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Sprayable fire-protective layers in traffic tunnels

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ABSTRACT: Fires in tunnels are characterized by a rapid increase in temperature with maximum temperatures rising up to 1300 degrees Celsius. Thermal stresses, material deterioration and explosive spalling may reduce the load bearing capacity of a tunnel lining. For new tunnel constructions there are a number of measures that may be taken for coping with the load scenario resulting from such fire ingress. When it comes to rehabilitation of existing tunnels, the subsequent application of a protective layer is generally the only course available. Protective layers must safeguard the structure within defined time limits against excessive temperatures, but also withstand the rough tunnel environment and the alternating stresses of suction and pressure caused by passing traffic over long periods. Shotcrete with polypropylene micro-synthetic fibres (PP fibres) as well as sprayable lightweight mortars are successfully used as protective layers. Requirements, test results and recent applications in Austrian tunnels will be discussed.

1 INTRODUCTION

1.1 *Tunnel fires*

Fire disasters in traffic tunnels (Kusterle et al. 2004), such as the fires in the Storebælt Tunnel—1994, in the Euro Tunnel—1996, 2008, in the Mont Blanc Tunnel—1999, in the Tauern Tunnel—1999 and in the Gotthard Tunnel—2001, not only interrupted important European traffic connections for a long time but also severely damaged the concrete inner lining of these tunnels.

Goods transported through our tunnels by train and lorry may release energy at a rate of up to 300 MW when burning. These fires exceed temperature-time curves such as the ISO 834 standard fire. Most impressive is the fast temperature rise within a few minutes to more than 1000° Celsius (Figure 1).

Concrete does not burn, but ordinary concrete does not always handle fire very well. The high temperatures generated in hydrocarbon fuelled fires (gasoline or diesel fuel, cooking oils, animal fats, tyres, etc.) lead to a rapid temperature rise in close-to-surface layers, heat up pore-water and may quickly convert moisture in the concrete matrix into steam. Moisture in ordinary concrete is heated faster than it can migrate away from the heat source. As this process continues, the vapour pressure exceeds the concrete's tensile strength, and at this point, explosive spalling occurs (Tatnall, 2002).

Even if spalling does not reach deep parts of the structure, it will expose reinforcement directly to the effects of fire ingress at a very early stage, thus reducing the load-bearing capacity of the structure (Figure 2). Besides spalling, temperature penetration will reduce the strength of concrete and reinforcement and lead to restrained stresses in the structure.

1.2 *Influence of micro-synthetic PP fibres (ppf) on concrete exposed to fire*

PP fibres cannot protect concrete from thermal deterioration. However, in case of fire ingress micro-synthetic PP fibres intermixed into the concrete can have the following effects.

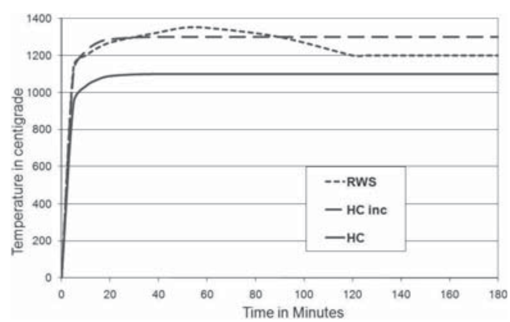

Figure 1. Temperature-time curves which have to be applied for testing and design according to OEVBB (2005), OEVBB (2006) in Austria (HC and HC increased for hydrocarbon fires with different duration, if detailed fire design is not performed, RWS (Rijkswaterstaat, a Dutch requirement) for proving fire resistance class BBG (fire resistant concrete tested in large scale test, "Beton erhöhter Brandbeständigkeit geprüft im Großversuch") and for protective layers).

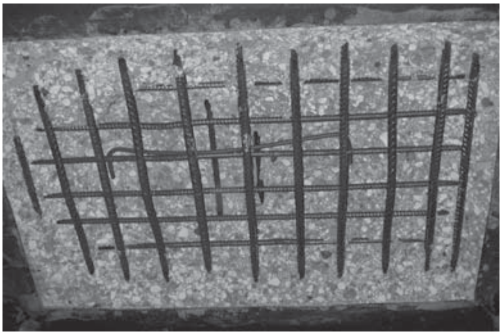

Figure 2. Reinforced concrete test panel after fire ingress showing heavy material loss due to spalling (Kusterle 2004).

