Fire Resistance of Fibre- Reinforced, Reinforced and Prestressed Concrete Structures

Extended English Summary

Preface

The English-language abstract of the German-language Research Report "Fire Resistance of Fibre-Reinforced, Reinforced and Prestressed Concrete" should help the English-speaking reader to understand more exactly the results of this research project. For economic reasons it was not possible to have the complete research report translated in English. Please see the enclosed CD-rom containing figures and tables with German and English captions.

The present English-language abstract gives summaries of each chapter indicating the corresponding pages of the German-language research report.

1. Introduction and aim of the project (p. 11)

2. Fires in tunnel structures (p. 13 ff)

Fires in traffic tunnels and the resulting damages are described.

3. Failures in consequence of fire (p. 28 ff)

3.1 Influence of high temperatures on the characteristics of normal-strength concrete (p. 28)

The most important high temperature properties of concrete described in the literature and the residual strength parameters measured after fire exposure are described.

3.2 Influence of high temperatures on the characteristics of reinforcing and prestressing steel (p. 35)

After an introduction to steel production, high temperature characteristics and residual strengths measured after fire exposure are described.

3.2.1 Steel production methods

3.2.2 Exposure of reinforcing and prestressing steel to high temperatures

3.2.2.1 Strength of reinforcing and prestressing steel at high temperatures

Reference values regarding high temperature characteristics can be found in the appropriate regulations and in the literature [25,42,44,49].

The values regarding reinforcing and prestressing steel are given as recommended values, see fig. 3.18 to fig. 3.21. However, it has to be considered that the results may vary significantly depending on the experimental set up, the steel quality, and the strain conditions (fig. 3.19).

3.2.2.2 Residual strength of reinforcing steel after cooling

The kind of steel and the production method are of particular importance describing the residual post-fire strength.

As far as cold-deformed reinforcing steel is concerned, a temperature rise to 250°C causes the tensile yield point to increase and to come closer to the tensile strength which is also increasing. Therefore, the ratio R_m/R_p is approaching the value of 1. At temperatures exceeding 250°C, both values are decreasing and diverging from each other; the ratio R_m/R_p is increasing due to tempering effects and ductility is again increasing.

Generally, at temperatures rising to approximately 550°C reinforcing steel is showing only slight changes in strength. At temperatures exceeding approximately 400°C, both ductility and the strain at ultimate stress are increasing continuously. Prestressing steel loses its property of very low relaxation (fig. 3.22).

At temperatures exceeding approximately 400°C, Tempcore-steel loses its martensite content and gets tempered to such an extent that no structural difference to fine pearlite is visible under the light microscope. Hot-rolled steel (without any cold deformation or quenching effects) remain stable at temperatures rising up to 650°C, after being cooled down it regains approximately the same strength it had before.

Cold-formed steel is recrystallised at temperatures ranging from 550°C to 650°C. Thus, the gain in tensile strength through cold deformation is lost. The tensile strength of cold-formed steel returns to the value of the wire rod used for its production.

At temperatures ranging from 650°C to 710°C, the cementite lamellas of the pearlite are spheroidized and the steel loses up to 50% of its strength. This is valid for all kinds of unalloyed steel.

At temperatures exceeding 720°C, the so called A1-temperature, the structure of all kinds of steel gets transformed. Pearlite transforms into γ-iron, the so called austenite. Depending on the carbon content, austenitizing is finished at temperatures according to the A3-line, rising up to 910°C where also α-iron, the so called ferrite, transforms into γ-iron. The strength after the cooling depends to a great extent on the cooling rate:

- Very low cooling rates result in spheroidized (globular) cementite, i.e. the steel becomes very soft
- Higher cooling rates, similar to that used in wire rod production, lead to a ferrite-pearlite structure with tensile strength similar to that of wire rod
- Very high cooling rates may result in bainite (intermediate stage) or even martensite with high strength but low ductility.

At temperatures higher than 900°C, the growing of austenite grains starts and is recognizable within the structure also after cooling. Big grain sizes lead to a reduction in ductility of the steel, the steel becomes more brittle.

At temperatures ranging from 1000°C to 1200°C, the grain boundaries may oxidise and, consequently, form cracks if the steel is stretched under these conditions. Finally, due to crack propagation, ruptures of the steel may occur at high temperatures or after cooling.

The elements Cu and Sn accumulate along grain boundaries (fig. 3.23) and therefore have very negative effects in this regard.

3.3 Types of failure of concrete and reinforced concrete components (p. 44)

Possible causes for a failure of reinforced concrete constructions are described.

3.4 Concrete failure in consequence of spalling (p. 46)

Generally, the detaching of concrete fragments as a consequence of exposure to fire loads is defined as spalling. Spalling reduces the cross-section and may therefore lead to a failure of the structure. As far as reinforced concrete structures are concerned, the reinforcement may become directly exposed to the fire. There are three different kinds of spalling [25]:

- Explosive spalling of near-surface concrete layers
- Sloughing off
- Aggretate spalling

3.4.1 Causes of spalling

3.4.1.1 Internal stresses

3.4.1.1.1 Internal stresses caused by the heterogeneity of concrete

The different thermal expansion coefficients α_T of the reinforcing bar and the concrete may lead to a dissolution of the bondage and to cracks occurring around the reinforcing bar which, consequently, may favour spalling [52]. According to [53], internal stresses may also occur within the concrete (different α_T of hardened cement paste and aggregates).

3.4.1.1.2 Internal stresses caused by restrained dilation due to the specimen geometry

Resulting from the energy intrusion into the structure and the resulting heat penetration curve the expansion rate within the concrete structure varies with depth (fig. 3.32). Considering the condition of deformation compatibility, this will lead to compressive stresses in the heated zones and to tensile stresses in orthogonal direction to the direction of heat penetration. Fig. 3.32 and 3.33 show that the differences in expansion rates and consequently the internal stresses depend on the spatial gradient of the temperature distribution.

In [52] it is said, that the exceeding of compressive strength on the fire-exposed surface certainly does not lead to spalling. However in [55] it is suggested, that internal stresses, as described above, may lead to spalling as shown in fig. 3.34.

3.4.1.2 Restrained stresses

If dilation (e.g. because of great distances between movement joints) or free rotation of the structure, e.g. at edges, is restrained, compressive stresses and tensile stresses may occur, which could lead to spalling.

