Protection of road tunnel linings in cases of fire

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Abstract
Recent fire disasters in European road tunnels have shown that fires in a tunnel represent high risks. The users and the rescue services are endangered by heat, smoke and also explosive concrete spalling of the tunnel lining. The tunnel itself is often damaged considerably. The necessary long refurbishment works have negative effects on the tunnel service availability and also cause high costs for the tunnel owner. Thus high safety demands must be placed on complex infrastructural facilities such as road tunnels. Preventive measures designed to avoid hazards caused by fire are constantly becoming more and more important. In addition, structural fire protection is as well a point of increasing interest.

In the event of fire the temperature in a tunnel rises extremely rapidly within a short amount of time. Large scale fire tests have shown that maximum temperatures of 1200°C or even above could occur. The result is an increased risk of explosive concrete spalling of the tunnel lining. Depending on depth and quantity of these spallings, the structure could be damaged seriously and in the worst case the tunnel stability could be influenced negatively.

Different possible structural measures to protect the concrete tunnel lining in order to reduce or avoid damages in cases of fire are explained and discussed. A fire-proof concrete is one relatively new and promising measure to avoid explosive concrete spalling of the tunnel lining during a fire. The fire resistance of concrete can be improved by adding polypropylene fibres as well as through the application of selected concrete mixtures and aggregates. Within the scope of a research project of the Federal Highway Research Institute of Germany (BASt), fire protecting systems and especially fire-proof concrete, as well as their fire behaviour and application possibilities in road tunnels are examined.

Keywords
Tunnel fire, tunnel safety, tunnel construction, concrete spalling, structural fire protection, fire-proof concrete

1 Introduction
Beside bridges tunnels are the most expensive investment parts of highways, namely not only concerning initial investment costs for the construction of the tunnels but also with regard to later costs of operation, maintenance and preservation. Due to the fact that the number of constructions of road tunnels has considerably increased in recent years (Fig. 1) the Federal Ministry of Transport, Building and Urban Affairs (BMVBS) and the Federal Highway Research Institute of Germany (BASt) have listed the essential demands for structural design, suitability of use, durability, economy and demands for later operation and maintenance of these tunnels in a set of technical regulations. Structural fire protection plays an important role because of the substantial damages which can arise from fire in a tunnel.

In the last two decades the number of road tunnels in Germany has increased disproportionately compared with the increase of the total road net. Thus, the amount of highway tunnels has more than doubled from 90 in 1992 to 213 in 2005. In the same period the total length of tubes increased from 50 to almost 212 km, that corresponds to an average tube length of
665 m statistically (Fig. 1). At the end of 2005, 25 tunnels were under construction, 45 tunnels were in the process of planning or in the preparation phase just before building and 60 tunnels were in the pre-planning phase.

**Fig. 1: Tunnels of the federal highways in Germany**

2 Fire accidents and their effects on the tunnel structure

Fires in road tunnels are characterised by the affected persons being endangered and in many cases by the considerable amount of damage caused to facilities. A number of serious accidents that took place nationally and internationally in the recent years (Tab. 1) lead to an increasing public interest in tunnel safety and to efforts by the highway authorities in order to make tunnels safer.

<table>
<thead>
<tr>
<th>Year of Fire accident</th>
<th>Tunnel</th>
<th>Number of killed people</th>
<th>Damage to lining depth [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>Mont Blanc Tunnel</td>
<td>41</td>
<td>&gt; 40</td>
</tr>
<tr>
<td>1999</td>
<td>Tauerntunnel</td>
<td>12</td>
<td>10-15</td>
</tr>
<tr>
<td>2001</td>
<td>St. Gothard Road Tunnel</td>
<td>10</td>
<td>ca. 35</td>
</tr>
<tr>
<td>2005</td>
<td>Frejus</td>
<td>2</td>
<td>?</td>
</tr>
<tr>
<td>2006</td>
<td>Viamala Tunnel</td>
<td>9</td>
<td>?</td>
</tr>
</tbody>
</table>