PP fibres at normal dosage levels for FRC do not significantly change the thermal conductivity of concrete, but the addition of micro-synthetic fibres may lead to a cooling and pressure relief effect within moist concrete because of additional possibilities for the water vapour to escape (Kusterle et al. 2004; Waubke, 1973). It has been recognized that the temperature distribution within micro-synthetic fibre-reinforced high performance concrete depends on the micro-synthetic fibre content (Wille et al. 2003).

A sufficient volume of micro-synthetic PP fibres (and maybe other polymer fibres) can protect close-to-surface layers of concrete from explosive spalling (OEVBB, 2005). Persson (2006) states "In order to estimate the required amount of PP fibres (ppf) more than 300 tests over 20 years were evaluated to estimate the effect of the diameter of fibres, dimensions of the structure, moisture level, heating rate, loading level, reinforcement, relative humidity, surface mesh reinforcement, w/c, and so forth. These numerous test results and recommendations from fire resistance tests prove the function of ppf".

But the exact mechanism of the way microsynthetic fibres act is still unknown, even if many theories exist (see Section 2). This is a major drawback: as the working mechanism is unknown, the creation of a tailor-made fibre for this purpose is not possible at the moment. Note that the addition of fibres may also influence other fresh and hardened concrete properties.

2 EXPLOSIVE SPALLING

2.1 *Definition and reasons for explosive spalling*

Generally, the detaching of concrete fragments as a consequence of exposure to fire is defined as spalling. Three different kinds of spalling can be identified (Kordina & Meyer-Ottens, 1981, 1999):

- Explosive spalling of close-to-surface concrete layers,
- Sloughing off,
- Aggregate spalling.

In the following, only explosive spalling will be addressed as 'spalling', as the other two types of spalling do not have any practical importance. "Rapid heating is necessary for spalling of traditional concrete. The rapid heating gives rise to large temperature and moisture gradients in the fire-exposed parts" (Hertz, 2003). Water and water vapour in the pore system are the main reason for explosive spalling. But this is a dynamic system (Wetzig, 2000a), since the formation of water vapour takes place as a function of time, and part of the water vapour can escape via the pore structure that is present. Damage only occurs when more water vapour is formed in the matrix than can escape via the pore structure.

Fire spalling is therefore influenced, among other parameters, by:

- the moisture content of the concrete
- the porosity of the concrete (w/c, strength class) and
- the temperature gradient (heating rate),

and also by

- the mechanical stress level,
- the fibre content (steel or plastic fibres) and the mix design as well as the constitutive materials used (aggregates, fines…),
- the geometry and dimensions of the structure,
- the reinforcement layout and concrete cover.

2.2 *Common explanations*

Most authors agree that water is the main cause of spalling: "All other reasons mentioned may contribute to the effect of spalling, but cannot cause spalling without moisture" (Hertz, 2003). The moisture in the pore system and the physically and chemically bound water in the concrete evaporate at high temperatures, leading to an increase of vapour pressure in the concrete structure. After evaporation of water the vapour is advected towards the fire-exposed surface as well as into the concrete structure where it cools down and condenses. As a result, a quasi-saturated layer is formed which is quasi-impermeable for water vapour (also known as a "moisture clog", Kalifa et al. 2000, see Figure 3 from Schneider & Horvath, 2002). The magnitude of the stresses occurring essentially depends on the heating rate, 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