3.4.1.3 Chemical processes within the concrete

Damage of concrete caused by various chemical processes is frequently described in the literature (e.g. [51, 53, 55, 57, 58]). Depending on the temperature of the concrete, minerals of the hardened cement paste or the aggregates are chemically transformed.

3.4.1.4 Vapour pressure and water vapour flow

The moisture in the pore system and the physically and chemically bound water in the concrete evaporate at elevated temperatures, leading to an increase of vapour pressure in the concrete structure. The magnitude of the occurring stresses essentially depends on the temperature, on the amount of pore water (ratio of physically and chemically bound water) and on the pore structure through which the water vapour is transported. If the amount of water vapour produced per unit time exceeds the amount of vapour transported out of the pore structure, vapour pressure increases within the layer in which the evaporation occurs. With increasing pressure more water vapour escapes from the concrete which means that vapour pressure and the amount of advected water vapour depend upon each other. The position and the time of evaporation depend on the “history of evaporation”. A condition of critical vapour arises at a temperature of 374°C [61].

During evaporation the water vapour is advected towards the fire-exposed surface as well as into the concrete structure where it cools down and condensates. As a result a quasi-saturated layer is formed which is quasi-impermeable for water vapour (moisture clog) [53,63].

There are different theories explaining possible causes for spalling as a result of evaporation of water [52]. On the one hand, there is the assumption that a static pressure within the pores will lead to spalling if the tensile strength of concrete is exceeded. According to [48], the tensile strength of normal strength concrete may be reached due to the increasing vapour pressure at temperatures of approximately 250°C (fig. 3.38). On the other hand, the fluid transport within the concrete is also considered to cause tensile stresses leading to spalling. It is also explained in [54] that the expansion of the heated water causes pore pressures just before evaporation occurs, which might cause explosive spalling. However, in our opinion, the influence of expansion has to be quantified.

3.4.2 Types of spalling

The occurrence of spalling depends on various parameters [64]:

- Moisture content (no spalling at moisture contents < 2 % by mass determined at 105°C)
- Temperature – time curve (maximum temperature, temperature gradient)
- Geometry and dimension of the structure
- Loading condition (compressive or tensile stresses)
- Pore structure (porosity, permeability)
- Concrete strength
- Type of aggregate and grain sizes
- Fibre content (steel or plastic fibres)
- Degree of reinforcement and concrete cover

3.4.2.1 Explosive spalling of near-surface layers

3.4.2.1.1 Moisture content and water vapour pressure

It is suggested [61] that the main cause of spalling is free water and the moisture gradient within the concrete. Accordingly, normal-strength concrete cannot spall at moisture contents lower than 3 % by mass and below a certain moisture content also no other possible causes mentioned above can lead to spalling. Hereby a moisture content < 2 % by mass is indicated [25] (note: this value seems more reliable according to the results of the present research project).

3.4.2.1.2 Stress condition

High compressive stresses reduce the number of cracks occurring within the concrete structure and therefore reduce the possibility for the vapour to escape. As a consequence the spalling rate will increase.

3.5 Monostrands under fire exposure (p. 55)

Description of investigations performed so far.

3.6 Fibres in concrete exposed to fire (p. 58)

Production, processing, and effects of fibres in concrete structures as well as their application are described.

4. Methods of fire testing (p. 64)

Fire experiments described in the literature are analysed and listed (see also enclosed CD-rom).

5. Overview of the research programme (p. 66)

A general overview is presented, a detailed description of the experiments and the results can be found in chapter 7 and in the subsequent chapters.

6. Preliminary tests (p. 68)

Fire experiments on small-scale specimens made of fibre reinforced concrete and normal-strength concrete provided with monostrands are described.

7. Experimental setup (p. 72)

In order to simulate fires in tunnel structures, it was decided to use specimens with a height of 500 mm and 300 mm, respectively, corresponding to usual thicknesses of tunnel linings.

7.1 Specimens (p. 72)

In order to simulate realistic spalling conditions, the fire exposed surface was dimensioned 1200 mm x 800 mm (fig. 7.1). In order to avoid boundary problems and to simulate larger dimensions of construction components, the lateral surfaces and parts of the bottom surface not exposed to the fire were covered with steel sheeting (fig. 7.1).

7.2 Reinforcement (p. 72)

The reinforcement of the specimens was chosen in accordance to typical reinforcement layouts of cut-and-cover tunnels and linings of mined tunnels. Reinforcing steel BSt 550 and prestressing steel St 1570/1770 (monostrands) were used (fig. 7.2 and fig. 7.6). Some specimens were reinforced with three- or four-layered reinforcement in order to examine if this “protective reinforcement” may prevent the spalling front from reaching the main reinforcement.

7.3 Concrete mix designs (p. 73)

Water-proof concrete was chosen as standard concrete [101]. Furthermore, one high performance concrete mix and one concrete mix containing siliceous aggregates instead of limestone was used.

7.4 Fibres and fibre content (p. 74)

Monofilament PP-fibres (∅ 18 µm, l = 6 mm, dosages: 1.5 kg/m³ and 3.0 kg/m³) were used.

7.5 Storage conditions (p. 75)

The specimens (see table 7.2) were stored after production at three different conditions:

1. inside the mould with applying water constantly on its top, called “water” in the following
2. outside the mould and protected from weather, called “dry/air” in the following
3. as item 2 but with heating mats embedded in the centre of the specimen (inner temperature 50°C), called “dry/heating” in the following

Because of the relatively short storage time (ranging from 1 to 2 month(s)) moisture contents were high for all three storage conditions. Therefore, two specimens were prepared for long-term storage (specimens VK51 and VK52).

7.6 Moisture content (p. 76)

The moisture content was determined on separate specimens with the dimensions 1.0 m x 1.0 m x 0.5 m after splitting the panels and drying of the specimens at 105°C.

7.7 Prestressing (p. 76)

In order to simulate a restrained dilation, the specimens were prestressed in longitudinal direction (0.5 MPa). In transversal direction, prestressing at 1.16 MPa, 6.5 MPa or 9 MPa was applied. Moreover, tensile stresses at the bottom surface of the specimen were applied by excentric prestressing for some specimens. The prestressing was realized by stressing tendons and partly by external prestressing (fig. 7.6, fig. 7.10). The different stress conditions (see table 5.1) should give information about the spalling behaviour under different loadings.

