FIRE SPALLING BEHAVIOUR OF SELF-COMPACTING CONCRETE (SCC) FOR TUNNEL CONSTRUCTION - TAKING THE MALMÖ CITY TUNNEL AS AN EXAMPLE

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Abstract
Self-compacting concrete (SCC) has already been successfully employed on many occasions in tunnel construction. One problem that arises with this particular application is that of the basic fire spalling properties of SCC in the specific scenario of a tunnel fire. This paper takes into account, firstly, investigations into various self-compacting tunnel concretes conducted as part of a research project, and secondly, large-scale loading tests of components undertaken for the construction of the Citytunnel in Malmö (CTM).

1 FIRE SPALLING PROPERTIES OF SELF-COMPACTING CONCRETE (SCC) FOR TUNNEL CONSTRUCTION

The fact that numerous investigations have been conducted into the fire spalling properties of standard concrete over the past decades means that engineers are today able to design relevant parts so that they do not lose load bearing ability for the duration of a fire.

The main cause for the loss of load-bearing ability is usually quoted as being the explosion-like spalling of concrete as a result of heightened water vapour pressure. A major factor also contributing to concrete spalling is the cement content, but there are also numerous others, such as, for example the petrographic, i.e. the chemical and mineral, composition of the aggregate, the part dimensions, the position of the reinforcement and, especially, the prevailing loading. The occurrence of explosion-like concrete spalling has been explained severally by changes in the aggregate state of the pore water resulting from the heating of the concrete body. Heating leads to water vapour flowing to the side of the part exposed to fire as well as in the interior which then condenses in colder zones of the concrete body and fills the pores existent there (in particular capillary pores) until they are fully saturated. The water then stops flowing into the cross-section; a flow-through of this condensation zone is not possible. The vaporisation of the water can now only take place in the direction of the surface exposed to fire. This leads to a successive rise in the saturation vapour pressure in the pores. Once the tensile strength of the concrete has been reached, explosion-like spalling takes place. Explosion-like concrete spalling can be observed on self-compacting concrete in fire tests.

Hardly any tests have so far been published which focus on the fire spalling properties of self-compacting concrete (SCC). In [1] the influence of temperature on the mechanical parameters of SCC is showed. Borström describes in [2] tests conducted on SCC supports how violent spalling was recorded when subject to all-encompassing fire. The tests also show that...
the extent of the spalling could be reduced by adding synthetic fibres – primarily polypropylene fibres.

A further battery of SCC fire testing was carried out at the University of Stuttgart [3]. However, in these tests the cuboid test pieces were subject to fire loading in accordance with the standard temperature-time curve (TTC) of DIN 4102-4 and are thus not applicable to tunnel construction.

The most extensive study of fire and spalling behaviour of self-compacting tunnel concrete so far conducted has been summarised in [4]. A research project financed by the Federal Highway Research Institute (BAST)/ Federal Ministry of Transport, Building and Urban Affairs set out to verify which constructional and concrete-relevant measures are necessary in order to fulfil the road tunnel requirements of the ZTV-ING (Zusätzlich Technische Vertragsbedingungen und Richtlinien für Schutz und Instandsetzung von Betonbauteilen [Additional technical terms and conditions of contract and guidelines for the protection and repair of concrete components]), Part 5, Tunnel Construction. A total of 30 self-compacting concretes of the particulate powder and combination type were developed for the tests and which basically differed in the type and the content of the cement used (CEM I 32,5 R; CEM II / A-LL 32,5 R and CEM III / A 32,5 N; 330 to 360 kg/m³), the type and content of the concrete admixtures used (limestone particulate and hard coal fly ash), the type and content of the aggregate (quartzite and calcitic) as well as the fibre content and the fibre geometry. Development of the mixes took into account tunnel inner shell concretes as per ZTV-ING, Part 3, Solid Construction and Part 5, Tunnel Construction. To ensure the greatest possible application to tunnel construction, the self-compacting concretes were devised so that they conformed to the loading in the entrance area of tunnels in closed and open construction (exposition classes XF 2 and XD 2). In order to be able to better evaluate the fire spalling behaviour of the SCC, a further six conventional vibrated concretes (reference concretes) for tunnel inner shells as per ZTV-ING, Part 5, Tunnel Construction, were tested. Vibrated concretes were able to be assigned to the consistency ranges F4 to F5.