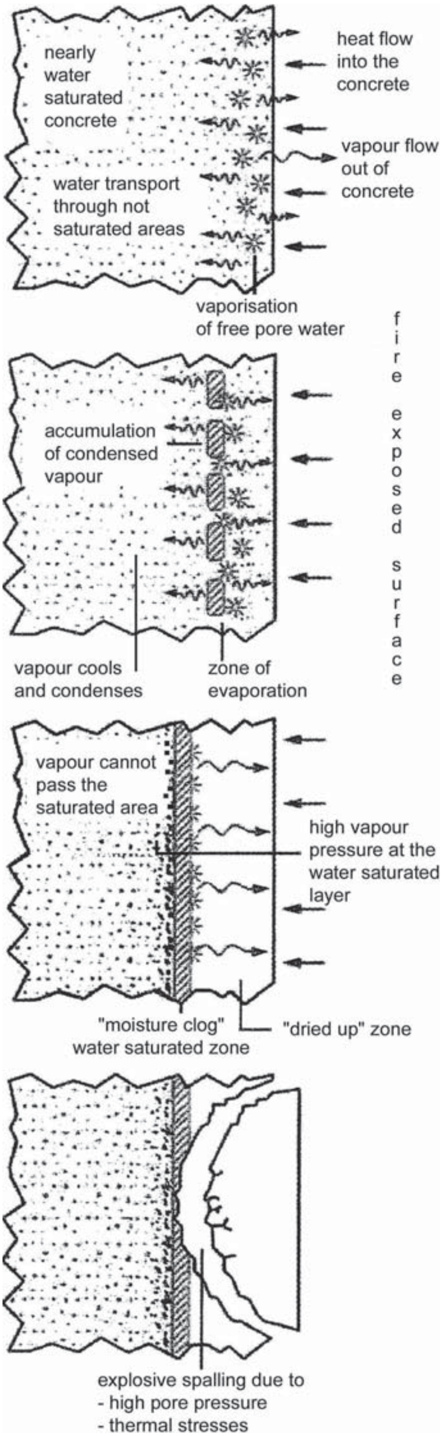

Figure 3. Schematic illustration of water vapour flow within a concrete structure heated from one side (Schneider & Horvath, 2002).

produced per unit of 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 the 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. Beyond this point a pore space cannot contain liquid and vapour at the same time, and pressure increases dramatically (Hertz 2003).

Sources of water in concrete are the evaporable water (e.g. physically bound water), dehydration (of non-evaporable water, e.g. calcium hydroxide and C-S-H), and dissociation (e.g. of calcium carbonate) taking place during the heating process. Accordingly, normal-strength concrete cannot spall at moisture contents lower than 2% or 3% by mass and below a certain moisture content no other possible causes can lead to spalling. Kordina & Meyer-Ottens (1981–1999) indicate a moisture content <2%. This value seems more reliable in the light of the results of a recent research project (Kusterle et al. 2004).

There are alternative theories explaining possible causes for spalling as a result of evaporation of water. 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 (Meyer-Ottens, 1972). According to Schneider et al. (2001) the tensile strength of normal strength concrete may be reached due to the increasing vapour pressure at temperatures of approximately 250°C. On the other hand, the fluid transport within the concrete is considered to cause tensile stresses leading to spalling. It is also explained (Florian, 2002) that the expansion of water during heating causes a pore pressure increase just before evaporation occurs. However, it is not stated whether this might cause explosive spalling.

According to Kalifa et al., "spalling results from two concomitant processes: the so-called thermo-mechanical process, associated with the thermal dilation/shrinkage gradients that occur within the element when heated, and the thermo-hydral process that generates high-pressure fields of gas (water vapour and enclosed air) in the porous network" (Kalifa et al. 2001).

2.3 *Other influencing factors on spalling reported in literature*

One additional factor that may encourage spalling is internal stress caused by the heterogeneity of concrete. The different thermal expansion coefficients α_T of a steel reinforcing bar and the concrete may lead to dissolution of bond and to cracks occurring around the reinforcing bar which consequently may favour spalling (Meyer-Ottens, 1972). According to Schneider & Horvath (2002) internal stresses may also occur within the concrete (hardened cement paste and aggregates). Internal stresses may also be caused by restrained dilation due to the specimen geometry. As a result of energy intrusion into the structure and the resulting heat penetration curve the expansion rate within the concrete structure varies with depth. Considering the condition of deformation compatibility this will lead to compressive stresses in the heated zones and to tensile stresses in the orthogonal direction to the direction of heat penetration. However, it has been claimed (Meyer-Ottens, 1972) that exceedance of compressive strength on the fire-exposed surface certainly does not lead to spalling. It is suggested (Ulm et al. 1999) that internal stresses, as described above, may promote spalling.