7.7.1 Prestressing tendons

For specimens VK01 to VK12 monostrands were used. The tendons were externally anchored with anchor plates, an anchor body and, in addition, equipped with a wedge sliding compensation (fig. 7.7 and fig. 7.8).

7.7.2 External prestressing by a steel frame

Within the extended research programme, the simulating of the corresponding stress conditions by means of a “stressing frame” proofed to be the more economical method (fig. 7.10).

7.8 Instrumentation (p. 79)

The temperature distribution over the cross-section were determined by means of temperature sensors placed at selected depths (fig. 7.11). The thermo elements (iron-constantane) were placed at the reinforcement, at the prestressing reinforcement and within the concrete. Furthermore, vapour-pressure measuring devices, acceleration measuring devices and microphones were used (see chapter 8).

7.9 Furnace (p. 81)

The furnace was made of gas-aerated bricks and lined with fire bricks.

Outer dimensions:	L x W x H = 1880 mm x 1430 mm x 750 mm
Furnace dimensions:	L x W x H = 1200 mm x 800 mm x 570 mm

The furnace temperature was measured by means of two platinum-rhodium platinum-sensors (Pt10-Rt-Pt), which were placed each in a hole bored through the long side of the furnace at 150 mm from the heated surface of the specimen.

7.10 Temperature – time curves (p. 82)

The experiments were performed using the fire temperature-time curves indicated in fig. 7.19.

8. Experimental results (p. 85)

In the course of the experiments the following experimental data were recorded:

- Temperature measurements in the furnace and within the specimens every 30 seconds
- Registration of the results every two minutes
- Acoustic and subjective observations during and after the fire experiment
- Acoustic registration of the spalling noises (VK29 to VK 32, VK 58 and VK 59)
- Photographic documentation of the bottom surfaces of the specimen immediately after the fire test and one day after the experiment
- Performing a raster representation and producing a contour plot of the spalling depth
- Determination of the mass of the specimen before and after the fire exposure and determination of the amount of spalling
- Determination of the vapour pressure development (VK29 to VK32)
- Determination of the changes in prestressing force (VK01 to VK12)
- Determination of the grease pressure increase in the monostrands embedded in the concrete (VK07, VK09; VK10; VK15; VK23 to VK26)

8.1 Temperature measurements (p. 85)

8.1.1 Temperature registrations during the fire experiments

The extent of heat penetration versus time into the concrete mainly depended on whether spalling occurred or not. In case of severe spalling the temperatures of the sensors increased immediately whereas in case of little or no spalling heat penetrated much slower. (fig. 8.1, fig. 8.2, table 8.1)

8.1.2 Temperature distribution

8.1.2.1 Temperature distribution plots

The temperature distribution plots of all specimens indicated in table 8.1 are shown [106]. Chapter 11 “Interpretation of experimental results” contains a comparative evaluation of the curves.

8.2 Evaluation of spalling behaviour (p. 98)

The evaluation of spalling includes consideration of the spalling histories and the spalling depths at various times during the experiment.

8.2.1 Spalling depths

8.2.2 Mass change and water loss

8.2.3 Influence of the experimental setup on the spalling depth

After the occurrence of cracks within the specimens the vapour could escape through the cracks and spalling stopped. Hence, the maximum spalling depth reported in this research programme depends on the experimental setup.

8.2.4 Spalling versus time (spalling history)

8.2.4.1 Spalling histories (spalling depth versus time diagrams)

Spalling depth versus time diagrams were produced in order to compare the spalling rates. These diagrams should document the impact of the concrete mix, the degree of reinforcement, the temperature-time curve, and the stress condition. The diagrams provide more information than the indication of the maximum spalling depth and they also allow to determine spalling rates (mm/min). The evaluation has been performed on the basis of the following data:

- Observations performed during the experiments (acoustic perceptions, occurrence of cracks, spalled material coming out from the smoke tube, moisture penetrations)
- Temperature measurements in the furnace and within the specimens
- Plots indicating the location of sensors
- Reinforcement drawings
- Acoustic registrations (VK29 to VK32, VK58 and VK 59)
- Contour plots indicating the spalling depth [104]

8.2.4.2 Acoustic registrations during fire experiments

Spalling was visualized by means of acceleration measurements (fig. 8.32 and 8.33).

8.2.4.3 Representation of spalling depth versus time curves (spalling histories)

Spalling depth versus time curves are represented in fig. 8.34 to 8.48 (x-axis: time in minutes, y-axis: respective spalling depth).

8.2.4.3.1 VK01/VK02: reduced furnace temperature (RWS “reduced” fire exposure)

8.2.4.3.2 VK05/VK06: different moisture content

8.2.4.3.3 VK07/VK08: PP-fibre content 1.5 kg/m³

8.2.4.3.4 VK11/VK12: high compressive stresses

8.2.4.3.5 VK 13/VK14: different moisture content

8.2.4.3.6 VK19/VK20: experiments with standard fire exposure (ISO 834)

8.2.4.3.7 VK21/VK22: concrete C30/37 containing microsilica (high performance concrete)

8.2.4.3.8 VK29/VK30: influence of a protective mesh reinforcement (AQ50, ∅ 5 mm, at spaces of 100 mm)

8.2.4.3.9 VK33/VK34: specimens without reinforcement

8.2.4.3.10 VK43/VK44: specimens made of normal-strength concrete with different moisture contents and two layers of reinforcement

8.2.4.3.11 VK54/VK55 and VK58/VK59: specimens with four layers of reinforcement

8.2.4.3.12 VK61/VK62: performance of a protective layer made of fibre reinforced sprayed concrete

8.3 Vapour pressure measurements (p. 120)

The development of vapour pressure was measured in various depths of the specimens VK29, VK30, VK31 and VK32.

8.4 Permeability measurements on normal-strength concrete with and without PP-fibres (p. 122)

The results of this research project have shown a great influence of the polypropylene (PP) fibre content on the spalling behaviour of concrete under fire loading. Based on the identification of the permeability as the parameter with the greatest influence on spalling, results of permeability tests on normal-strength concrete without and with PP-fibers (1.5 kg/m³) were performed. In order to obtain deeper insight into the pore structure and its effect on the permeability, mercury-intrusion-porosimetry (MIP) tests were performed [112].

