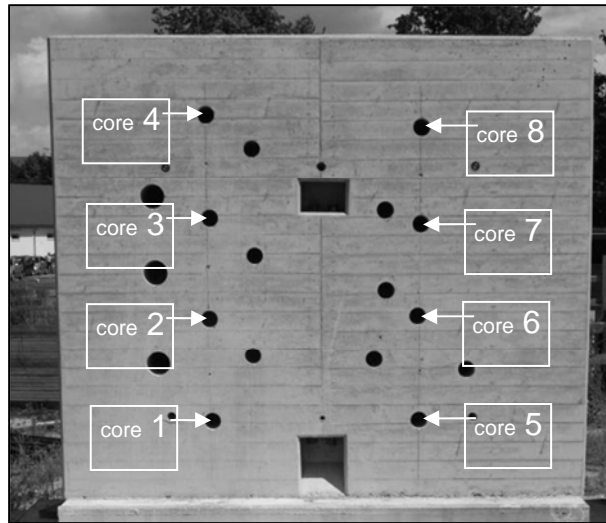


Figure 4: Sample wall at the Tunnel Bautzen with core sampling points

The quality protection measures carried out during the tunnel construction and the associated concrete parameters are presented in Table 5.

Table 5: Scope of testing and Parameters

Parameter	Scope of testing on the construction site	Target value	Tolerance limits
Consistency according to DIN EN 12350-5	Each delivery vehicle	480 mm	Single value: +/-20 mm
Fibre content according to Austrian regulations (ÖBV, 2013)	The first ten days of concreting: once per day of concreting From the 10th day of concreting: every third day of concreting	2.04 kg/m ³	Smallest single value: 1.84 kg/m ³ Smallest mean value: 1.94 kg/m ³
Concrete temperature	Each delivery vehicle	≥ 8°C ≤ 25°C	Discard in case of non-compliance

Fresh concrete density according to DIN EN 12350-6	At test sample production		
28-day compressive strength according to DIN EN 12390-3	3 specimens per day of concreting	C35/45	According to DIN 1045-3
Hardened concrete density according to DIN EN 12390-7	At compressive strength test		

4.3 Conclusions (Regulations)

The tests carried out according to the quality assurance plan were conducted satisfactory throughout the complete construction process. As a consequence an information sheet for the ZTV-ING was created and stated. By this information sheet PP-fibre modified concrete has to be used for the construction of every Federal road tunnel in Germany whether done with the cut-and-cover technique or with the mining technique to improve the structural fire protection.

The dosage and the geometry of the PP-fibres set in the information sheet corresponds to the values of the pilot project Tunnel Bautzen and the values as a result of the research project.

However, a possibility of deviation thereof was created. By fire tests, an equivalent structural fire protection effect of the PP-fibre modified concrete can be demonstrated for a different dosage or geometry of the PP-fibres.

In the information sheet to the ZTV-ING the necessity of a galvanized mesh reinforcement for the ceiling of a tunnel constructed with the cut-and-cover technique is abolished.

5. PILOT PROJECT MINING TECHNIQUE – BÜHLTUNNEL SIEGEN

5.1 Boundary conditions

As part of the construction of the B54/62n in Siegen the Bühltunnel was excavated. The Bühltunnel is a single-tube bi-directional tunnel with a standard road cross section of RQ 10,5t and a length of 525 m. 417 m were done using the mining technique, 57 m made with the top-down technique and 51 m done with the cut-and-cover technique. Due to the requirements of the RABT an emergency exit is required, which is arranged in the middle of the tunnel. The emergency exit leads through a tunnel of about 150 m to the terrain surface.

The tunnel was excavated with the New Austrian Tunneling Method starting with a top heading and a subsequent bench excavation. The tunnel has an umbrella waterproofing. The drive commenced in June 2012 and the top heading was broken through in December 2012.

The installation of the operating hardware and the completion of the road construction will be finished in 2016.

5.2 Production of PP-fibre modified concrete

In order to validate the results of the research project for tunnels constructed with the mining technique the well-known dosage and geometry of the PP-fibres (dosage 2kg/m³, diameter 0.016 – 0.020 mm, length 6 mm) was added to the tender documents. However, through the information sheet to the ZTV-ING the already mentioned possibility of deviation thereof was created.

The contractor made use of this possibility and opted for a PP-fibre with a diameter of 0.0154 mm and a length of 6 mm. In addition a smaller dosage of the PP-fibres should be used. Thus fire tests to ensure the structural fire protection of the PP-fibre modified concrete were necessary.

Because of experiences of the external consultant the fire tests were carried out on middle-scaled specimens sized 850 x 700 x 300 mm³. For these fire tests 1.2 kg/m³ of the PP-fibres with a diameter of 0.0154 mm were added to the concrete mixture. Because of the non-compliance with the 300°C-criteria for the maximum temperature of the bearing reinforcement this PP-fibre modified concrete was not able to demonstrate an equivalent fire and spalling behaviour. Hence, the decision was taken to increase the amount of PP-fibres in the concrete mixture to 1.4 kg/m³ and to adjust the content of superplasticizer in the concrete mixture due to the higher water demand. The used concrete mixture can be seen in table 6.