Tab. 1: Chronology of recent fire events [12]

Major fires can result in tunnel users coming to harm and vehicles being seriously damaged quite apart from effects on the tunnels themselves (Fig. 2). The damage is caused particularly by the spontaneous development of great amounts of heat and aggressive fire gases. Following the fire, the damage caused to the tunnel itself can badly affect the service availability because the tunnel is closed to traffic due to the necessary refurbishment works. Depending on the duration of the fire and the chronological temperature development, the stability of the tunnel can be negatively influenced. Redevelopment and the associated discontinuation of services can last for weeks or even months.

**Fig. 2: Fire accident Mont Blanc Tunnel 1999**

The main damage patterns to a tunnel obtained from investigations on fire accidents [2] can be summarised as follows:

- Some 5 – 10 min. must be estimated for the “flash over” – the time required for a smouldering fire to become a “full fire” resulting in a steep rise in temperature in the affected area in the case of heavy vehicles.
- The duration of the fire varies considerably – between 30 minutes and a number of hours.
- The in some cases considerable damage to the tunnel structure resulting from major fires is caused by the high fire load of heavy vehicles.
- Damage to the concrete tunnel lining is mainly caused by spallings as well as the condensation of smoke gas on the tunnel wall, the ceiling and the operational installations.
During a fire in the Tauern Tunnel on May 29, 1999, a total of 34 vehicles were destroyed (Fig. 3). 12 persons lost their lives and considerable damage was caused to vehicles and to the tunnel structure. Concrete spallings with a depth of 10 to 15 cm were measured at the tunnel lining.

3 Temperatures during a tunnel fire

In order to determine the temperature development and the damage pattern during a tunnel fire more detailed a lot of fire tests were executed during the last 15 years. The most comprehensive tests serial with realistic fire loads was undertaken within the scope of the so-called “EUREKA program” (EU 499 Firetun) between 1990 and 1992. In a 2.3 km long, abandoned mine tunnel (Repparfjord-Tunnel) in the north of Norway with a 35 m² cross-section a total of 20 fire tests with road and rail vehicles were executed. The test results were later completed by additional fire tests of single structure elements in laboratories also in Germany.

The most essential measurement results for hot gas temperatures that occurred in the mine tunnel during a fire test with a heavy truck is provided in figures 5 and 6. The heavy truck was loaded with 2 t of office furniture and burned out within 75 minutes (Fig. 4). The fire load amounted to some 100 MW. The fast rising of the temperature after the flash over after about 5 to 10 minutes up to temperatures of 800 to 1000 °C is significant (Fig. 6). The maximum temperatures for road vehicles of nearly 1000 °C were measured at the top of the tunnel as well as at the sides (Fig. 5).

The test results of the EUREKA-program were the basis for the definition of the currently valid dimensioning values for the different temperature time curves in the case of tunnel fires (Fig. 7). These temperature time-curves are used for fire tests of all tunnel parts for which the fire resistance have to be examined (e.g. fixing...
elements for tunnel installations) as well as for static calculations of the tunnel structure itself. The temperature time curve for road tunnels in Germany, laid down in the “Additional technical contract terms and guidelines for civil engineering works (ZTV-ING)” [1], relates to a fire duration of 30 minutes at 1200 °C, followed by a 110 minute long cooling down phase (Fig. 7, curve [1]). Although the progress of this curve is shorter when compared directly with the ETK/ISO curve (Fig. 7, curve [5]), it is substantially more aggressive when rising higher in terms of the temperature reached and more critical due to the very fast rising of the temperature up to 1200 °C within 5 minutes. The longer fire duration of the EBA-curve (Fig. 7, curve [6]) for railway tunnels can be explained by the longer required time for rescue services to reach the fire compared with road tunnels.