8.5 Material parameters after fire exposure (p. 132)

8.5.1 Residual strength of concrete

In order to determine the residual strength after the fire experiment, vertical cores with ∅ 100 mm were taken from the specimens (fig. 8.66). Afterwards, cores with ∅ 50 mm and l = 50 mm were drilled in orthogonal direction to the core axis (parallel to the heated surface) in various depths and their strength was determined according to ÖNORM B 3303 (table 8.5). Comparing the experimental results (fig. 8.67) with [42,45,46, 47] it can be recognized that significant strength losses already occur at relatively low maximum temperatures.

In comparison with the above mentioned experiments on small-scale specimens the experiments on large-scale specimens were performed under different conditions:

- For the first time fibre-reinforced concrete with high moisture content and high vapour transport rates was tested
- High temperature gradients were observed in near-surface layers
- The experiments were performed under restrained dilation

These conditions occurred in near-surface concrete layers exposed to high mechanical and thermal loadings. Concerning the residual strength of the surface layers (thickness 100 mm) which were exposed to temperatures higher than 200°C, more detailed examinations have to be performed.

8.5.2 Influence of the experimental setup on structure and strength of reinforcing steel

At temperatures below the A1-line of austenite-transformation (fig. 8.68) the original grain structure of cold-deformed steel remains unchanged. Re-crystallization starts at temperatures higher than approx. 650°C. As the reinforcing steel used had only slight cold deformation with very small longitudinal deformation of the steel grains (in opposition to prestressing steel, see fig. 8.70), it cannot be determined whether re-crystallization occurred or not.

At temperatures exceeding approximately 700°C, the steel grains are transformed into austenite. Hereby, the grains that are transformed during the following cooling are the bigger the higher was the temperature to which the steel has been exposed. In nearly all cases the resulting structure consisted of ferrite and pearlite (fig. 8.69 and 8.71) and was more or less fine depending on the cooling rate.

Reinforcing steel produced by the Tempcore method (chapter 3.2.1.1) represents a special case in this regard. The area of the cross section near the surface, consisting originally of martensite (fig. 8.72) is transformed into high tempered martensite at relatively low temperatures ranging from 400°C to 600°C. However, all examined specimens reached higher, temperatures and were completely transformed into austenite and finally ferrite-pearlite-structure (fig. 8.73).

8.5.3 Laboratory examinations regarding the residual strength of reinforcing steel and prestressing steel

After the fire experiments some samples of reinforcing and prestressing steel were taken from selected specimens (fig. 8.75). In order to document the development of strength with continually increasing temperatures on a single test sample and in the full range of possible temperatures, a sample of prestressing steel with ∅ 9,4 mm was put into a wire welding machine and exposed to a temperature increase to 950°C over a length of 220 mm (fig. 8.76). Then the hardness HRC was measured every 5 mm, starting at the clamping towards the centre of the zone exposed to heat. Subsequently, the determined HRC values were converted into tensile strength values. Tensile strength values determined in this way represent only reference values but give adequate knowledge about the development of tensile strength with temperatures up to the maximum temperature reached in the experiment (fig. 8.77 and fig. 8.7).

8.5.4 Monostrands exposed to fire

In order to determine the development of the pressure of the grease responsible for corrosion protection inside the plastic sheathing containing the monostrand during fire exposure (see chapter 7.8), monostrands were placed in selected specimens in the second reinforcement layer (approx. 50 mm to 60 mm from the heated surface). If spalling reached the plastic sheathings containing the monostrands they were destroyed together with the grease (VK05, VK06 and VK08). This was observed also on monostrands placed deeper in the concrete. If no or only little spalling occurred, no damage was visible at the surface (VK07, VK09, Vk10, VK17, VK23). In some cases local grease outflows occurred in weak areas of the concrete cover (VK15, VK25 and VK26), see fig. 8.79. Despite of high grease pressures, under no circumstances spalling was caused by monostrands.

8.5.5 Fibres before and after exposure to high temperatures

In order to gain information about the diameter of the used fibres, two samples were examined under the scanning electron microscope. Further results of the examinations performed after fire exposure can be seen in fig. 8.87 and fig. 8.88.

9. Methods for determination of the load-bearing capacity in case of exposure to fire loads and the residual load-bearing capacity after the fire (p. 148)

For a short description see chapter 12.4 of this summary.

10. Influence of fire loading on the load-bearing capacity (p. 155)

For a short description see chapter 12.4 of this summary. The results of calculations performed for various tunnel cross-sections are shown in fig. 10.1 to 10.10 and in the enclosed CD-rom.

11. Interpretation of the results (p. 161)

11.1 Impact of different fibre dosages and fibre types (p. 161)

11.1.1 Temperature distribution

In order to determine the dependence of the temperature distribution on the fibre content, the experimental results of specimens VK07, VK09 and VK17 were compared (fig. 11.1). The temperatures were measured 30, 60, 90 and 120 minutes after starting the experiment in a depth of 50 mm. The results of the measurements showed varying temperature distributions depending on the fibre dosage.

The addition of fibres leads to a better cooling effect because of additional possibilities for the water vapour to escape [62]. It has been recognized that the temperature distribution of fibre-reinforced high performance concrete depends on the fibre content [132].

11.1.2 Spalling behaviour

Under extreme experimental conditions, 1.5 kg/m³ of PP-fibres seem to be a threshold value for preventing spalling. In case of a PP-fibre content of 1.5 kg/m³ an additional dosage of 30 kg/m³ steel fibres had a positive effect on the spalling behaviour. Spalling depth reached 10 mm.

A dosage of 3.0 kg/m³ PP-fibres (no steel fibres) could prevent spalling completely; only in one case (VK24) a local, 5 mm deep, damage occurred.

11.2 Impact of different moisture content (p. 162)

All specimens had relatively high moisture contents. As observed, spalling increased with increasing moisture content. A high moisture content also diminished the rate of temperature penetration.

11.3 Impact of different stress condition (p. 165)

After the fire in the Tauern Tunnel the effects of restrained dilation due to the tunnel geometry were recognizable on the vault [32]. Whereas the concrete spalled away exposing the underlying shotcrete in the central part, the joint areas exhibited less spalling.