Verification of the fire spalling properties was effected both on small and large-scale test pieces as well as on an arch test. The test pieces were subject to fire in a loaded and unloaded state.

It was observed that the fire spalling behaviour of self-compacting concretes is not uniform. It is considerably dependent on the composition of the SCC. Factors influencing behaviour include not only exterior effects, but also, and in particular, the cement and the aggregate employed.

2 PROJECT MALMÖ CITY TUNNEL

The Citytunnel project in Malmö, Sweden, connects the Malmö Central Station with the Öresund Bridge via a railway line spanning approximately 17-kilometres in length. Its aim is to concentrate the rail traffic in Southern Sweden and, at the same time, cater for the rise in capacity expected in the future. The measures below ground comprise a total of around six kilometres, including a bored tunnel section measuring 4.5 kilometres long and consisting of two parallel tubes. Various subterranean stations are also to be constructed to link the railway line to the city, e.g. in the heart of Malmö - Triangeln Station. Because of the in places complicated building situation, in particular around the header beams (figure 1) of the supports, it
was decided to use self-compacting concrete in the station area. Figure 2 shows the situation before use and after striping of the SCC.

![Figure 1: Complicated building situation, in particular around the header beams](image1.png)

![Figure 2: SCC supports for Triangeln Station (photos: Malmö Citytunnel Group, MCG)](image2.png)

2.1 Conception if the tests and test set-up

Due to its experience with large-scale fire testing (e.g. in [5]) and self-compacting concretes in tunnel construction (e.g. [6]), the Malmö Citytunnel Group (MCG) commissioned in the spring of 2006 the MFPA in Leipzig to conduct tests with the aim of verifying whether design and concrete of the supports in the station belonging to the building project outlined above were suitable to ensure sufficient structural stability in the event of a defined fire.

To do this, fire testing was conducted on so-called “panels”. For purposes of comparison, test pieces of vibrated concrete were also tested in addition to the SCC panels. The block -
shaped, axially loaded reinforced elements represent a section of the periphery area of the supports to be tested (figure 3).

Figure 3: Dimension of the test panels

In particular investigation of the spalling behaviour in a defined fire scenario was taken into account to evaluate the structural stability in the event of fire. A medium spalling depth of the concrete measuring a maximum of 40 mm and a percentage of maximum ten per cent of the areas under investigation with spalling depths of > 100 mm were in this respect defined as meeting protection targets. The fire was defined by a temperature-time curve which spanned over five hours and reached a maximum temperature of 1,300°C after three hours. In order to be able to subject the panels to a uniform one-sided fire loading with simultaneous axial loading, they were laid horizontally on the opening of a test furnace (figure 4) which had been specifically designed for the purpose, but had differing geometries and loaded via a horizontal loading frame and hydraulic presses (figure 5).

Figure 4: Test furnace
2.2 Specimen geometry, concrete technology and testing programme

Concrete mix, reinforcement, compacting and striping methods of the panels corresponded to those planned for the supports. The panels were manufactured in-situ on the building site of the MCG and measured W x L x D = 1200 mm x 2200 mm x 400 mm. The following concretes were subject to fire testing:

Type 1: Two tests on panels of self-compacting concrete with the admixture of polypropylene fibres CEM I 42.5-NW-NA, limestone powder, silica fume, w/c ratio: 0.37. The concrete was cast in standing shell boxes with bottom feeder pipes. IFT Polyloc 2.8 dtex / 6 mm was employed as polypropylene fibres.

Type 2: Testing on a panel of vibrated concrete without polypropylene fibres, yet planked with 200 mm thick CaSi slab and otherwise of comparable mix.

To determine the temperature profiles an extensive number of temperature sensors were placed in the test piece bodies before concreting. The test pieces were transported from Malmö to Leipzig one week after the concrete casting process. There, the panels were conditioned for two months under water at a constant temperature of 20°C and stored for a further month until they were tested protected from the elements under PE film (20°C, 65% rel. humidity).

2.3 Conducting the tests and test results

A controlled force was applied during the loading phase using three hydraulic presses. The static system selected was able to separate out the internal stress caused as a result of temperature influences. The loads were applied gradually before the application of fire and held constant over the duration of the test.