![Fig 7: Temperature-time curves](image)

Currently new major fire investigations were performed within the scope of a new research project called UPTUN (UPgrading methods for fire safety in existing TUNnels) [8]. This important research project started in 2003 and is, similar to the former EUREKA-project, funded by the European Union, but also supported by industry partners. First published results started a new discussion in Europe about temperature-time curves for the dimensioning of tunnel linings against fire loads. During a first large scale fire test with a single simulated truck loaded with roughly 10 t wooden and plastic pallets, carried out again in an abandoned rock tunnel in Norway (Runehamar tunnel), temperatures up to 1350 °C within 35 minutes in keeping with the RWS-curve (Fig. 7) and a total fire load of 203 MW were measured. Due to the smaller cross-section of the Runehamar tunnel compared with a normal road tunnel cross-section, these test results could not be transferred directly to German road tunnels, but have to be considered for the possible adaptation of the valid guidelines for tunnels in the future.

As a consequence of all major fire test and especially because of the critical features of tunnel fires, special fire protection measures have to be considered as essentially important.

4 Damage mechanisms in the case of fire

The effect of temperature on the concrete tunnel lining can lead to damage in many different ways:

- The spalling process is largely influenced by the speed at which the temperature rises, the moisture of the concrete and through the pore structure (compactness). The formation of water vapour leads to stresses in the concrete matrix as from 100 °C, which can in some cases lead to large-scale spalling. Depending on the residual moisture and the concrete matrix set-up it cannot be precluded that the extent of damage eats it way further into the concrete cross-section as the duration of the fire progresses.

- At higher temperatures (400 to 600 °C), chemical transformations occur in the case of various minerals in the concrete aggregates. Water and/or gas separations can be the result. This leads to an increase in volume (e.g. quartz transformation, quartz leap). The spalling mechanisms that were previously described can be strongly supported depending on the nature and size of the aggregate grain.

- Temperature-related internal and constraining stresses can also lead to concrete spillings.

- Reinforcements, which are located merely a few centimetres beneath the
surface, are exposed by the above described spallings and completely lose their bearing capacity owing to the extremely high temperatures in the first zone. Thus temperatures in excess of 300 °C should be avoided in order not to affect the steel’s bearing capacity considerably.

If concrete is subjected to such mechanisms without any protection, then the damage eats far into the tunnel lining. This peeling effect is caused by the fact that new concrete surfaces are being constantly exposed. The damage mechanisms that have been described can last over a lengthy period of time. For the special case of a tunnel fire the spalling effect starts with the steep temperature rise after about 5 minutes from the beginning of the fire event (see also Fig. 7). Spalling usually takes place within the first 20 minutes after the fire has started. But also as the permanent tunnel lining have cooled down, further concrete parts can loosen and subsequently fall down. Thus concrete spallings could endanger emergency services during the rescue phase as well as people carrying out reconstruction works.

5 Structural fire protection measures

In order to assure structural fire protection for road tunnel linings in Germany a concrete cover of at least 6 cm is required in the currently valid technical guidelines (ZTV-ING) [1]. This concrete cover, acting like a “thermal protective layer”, should assure that the bearing reinforcement will not heat up in excess of 300 °C. Below this limit value, it can be assumed that no loss in strength worth mentioning or reduction of reinforcement’s elasticity module occurred during the fire. In other words, the bearing capacity was retained during the fire so that no lasting deformations affecting the design are present following it.

Frame-like tunnel constructions (usually tunnel constructed with the “cut and cover” method) are subjected to considerable temperature stresses especially in the corner zone between the wall and the ceiling. This can lead to crack forming, which penetrate the cross-section of the bearing elements from the outside. Due to this sensitivity of frame-like tunnel constructions in cases of fire an additional fire-proof reinforcement within the 6 cm concrete cover of the ceiling is required in the ZTV-ING [1]. The fire-proof reinforcement consists of a reinforcing steel mesh made of stainless steel and should help to keep the concrete cover for a longer time during a tunnel fire.