11.3.1 Temperature distributions

In order to examine possible impacts of external stress conditions on the temperature distribution, the experimental results of specimens VK07/VK16 were evaluated. The specimens contained 1.5 kg/m³ PP-fibres and were stored at condition “water”.

Possibly, because of the failed tension zone the water vapour could escape more easily towards the fire-exposed surface cooling the concrete at the same time; this effect increased with increasing duration of the experiment.

11.3.2 Spalling behaviour

With increasing compressive stresses (up to 9 MPa) the rate of spalling increased.

11.4 Impact of different degree of reinforcement (p. 167)

For cut-and-cover tunnel structures zinc coated mesh reinforcement N94 (∅ 3 mm, at spaces of 75 mm) are provided for fire protection reasons [135] in order to prevent the spalling from progressing further into the structure. The effectiveness of this measure could be demonstrated in many cases (however, at lower temperature gradients).

11.4.1 Spalling behaviour

11.4.2 Effects of mesh reinforcement

If spalling reaches the reinforcement mesh deeper parts of the underlying concrete are kept in place by the mesh. Arches are formed between the reinforcement bars which may prevent spalling from progressing further (fig. 11.9).

The experiment showed that reinforcement meshes ∅ 20 mm, at spaces of 100 mm may prevent spalling for a certain time but cannot stop it completely (see spalling rates fig. 8.35, chapter 8.2.4.3 and fig. 12.1, chapter 12.1). Only massive mesh reinforcement with smaller distance between centres anchored back in deeper concrete prevents spalling from progressing further by forming arches and retaining fragments of concrete which have broken away.

11.5 Impact of concrete mix design (p. 169)

The influence of the concrete mix design on the spalling behaviour is low, except for high-performance concrete.

11.6 Impact of different temperature gradients (p. 170)

In the course of the experiments the impacts of four different fire curves with different temperature gradients during the first few minutes were examined.

The temperature increase in the first few minutes of a fire proved to have an essential influence on the spalling behaviour.

11.7 Impact of high temperatures on monostrands (p. 171)

The behaviour of monostrands at high temperatures and their influence on the spalling behaviour was examined on selected specimens. The grease pressure increase in the plastic sheathing containing the monostrands was measured (fig. 11.12).

11.8 Impact of high temperatures on the residual strength of concrete and steel (p. 172)

Samples taken from the specimens after fire exposure reflect production and testing conditions. Therefore, they cannot be compared with samples of small dimensions examined under defined laboratory conditions.

11.8.1 Reinforcing and prestressing steel

11.8.2 Normal-strength concrete

11.8.3 Fibre-reinforced concrete

The residual strength of fibre-reinforced concrete after fire exposure is illustrated in table 8.5. At temperatures ranging from 100°C to 200°C, at which high vapour pressures occurred, the residual strength of fibre-reinforced concrete was determined to be only 40% to 60% of the strength at room temperature. The residual strength values measured on laboratory samples and on specimens from small-scale fire experiments reach higher values than the values mentioned above.

11.9 Impact of the fibre content on the consistence (p. 173)

The reduced consistence (flow) due to the addition of PP-fibres could be compensated by adding plasticizers. Further experiments with regard to construction practice have been performed in Austria [94].

11.10 Impact of fibre-reinforced sprayed concrete as protective layer (p. 173)

A 60 mm thick fibre-reinforced sprayed concrete layer was applied on specimens VK60/VK61 in a similar way to rehabilitation measures serving the increasing of concrete cover. In order to ensure a durable bond between sprayed concrete and its substrate, a steel mesh was embedded and anchored in the normal-strength concrete.

Fire experiments showed that the normal-strength concrete could be protected from temperature penetration by this measure. Therefore, the described procedure can be considered as an economical measure to improve the fire resistance.

11.11 Interpretation of temperature distribution curves (p. 174)

The temperature distribution in two-dimensional structures may be determined by solving the differential equation analytically considering the heat transfer (radiation and convection) and heat conduction. In order to obtain realistic results, however, it is necessary to consider all parameters correctly. Up to date, the main influence parameters (λ, c_p, ρ) have been repeatedly adapted for the recalculation of experimental results and they are now discussed [124,136]. In case of standard reinforcement degrees, the local discontinuity represented by the reinforcement bar may remain unconsidered.

The thermal material parameters of concrete (λ, c_p, ρ) depend on the temperature (see e.g. [43, 44]). The moisture content of concrete has a major influence on the thermal conductivity, especially regarding the evaporation of water. “Moreover, it has to be considered that the differential equation solves the problem only approximately, because, in concrete structures thermal transport processes and significant moisture transport processes take place, so that there are two parallel transport processes which, according to the rules of irreversible thermodynamics, have to be considered by a system of partial differential equations [25,26]”.

Concerning moist fibre-reinforced concrete where both transport processes have to be considered, the research is still at its beginnings. Qualitative considerations regarding changes of heat conductivity due to a changing moisture content are given in fig. 11.17 [62].

Regarding the determination of the originally unknown surface temperature, assumptions have to be made regarding the convective and radiative parts of the heat transfer coefficient and the radiation conditions. This is possible only by knowing the air velocity, the characteristics of the smoke and the colour of the concrete surface as well as their time- and space- dependent changes.

The temperature distribution in the present research project shows differences of up to 200°C between the results of the single experiments. The responsible parameters (e.g. moisture content, stress condition, fibre content) are described in chapter 8.1.2.1. Moreover, the following parameters regarding all experiments have to be considered:

- Firing (class D fuel oil, furnace chamber design, air pressure-distribution)
- Time at which the maximum temperature is reached
- Colour of the concrete surface
- Occurrence of cracks during the fire test
- Spalling (also of thin layers)
- Dimensions and thickness of the specimen
- Dimensions of the furnace chamber

Considering these parameters, it can be said that the determination of temperature distribution curves by means of experimental results or by calculation both depends on a more or less exact estimation of the temperatures.

12. Conclusions from the experimental results (p. 176)

12.1 Concrete spalling – influencing parameters and prevention (p.176)

The prevention of explosive spalling of near-surface concrete layers is of essential importance for the maintenance of the load- bearing capacity of structures. Therefore, it is necessary to consider the respective influencing factors.

Regarding specimens showing severe spalling the average spalling rate (fig. 12.1) was determined by means of spalling versus time diagrams (8.2.4.3). As far as reinforced specimens are concerned, it has to be considered that the progression of the spalling front is delayed when spalling reaches the reinforcement. In fig. 12.1 this delay is distributed evenly over the entire spalling duration.