Restrained stresses can occur if dilation (e.g. due to great distances between movement joints) or free rotation of the structure (e.g. at the edges) is restrained, whereupon compressive stresses and tensile stresses may occur which consequently could favour spalling. The general stress condition on the structure can also play a role. High compressive stresses reduce the number of cracks occurring within the concrete structure and therefore reduce the possibility of the vapour escaping. As a consequence the spalling rate will increase.

Chemical processes within the concrete can lead to damage of concrete as has been frequently described in the literature, (e.g. Schneider & Horvath, 2002; Ulm et al. 1999; Wetzig, 2000b; Kalifa et al. 2001). Depending on the temperature of the concrete, minerals of the hardened cement paste or the aggregates are chemically transformed. A theoretical analysis regarding the possible causes for spalling is presented by Paliga (2003).

2.4 *Possible measures for preventing spalling*

Concrete has a very good fire resistance. The thermal conductivity of concrete structures is low, which means that a concrete member is only heated in the close-to-surface layers while the inner layers show only small temperature increases. In order to achieve further improvements, especially regarding the spalling behaviour, various measures have to be taken. In consequence of test results (Kusterle et al. 2004) several different ways of avoiding explosive spalling of close-to-surface concrete layers may be identified.

2.4.1 *Reduction of the temperature gradient*

A barrier (fire protective layer) is able to reduce the temperature penetration into the structure and to avoid explosive spalling by separating the structure from the fire. This barrier can be: (I) a plate-like protective layer (e.g. construction boards) mounted on the concrete surface or on underlying structures, or (II) fire protection mortar (sprayable lightweight mortar or micro-synthetic PP-fibre-reinforced shotcrete (Kusterle et al. 2006)) bonded to the concrete (Figure 4, for other materials see Section 3).

If fire protective layers are moist, they may also spall, an aspect not examined in many cases. Moreover, the performance of interface, which is influenced by compression and suction effects caused by traffic and by the dead weight of the protective layer, has to be considered. In the case of protective layers made of mortars, the fire load imposes stresses in the interface. Therefore, mesh reinforcements should be built in and anchored in the concrete. Moreover, long-term aspects of performance (e.g. moisture and frost resistance) and the difficulty of access to the construction for examination purposes should be considered. Fire protective layers will be addressed in detail in Section 3.

2.4.2 *Reduction of concrete moisture*

Assuming that the volume expansion of both liquid water and vapour is the main cause of explosive spalling, a reduction of the moisture content theoretically represents an effective protective measure.

2.4.3 *Providing expansion space*

In the 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 pores 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 of concrete has to be kept as low as possible. Therefore, as far as normal-strength concrete is concerned, the measure described above

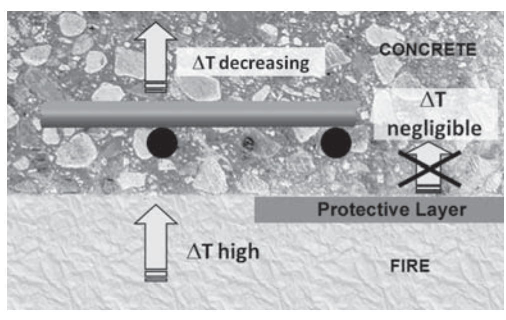

Figure 4. Reduction of the temperature gradient induced by fire to subcritical values by means of a protective layer.

is suitable for diminishing the existing vapour pressure only to a certain degree. Artificially entrained air bubbles provide a limited expansion space, which has been shown to be effective in case of volume expansion occurring as a consequence of frost. The usual air-pore content probably does not provide sufficient expansion space for vapour. Therefore, longitudinal pores are more suitable to serve as canals. However, they should serve as transport canals only in case of fire and prevent flow of air, water, and harmful substances under normal conditions. Research (e.g. Persson, 2006) has shown that micro-synthetic polymeric fibres (especially polypropylene fibres) possess these characteristics, even if the mechanism has not been clarified in detail up to now. They can be used in protective layers too.

2.4.4 *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). But this is only possible to a limited extent, e.g. by the addition of steel fibres.