For single shell tunnels with a lining of reinforced concrete block segments additional fire protection measures are required due to the many joints of this lining system and the special characteristic of the concrete applied. The high strength concrete with an extremely tight texture used for the segments is particularly jeopardised for spallings.

There are several possibilities of additional structural fire protection measures in tunnels:

1. Linings installed on the outer side (e.g. fire-proof panels / Fig. 8)
2. Sprayed on fire protection (e.g. fire-proof render)

Fire-proof linings (1.) and sprayed on fire protection (2.) work as an insulation layer and have the following advantages:

- good fire resistance and protection of the concrete tunnel lining against heat
- easy replaceable after a tunnel fire
- upgrade for existing tunnels possible

But also the following disadvantages have to be mentioned:

- Additional space inside the tunnel (“clearance profile”) is needed, which leads to higher construction costs.
- A lot of attachment points are required for the fixation of the panels or the
steel mesh reinforcement needed for spray on systems. This makes the system expensive and the installation time-consuming.

- Expensive special solutions are required for attachment elements for e.g. signs and ventilation’s penetrating the fire-proof lining.

- Visual inspections and tests on the tunnel inner lining are no longer possible. Redevelopment and resealing operations always require the removal and renewal of the plates or spray on systems.

- No protection against fire during the construction period of the tunnel.

Fig. 8: Installation of fire-proof panels (photo: Promat)

Fire-proof concrete with PP-fibres (3.) and its advantages compared with the later installed fire-proof systems (1. and 2.) is described in the following chapter.

6 Fire-proof concrete

In recent years a lot of research work was done in order to develop a fire-proof concrete for tunnel linings. The fire-proof concrete should minimise explosive concrete spallings during a fire and protect the structure from losses of its bearing capacity. In order to improve the fire resistance of concrete polypropylene (PP) plastic fibres with approximately 2 until 3 kg/m³ of concrete are added. During a fire the PP-fibres melt through the effect of heat at a temperature of about 100 °C and provide a pore system in the concrete which provides space for the ensuring vapour. In this way, it is intended to reduce vapour stresses in the interior of the concrete and as a result, possible concrete spallings.

Beside adding of PP-fibres to the concrete mixture the mineralogical character of the aggregates and the grain-size distribution curve have a great influence in order to create a fire-proof concrete.

Recent fire tests on rail tunnel lining elements with realistic dimensions and loads have shown that the spalling behaviour of the concrete could be improved significantly by the use of fire-proof concrete mixtures containing PP-fibres. Fig. 9 and 10 show results of such fire tests on concrete samples without (Fig. 9) and with 2,0 kg PP-fibres per m³ concrete added (Fig. 10), through which the considerably more favourable fire behaviour of concrete with PP-fibres is obvious.

Fig. 9: Segment with 0 kg/m³ PP-fibres (photo: MFPA Leipzig/D)

Fig. 10: Segment with 2,0 kg/m³ PP-fibres (photo: MFPA Leipzig/D)

The depth of the concrete spallings was approximately 34 cm without PP-fibres
and only about 1 - 2 cm with 2,0 kg/m³ PP-fibres.

The advantages of the fire-proof concrete, based on national and international experiences and test results, can be summarised as follows:

- concrete spalling is reduced to a minimum
- fire protection is already assured during the construction state
- inspection of the tunnel bearing structure is always possible without any additional fire-proof insulation
- no special maintenance works for fire-proof insulation are needed
- the clearance profile is not restricted by fireproof insulation
- normal, flat concrete surface which is easy to clean (compared to e.g. sprayed on systems)