Table 6: Concrete mixture Bühltunnel Siegen

Compressive strength class	C30/37
CEM II/A.LL 42,5 N	350 kg/m ³
Fly ash	130 kg/m ³
Water-cement ratio	0.49
Plasticizer	Based on Polycarboxylateter (PCE)
Aggregate	Distribution AB 16
PP-fibres (l = 6 mm; d = 0.0154 mm)	1.4 kg/m ³

To ensure the operability of the PP-fibre modified concrete before the construction of the tunnel a sample wall was concreted. The size of the wall was 4.00 x 2.20 x 1.10 m³ (Figure 5). The wall was pressingly concreted through filling nozzles in the formwork like it was done subsequent in the formwork carriage at the tunnel construction.

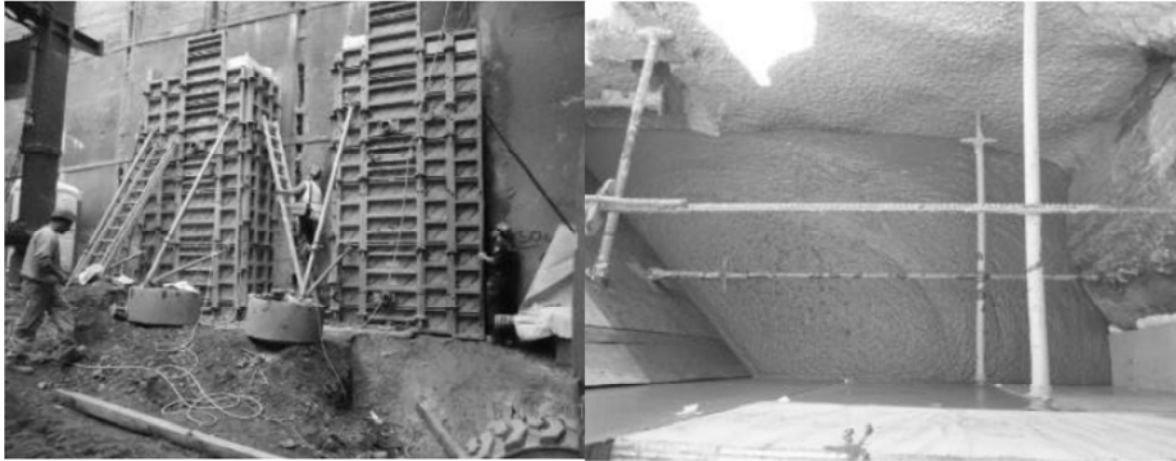


Figure 5: Formwork of the sample wall at Bühl tunnel

Due to the concreting of the sample walls important findings were gained regarding the influence of the pumping on the consistency of the concrete and the possibility to systematically obtain the desired fresh concrete consistency.

By taking cores at the sample wall and identify the recovery rate at the wash-out tests according to the regulations of the ÖBV a uniformly distribution of the PP-fibres was determined.

5.3 Conclusions

The accompaniment of the development and application of PP-fibre modified concrete at the Bühl tunnel has shown that even for very soft consistencies a sufficient robustness can be achieved. Furthermore, the requirements according to the ZTV-ING can be fulfilled. However, the PP-fibre modified concrete requires a more accurate quality assurance than a normal concrete without PP-fibres.

6. TRANSFER INTO THE REGULATIONS

To safeguard the requirements for the application of a PP-fibre modified concrete during the construction of a Federal German road tunnel the annex B for the ZTV-ING Part 5 Chapter 1 was created and announced.

The document defines requirements to PP-fibres. In particular, for the use of a PP-fibre a building approval from the DIBt is needed. Furthermore the results of the research and pilot projects are considered in the Annex B by including the geometry (diameter 0.016 – 0.020 mm, length 6 mm) and the dosage (2 kg/m³) of PP-fibres. The possibility of deviation of the geometry or dosage by fire tests on loaded large-scale specimens remains. The minimum dimensions of the test specimens and the structure of the furnace is also defined in Annex B. The fire tests have to be evaluated by an external consultant.

The proof of conformity of the actual content of PP-fibres in the concrete has to be stated in fixed intervals. For the ready-mixed concrete manufacturer it's every 200 m³ of concreting or twice per week and for the production site it is every 300 m³ or every third day of concreting.

As in the pilot projects a sample wall has to be executed before the concreting of the tunnel starts. The minimum dimensions of the sample wall are 4.50 x 3.00 x 0.35 m³. The concreting of the sample walls has to be done with the same technology subsequent used at the concreting of the tunnel.

7. SUMMARY AND OUTLOOK

Through the conducted research projects, the accompanied pilot projects for the cut-and-cover and the mining technique and the transfer of the knowledge to contractual binding requirements the use of PP-fibre modified concrete for the structural fire protection has become the standard for new constructions of Federal German road tunnels.

Other non-answered questions exist regarding the durability of PP-fibre modified concrete as well as the technical possibilities of restorations of the PP-fibre modified concrete shell. To address these issues a new research project entitled “Quality assurance and restoration concepts for the use of PP-fibre modified concrete to improve the fire and spalling behaviour of road tunnel inner shells” is carried out by BAST.

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