12.1.1 Influence of the stress condition

The specimens were subjected to compressive stresses of 9.0 MPa (VK11/VK12) and 1.16 MPa (VK43) or to tensile stresses in order to simulate a failed tension zone on the fire-exposed surface (VK13/VK14). It could be seen that the spalling rate increased with increasing compressive stresses (up to 240 mm/h) and significantly exceeded the spalling rates of specimens subjected to tensile stresses (190 mm/h). On the fire-exposed surface subjected to tensile stresses water vapour could escape more easily because of the feasibility for the formation of cracks. This leads to a decrease of the spalling rate (fig. 12.2). Completely failed specimens, high-performance concrete (VK21 to VK24) excepted, allow a more rapid escape of the water vapour which avoids progressive spalling.

12.1.2 Influence of moisture content in the concrete

The moisture content in the concrete has a significant influence on the spalling behaviour and, consequently, influences also the spalling rate. This has been demonstrated by comparing the results of specimens subjected to restrained dilation (compressive stresses of 1.16 MPa) after storage condition “water” and “dry”. Specimen stored at condition “water” with a thickness of 500 mm had moisture contents exceeding 5 % by mass. Specimens stored at condition “dry” had moisture contents ranging between approx. 3.0 % by mass and 3.3 % by mass considering a specimen thickness of 300 mm and appropriate storage. At equal conditions the spalling rates increased from 170 mm/h to 210 mm/h if the moisture content increases by 2% (fig. 12.2).

12.1.3 Influence of the reinforcement degree and the reinforcement layout

The delay of the spalling front when it reaches the reinforcement influences also the spalling rates. Therefore, specimens with no reinforcement (VK33/VK34) showed a relatively high spalling rate of 300 mm/h (fig. 12.2). However, this high spalling rate may be caused not only by a lacking reinforcement but also by the moisture content of 4.7 % by mass. A double-layer reinforcement reduces the average spalling rate from 300 mm/h to a spalling rate ranging between 170 mm/h and 240 mm/h. Adding an additional mesh layer AQ 50 (∅ 5 mm, at spaces of 100 mm) to the first reinforcement layer does not have any essential effect on the spalling behaviour. Four reinforcement layers (specimens VK54/VK55) could stop the spalling from progressing further.

12.1.4 Influence of the temperature gradient

The time when spalling starts essentially depended on the temperature increase in the furnace within the first few minutes.

12.1.5 Influence of the concrete mix-design

Comparing the various concrete mixes, high-performance concrete showed the highest spalling rates. Therefore, concrete mixtures having a sufficient amount of pores have a positive effect on spalling rates. However, this characteristic is in diametrical opposition to other requirements for durable concrete.

Fine polypropylene fibres seem to be able to prevent spalling even under severe conditions by the formation of linear contact zones in the structure (every contact zone between the hardened cement paste matrix and the aggregates is characterised by a higher permeability, but normally not directed one-dimensionally) and giving way at high temperatures. Considering the given experiment conditions, the minimum dosage to obtain the desired effect was 1.5 kg/ m³ PP-fibres (length 6 mm, diameter 18 μm).

12.1.6 Possibilities to avoid concrete spalling

There are different ways for avoiding explosive spalling of near-surface concrete layers. Considering the experimental results spalling can be reduced or avoided by the following measures:

12.1.6.1 Reduction of the temperature gradient

For the dimensioning and the calculation of the construction the temperature increase and the fire loading (temperature – time curve) are defined. Therefore, the temperature penetration can be reduced only by a barrier (fire protective layer). This barrier can be (I) plate-like protective layers mounted on the concrete surface or on underlying structures or (II) fire protection mortar bonded to concrete.

If fire protective layers are moist they may also spall, this aspect is not examined in most of the cases. Moreover, the bond performance, which is influenced by compression and suction effects caused by traffic and by the self weight of the protective layer, have to be maintained. In case of protective layers made of mortars the fire load imposes stresses in the joints, mesh reinforcement should be embedded and anchored in the concrete. Moreover, long-term aspects (e.g. moisture and frost resistance) and the aspect of a hindered access to the construction for examination purposes should be considered.

12.1.6.2 Reduction of concrete moisture

Assuming that the volume expansion of liquid water and vapour are the main causes for explosive spalling, the reduction of the moisture content theorertically represents an effective measure.

12.1.6.3 Providing expansion space

In case of great volume expansions of constituents of the concrete matrix, the existing stresses can be relieved by the escape of moisture through macroscopic cracks or microscopic pores (longitudinal cracks serve as escape ways, spherical voids serve as expansion spaces).

The water vapour should preferably escape through the pores. For reasons of durability the capillary porosity has to be kept as low as possible. Therefore, as far as normal-strength concrete is concerned, the above described measure is suitable to diminish the existing vapour pressures only to a certain degree. Artificially entrained air bubbles provide a limited expansion space which has shown to be effective in case of volume expansions occurring as a consequence of frost. But the usual air-pore content probably does not provide sufficient expansion space for vapour. Therefore, longitudinal pores and hollow pores are more suitable to serve as canals. But they should serve as transport canals only in case of fire and prevent flow of air, water and harmful substances under normal conditions. Research has shown that plastic fibres (especially polypropylene fibres) possess these characteristics.

12.1.6.4 Increase of the concrete tensile strength

Spalling could be delayed if the tensile strength of concrete is increased without increasing the compressive strength (and normally reducing porosity). However, this is only possible to some extent. A certain effect can be achieved by the addition of steel fibres.

12.1.6.5 Reinforcement and reinforcement layout

Thin mesh reinforcement protecting the main reinforcement has only minimal influence on the spalling behaviour. However, this reinforcement can serve as “support” for forming arches (supporting vaults) and as “barriers” for concrete parts broken off, if appropriate diameters and axis distances are chosen.

12.1.6.6 Providing space for dilation

Expansion joints may help to reduce spalling caused by restrained loads due to restrained longitudinal expansion of structures.

12.2 Behaviour of reinforcing and prestressing steel exposed to high temperatures (p. 180)

See chapter 11.8.1 for illustration.