7 Research work on fire-proof concrete

Within the scope of a current BASt research project, fire protecting systems and especially fire-proof concrete, as well as their fire behaviour and application possibilities in road tunnels are examined. The aim is to investigate if fire-proof concrete should be included in the technical demands for road tunnels laid down in the technical regulations of BMVBS / BASt [1]. Currently only the draft of the new technical regulations concerning shield driven tunnels with a segmental lining (ZTV-ING part 5 section 3 [1]) require additional fire-protection measures like fire-proof plates or fire-proof concrete. The currently valid regulations for drill & blast tunnels and cut & cover tunnel constructions (ZTV-ING part 5 section 1 and 2 [1]) demand a minimum concrete cover of 6 cm and for the case of frame-like tunnel constructions an additional fire-proof reinforcement in order to protect the tunnel lining from losses of its bearing capability (see chapter 5). When using fire-proof concrete it is maybe possible to replace the expensive and difficult to install fire-proof reinforcement for frame-like tunnel constructions and intermediate ceilings.

Large-scale fire tests with parts of the tunnel lining are planned to be executed end 2007. Currently preparation works for these tests are going on. This means in particular the definition of

- test conditions,
- geometry (thickness, bend),
- acting loads,
- measurement program,
- different concrete mixtures (kind of aggregates and the grain-size distribution) and
- addition of fibres (kind of and amount of PP-fibres)

for the tunnel lining parts to be tested.

Within a recently finished BASt-research project the fire-proof behaviour of self-compacting concrete (SCC) was investigated [6].

In a first step, fire tests at a total of 30 cube samples 300 x 300 x 300 mm with different concrete mixtures, partly with PP-fibres, were executed. The fire load was applied in order to follow the temperatures required in the ZTV-ING [1] temperature-time curve (Fig. 7, curve [1]). Test results showed that the amount and depths of spallings were minimised, if quartzite aggregates and a cement CEM III A 32,5 N instead of calcite aggregates and cement CEM II A-LL 32,5 R were used. The adding of PP-fibres has an additional positive impact in order to reduce concrete spallings to a minimum. Overall SCC-samples had a worse fire-behaviour compared with the also tested conventional normal strength concrete samples. The bad fire behaviour of the tight SCC concrete could be improved significantly by adding 2 – 3 kg/m³ PP-fibres.

In a second step fire tests with reinforced plates 600 x 500 x 300 mm were executed. The results corresponded very well with
the test results from step 1. In step 3 these plates were tested under load. Again the PP-fibre concrete showed the best test results with regard to concrete spallings.

In a last step the test results of the former 3 steps were verified by a test with a loaded arch (Fig. 11 and 12).

Finally the promising test results with PP-fibre modified concrete mixes lead to the decision to start a new research project dealing with plastic fibre concrete (see above).

![Fig. 11: Fire test with a loaded arch – experimental set-up [6]](image)

![Fig. 12: Underside of arch after fire test [6]](image)

8 Conclusions

The fire disasters over the past few years have shown that fires in tunnels represent high risks. The users and the rescue services are endangered by heat, smoke and concrete spallings of the tunnel lining. In addition the bearing structure is exposed to particular dangers on account of high temperatures and possible spallings. Constructional measures against concrete spalling are of great importance beside reducing the distances rescue services have to cover, the rapid disposal of smoke and dimensioning the structure to cope with the effects of fire.

Test results with fire-proof concrete were promising and prove that fire-proof concrete can help that concrete spalling is reduced to a minimum. Through concentrating additional measures such as adding plastic fibres, optimising the concrete composition and selecting the aggregates, the bearing tunnel structure can be protected against extreme effects caused by fire.

Within a current research project the application possibilities of fire-proof concrete for road tunnel linings are investigated. The promising results of former fire tests with plastic fibre concrete for the special case of SCC mixtures should be transferred to normal concrete mixtures for tunnel inner linings. Large scale fire tests for the investigation of tunnel lining parts with realistic dimensions and loads are planned to be executed at the end 2007.

Additional research work needs to be done in the future in order to investigate redevelopment measures for the fire-proof concrete after a tunnel fire. PP-fibres can only act once as a fire protection system and have thus to be replaced after a fire incident. A possible solution can be a removal of the damaged concrete layers and a replacement with PP-fibre sprayed concrete.

References


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