Loading of the panels of Type 1 totalled 8.6 N/mm², that of the Type 2 panel 11.6 N/mm², the corresponding superimposed loads totalled 4.8 MN and 6.5 MN. Fire was simulated by eight oil burners, which were controlled individually by means of fire room temperatures. The
panels were set up juxtaposed along a width of 200 mm each and exposed to flame over a surface of 1800 mm x 1400 mm.

To investigate the fire behaviour, the temperatures within the panel and in the fire room, the spalling sounds, the deformation as well as the applied forces were recorded during the test, and the material loss determined once the panels had cooled down. On account of the extensive requirements regarding temperature and force flow as part of the loading framework of the testing construction, it was not possible to carry out a visual monitoring of the surface exposed to fire during the test. Nevertheless, in order to be able to verify the chronological course of the spalling, acoustic recordings of the entire testing process were made. This was effected via a microphone which was positioned centrally on the panels. The recordings were then filtered in order to remove the background noise of the burners. The recording technology as well as the settings of the filters employed were identical for all tests so that the graphic evaluation of the wave formations constitute a comparative result. The wave patterns enabled to detect whether and when spalling took place.

The temperatures in the panels were recorded by means of 26 temperature sensors which had been fitted before concrete casting at distances of 10, 50, 100, 200, 300 und 400 mm from the fire-exposed surface on the reinforcement baskets. The kiln temperatures were recorded by six ambient temperature sensors at a distance of 200 mm below the fire-exposed surface of the panel. Apart from the customary Ni-Cr-Ni- temperature sensors, platinum sensors were also employed to control the defined fire room curve on account of the high temperatures.

The deformations in the axial loading direction and horizontally to the direction of loading were recorded using distance sensors.

Following the fire tests and following a defined cooling phase of the furnace and the panels, the spalling depth was determined on the fire-exposed surface by means of a grid of 50 mm x 50 mm (figure 7, 8).

The temperature sensors located below the panel and the acoustic evaluation revealed that spalling during the fire test mainly occurred between 14 and 32 minutes of fire exposure in the case of type 1 concrete. The depth of spalling ascertained by visual inspection is shown in table 1.

<table>
<thead>
<tr>
<th>Panel No.</th>
<th>Test Type</th>
<th>Average [mm]</th>
<th>Maximum [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>panel 1</td>
<td>type 1</td>
<td>37</td>
<td>65</td>
</tr>
<tr>
<td>panel 2</td>
<td>type 1</td>
<td>11</td>
<td>45</td>
</tr>
<tr>
<td>panel 3</td>
<td>type 2</td>
<td>no spalling</td>
<td></td>
</tr>
</tbody>
</table>

It is noticeable that the spalling on panel 1 is noticeably greater than on panel 2. This can be explained by damage sustained after the end of the fire tests (spalling of concrete layers as a consequence of chemical reactions of the concrete with air moisture). This damage led to large-scale spalling between the end of the fire test and the visual inspection on panel 1. The subsequently exposed surface therefore displayed no direct flame effect (figure 7: panel 1). It can therefore be assumed that the average spalling depth given here was lower directly after the end of the fire test than given in table 1. A quicker visual inspection was not possible due
to the temperatures in the kiln. In contrast, panel 2 did not show signs of material loss between the end of the fire test and the spalling inspection.

During the fire test of the type 2 panel, there was minor spalling which was not relevant to the test.

![Figure 6: Fire exposed surfaces of panel 1 and 2 and measured spalling depth](image)

### 3 INTERPRETATION AND FINDINGS

Considering the findings of the tests regarding the type 1 panels taking into account the temperature profiles and the acoustic evaluations, generates an identical damage profile. As regards this aspect the spalling tendency of panel 2 is most conclusive for this type. An average spalling depth of 11 mm lies at 27.5% of the protection target stipulated as the maximum. There was no spalling over 100 mm. All investigations displayed on average a lower spalling depth than the 40 mm defined as the protection target. The maximum spalling depth following the fire tests was lower than 100 mm for all panels.

No spalling was recorded during testing of the panels clad with fire protection slabs (type 2); the heat transfer into the concrete was low.

Sufficient structural stability for both types was verified for the Citytunnel Malmö Project and is verified and ensured in the event of fire if corresponding concrete is used.

### REFERENCES