12.3 Behaviour of monostrands in case of fire (p. 180)

In case of fire monostrands are normally better protected (by a second reinforcement layer) than the reinforcing steel. In case of steep temperature gradients the protection layer may spall off more rapidly and the monostrand gets directly exposed to fire. As a consequence, the corrosion protection is destroyed. If the concrete is not spalling off, the monostrand is durably protected by the concrete; it is heated slowly and the following processes can be observed:

The HDPE-sheath can resist temperatures ranging from 120°C to 140°C for a short duration and can resist temperatures of 100°C for a longer duration. Higher temperatures will lead to a slow degradation (decompensation). If for instance the prestressed strand is deflected inside the structure, it exerts lateral forces to the plastic sheathing which may result in perforation of the plastic sheathing even at temperatures of only 75°C (softening point). The agent for corrosion protection (grease) remains unchanged up to a temperature of 180°C. If temperatures exceed this value, the presently used greases get destroyed. Because of the temperature increase the corrosion protection mass expands causing pressure in the plastic sheathing. Test results show pressures up to 9 bar inside the plastic sheathing, without causing any spalling of the concrete.

Summing up, it can be stated that a long-term durability of monostrands after fire exposure is provided by the used corrosion protection systems up to maximum temperature of approximately 150°C in case of linear prestressing tendon layouts and of approximately 100°C in case of deflected prestressing tendon layouts. Even if the corrosion protection system is destroyed a short-term use of the monostrands is possible under the above described conditions.

12.4 Influence of the fire load on the load-bearing capacity (p. 180)

The analysis of the load-bearing capacity during a fire and the residual load-bearing capacity after a fire can be performed by a structural analysis assuming linear elasticity or by using the finite element method. In both cases the temperature curves resulting from the temperature loads are determined first by a thermal analysis and a mechanical analysis is performed afterwards. The mechanical analysis by means of the finite element method is more complex and needs non-linear-elastic definitions of the material parameters of the concrete and of the reinforcing or prestressing steel. In order to perform the examination by means of a structural beam element analysis assuming linear elasticity, additional calculations and simplifications have to be made before.

Firstly, the non-linear temperature penetration curve has to be linearized so that it can be inserted in a static model. In order to do so, a bar with a length of 1.00 m is divided into layers and the corresponding temperature according to the temperature curve is assigned to each layer. At the same time the temperature-dependent material parameters (compressive strength and modulus of elasticity) are determined for each layer and the restrained loads caused by thermal expansion are calculated. Integrating the resulting stresses over the structure`s height, the resulting restrained internal forces (normal force N(T) and moment M(T)) are determined.

After the determination of the restrained internal forces a bar with the length of 1.00 m is exposed to a uniform temperature increase T_m and a linear temperature gradient ΔT imposing the same restrained internal forces N(T) and M(T). The resulting “equivalent temperature load” serves as initial parameter for the static model.

After the insertion of the “equivalent temperature load” in the static model the material parameter of the supporting structure have to be adapted to the temperature load. For the concrete cross section the average values for the modulus of elasticity and the compressive strength over the cross-section or the height of the compressive zone have to be determined. The material parameters of the reinforcing and the prestressing steel may be determined according to the temperature in the corresponding depth.

According to ÖNORM or EUROCODE, the fire load has to be considered as a “accidental design situation” [43, 44, 117, 118, 122]. In order to analyse the residual load-bearing capacity and the safety factors of the “persistent and transient design situation” (according to ÖNORM [117,122]) have to be considered.

12.5 Regulations regarding the examination of the fire resistance of concrete (p.181)

The examination method performed within this research project has been inserted into the guideline “Concrete for tunnel linings” of the ÖVBB (Austrian Society for Concrete and

Construction Technology) [137] as reference test for determining the fibre-reinforced concrete class BB 1G and BB 2G (see Appendix 5 of the guideline “Concrete for tunnel linings”).

12.6 Quality management measures regarding fibre-reinforced concrete of classes BB 1G and BB 2G

Apart from the usual tests of fresh and hardened concrete performed in the course of the initial test and in the course of both conformity test and identity test, the following additional measures must be performed in order to ensure the required characteristics of fibre-reinforced concrete.

Quality management measures of the fibre producer:
- Initial suitability fire test of the fibre-reinforced concrete class according to the guideline “concrete for tunnel linings” [137] of the ÖVBB, Appendix 5
- Internal and external control according to the guideline “fibre-reinforced concrete” [72] of the ÖVBB, table 11/2
- External quality control according to the guideline “fibre-reinforced concrete” [72] of the ÖVBB, chapter 11.4
- Exact inscription of the fibre-type on the packages

Quality management measures of the concrete producer:
- Control of the delivery ticket and optical examination at delivery according to the guideline “fibre-reinforced concrete” of ÖVBB, table 11/2 [72]
- Extraction of control samples from every delivery
- Spot-checking of the fibres (length, diameter) once a month
- Regular calibrations and checks of the functionality of the proportioning devices
- In case of manual dosage: addition to the aggregates, registration of amount and time of the mixing in a protocol, joining the protocol with the charge protocol and concrete production statistics
- Indication of fibre addition on the delivery ticket
- Initial test: proving the uniform fibre distribution in the mixture, possibly, fixing the tolerance for the fibre dosage

Additional examinations to be performed on fresh concrete:
- Initial test regarding the uniform distribution of the fibres
- Continuous optical controls regarding the fibre content
- Determination of fibre content by means of wash-out tests
- Compliance with the dosage according to the guideline “fibre-reinforced concrete” [72] of the ÖVBB, chapter 11.2.1

Additional tests to be performed on hardened concrete:
- Production of cubes with different fibre content serving as reference samples for the used concrete mix
- Controlling the fibre content of hardened concrete by comparison with reference samples
- Compliance with the dosage according to the guideline “fibre-reinforced concrete” [72] of the ÖVBB, chapter 11.2.2. Note: regulations regarding the determination of the fibre contents are still in elaboration [142].

Concept of compaction: adaptation of the casting and fibration concept to the fibre-reinforced fresh concrete with reduced consistence (higher yield point).

13. Summary and recommendations (p.185)

The main topics of the present research programme were the prevention of spalling through different measures, the discussion of influence parameters and the main phenomena to be considered in this regard. Moreover, the experiments should help to examine the behaviour of reinforcing and prestressing steel under high temperatures and the behaviour of debonded monostrands protected by a corrosion protection mass and a plastic sheathing.

In a series of preliminary experiments on small-scale specimens first examinations regarding the spalling behaviour have been performed. As a result it has been recognized that the following parameters have to be considered in order to simulate real tunnel fires:

- The furnace chamber shall not be too big and shall be provided with efficient fuel heating
- The dimensions of the specimen have to be as large as possible in order to ensure a uniform heat penetration and prevent non-uniform heat penetration
- The specimen shall be thick and wide enough in order to make it possible to apply tendons for simulating restrained dilation
- Specimens of adequate thickness shall be sealed at the lateral surfaces in order to prevent the escape of water through the lateral surfaces
- Possibilities to build in different reinforcement degrees and layouts
- Sufficient instrumentation, especially of temperature sensors, shall be applied
- Observation of limit values of dimension and masses regarding transport and experimental setup

A compromise could be found choosing the specimen dimensions of 1.80 m x 1.40 m x 0.50 m. Each fire experiment has been performed on a pair of specimens in order to consider also deviations within the single experiments. The results showed good reproducibility, the resulting maximum spalling depths of 360 mm and maximum spalling rates of 300 mm/h correspond to those measured under real conditions.

In the course of the experiments, the following parameter studies have been performed:

Different concrete mix designs
- fibre content, concrete strength
- type of cement
- silicafume content (microsilicate content)
- mineral composition of aggregates
- air content of entrained air

Different reinforcement degrees and layouts
- specimens without reinforcement
- double-layered reinforcement ∅ 14 mm, at spaces of 100 mm
- multi-layered reinforcement

Specimen thickness
- 500 mm and 300 mm

Different storage conditions
- wet storage (“water”)
- dry storage (“dry/air”, “dry/heating”)
- long-term storage ("dry")

Different stress conditions
- without pre-stressing
- compressive stresses (6.5 MPa, 9 MPa)
- tensile stresses on the fire-exposed surface (failed tension zone)

Temperature-time curves
- standard fire (ISO 834)
- Lainz 180 (LT 1) Lainzer Tunnel (object-related temperature-time curve)
- RWS and RWS reduced

Besides the fire experiments, examinations regarding the permeability of fibre-reinforced and plain concrete and the technological characteristics of the used building materials were performed.

The results of the research programme can be summed up as follows:

Concrete has a very good fire resistance. The thermal conductivity of concrete structures is low, which means that they are heated only in the near-surface layers, whereas the inner layers show only low temperature increases. In order to reach further improvements, especially regarding the spalling behaviour, various measures have to be taken.

Explosive spalling

In case of a fire spalling rates of up to 300 mm/h occur; of considerable influence are:
+ high moisture content
+ restrained dilation
+ steep temperature gradients
+ density and strength of the concrete
+ reinforcement degree and layout
Measures to prevent spalling are:
+ addition of polypropylene fibres
+ massive cross-layered reinforcements with anchorage in deeper zones
+ low moisture contents
+ adequate air content of entrained air
+ protective layers placed on the concrete surface
+ expansion space
+ addition of steel fibres
Negligible influence on the spalling behaviour have for example:
+ mineral composition of the aggregates
+ type of cement

For a practical use, 2.0 kg/m³ polypropylene fibres may be sufficient in most cases. As far as high-performance and high strength concretes are concerned, the dosage has to be increased if necessary.

Vapour pressure

The vapour pressure increased significantly when heat penetrated the concrete. By adding PP-fibres, the intrinsic permeability and, consequently, the permeability for water vapour is improved significantly.

Heat penetration

Within the present research project heat penetration in moist fibre-reinforced concretes has been examined on large-scale experiments for the first time. Water vapour could escape only towards the furnace chamber. Temperatures measured in the specimens differed by up to 200°C within the experimental programme.

Strength characteristics

Determining the strength of building materials under exposure to high temperatures was not the main aim of the research programme. However, it would be of great interest to examine the strength of vapour filled fibre-reinforced concrete under exposure to high temperatures. The results of small-scale laboratory experiments on cylinders do not seem to be sufficient for a realistic determination of the strength. The strength of reinforcing and prestressing steel during fire exposure has been estimated according to indications in literature and fixed as scales for the numerical determination.

After the fire experiments, steel and concrete samples were taken from various parts of the specimens exposed to different mechanical and thermal loads. Steel structure and stress-strain diagrams were determined and, for the first time, the arising of a annealed structure (spheroidized cementite) at temperatures of approximately 700°C, connected with a minimum strength, was considered.

The residual strength of core samples taken from fibre-reinforced concrete in comparison with samples not exposed to realistic fire experiments (tested under “laboratory conditions” instead) showed greater losses in strength than described in the literature so far. This is explained by a damage of the concrete matrix because of fibre destruction and vapour transports in combination with thermal stresses occurring in large-scale specimens. Measurements performed by means of accelerometers on selected specimens showed that cracks and microcracks were continuously occurring during the fire experiments.

Monostrands

Placed in fibre-reinforced concrete with sufficient concrete cover, monostrands resist to temperature curves such as during tunnel fires for approximately 30 minutes without being damaged. At temperatures according to ISO 834 (standard fire) monostrands are well protected in the dry normal-strength concrete when the concrete cover is chosen corresponding to the respective standards. However, the corrosion protection loses its effectiveness at temperatures exceeding 100°C.

Dimensioning

Numerical analyses of tunnel structures (e.g. cut-and-cover tunnel structures) were performed in the frame of the present research project. Analyses regarding the load-bearing capacity of a tunnel structure during a tunnel fire and determination of the residual load-bearing capacity after the fire were performed on the basis of the temperature distribution curves resulting from the experiments conducted within this research project. The material parameters and the temperature were determined in layers and inserted in form of elements in a model so that consequently by means of a beam element analysis the restrained internal forces could be determined on the basis of the temperature penetration rate.

14. Outlook (p. 188)

The following items regarding plain and PP-fibre-reinforced concrete require further research:

- Mode of action of PP-fibres in case of fire
- Durability
- Workability
- Temperature penetration in moist fibre-reinforced concretes
- Properties of fibre-reinforced concrete under exposure to high temperatures and under physical, chemical and mechanical loads
- Limit values regarding moisture contents with respect to spalling
- Consideration of the stiffness of the reinforced concrete construction under fire load in beam element analyses.