2.4.5 *Reinforcement and reinforcement layout*

Thin mesh reinforcement protecting the main reinforcement has only a minimal influence on spalling behaviour. However, reinforcement bars 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 and the bars are anchored in deeper parts of the structure (Kusterle et al. 2004).

2.4.6 *Providing space for dilation*

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

3 PROTECTIVE LAYERS

Reducing the temperature gradient in the outer concrete layers (Section 2.3.1) is a very effective measure to protect concrete from spalling (Kusterle et al. 2006). According to EN 1992-1-2 (2007) protective layers are defined as "any material or combination of materials applied to a structural member for the purpose of increasing its fire resistance". Recently the following products have become available:

- plate-like protective layers (construction boards) mounted on the concrete surface or on underlying structures,
- fire protective lightweight mortar bonded to the concrete,
- PP-fibre-reinforced shotcrete bonded to the concrete (OEVBB Guideline for Shotcrete 2004),
- (coated, perforated steel sheets or enamelled steel sheets),
- (intumescent (self raising foaming) coatings).

The last two materials have not acquired any importance in tunnels due to operating requirements. Protective layers have to protect the structure from any detrimental temperature ingress for a specified time. But for the whole service life they have to withstand the rough tunnel environment and stresses from compression and suction effects caused by passing traffic. The operator of the tunnel requires access to the construction, a bright surface appearance and easy cleanability. For existing tunnels protective layers are the only way of upgrading the structure with regard to fire resistance.

3.1 *Catalogue of requirements*

Requirements on tunnel linings are different from those usually made for the application of protective layers in houses or industrial buildings. Therefore the same materials are rarely used for both purposes. The requirements may be subdivided into:

- fire resistance and insulation effects,
- bonding to the substrate, especially during suction,
- durability (especially due to water and frost action),
- accessibility to the main structure and visibility of new cracks in the structure,
- appearance and cleanability (mainly in road tunnels),
- costs of application and maintenance.

In this context the protective layer has to sustain fire temperatures of up to 1350° Celsius and keep the temperature at the interface to the substrate and at the first reinforcement below specified threshold values, which on the one hand should be lower than the critical temperature of steel and on the other hand should prohibit constraint stresses in the structure (Figure 5). If this is not possible a complete fire design of the structure (Wageneder, 2006) at a reduced temperature level will be necessary. The bond to the substrate is loaded by the dead weight of the layer as well as compression/suction effects caused by traffic. The suction will increase with the speed of passing traffic and decreasing cross section of the tunnel. These effects require considerable high cycle fatigue (vibration) resistance of the material (Biennemann & Girnau, 2005; ZTV-ING, 2003; DB NETZ, 2002; EN 14067-3, 2003; EN 14067-5, 2006).

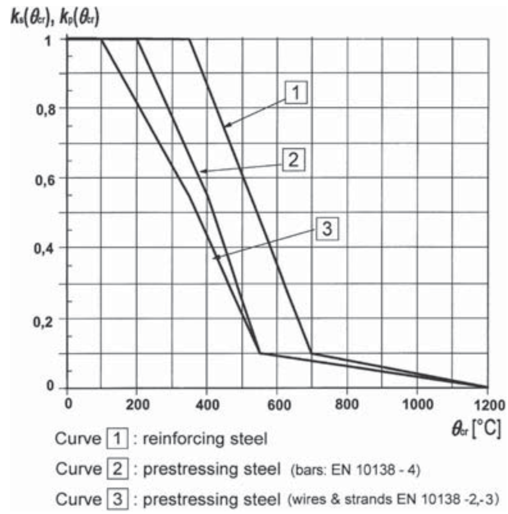

Figure 5. Reference curves for critical temperature of reinforcing steel θ_{cr} corresponding to the reduction factor $k_s(\theta_{cr}) = \sigma_{s,fi}/f_{yk}$ (20° Celsius) or $k_p(\theta_{cr}) = \sigma_{s,fi}/f_{pk}$ (20° Celsius) according to (EN 1992-1-2, Fig. 5.1, 2007), $\sigma_{s,fi}$ steel stress in fire situation.

Water and de-icing salts in road tunnels will be conveyed onto the tunnel walls as a result of splashing by heavy traffic. During the year the temperature of the tunnel lining will typically fall below dew point several times resulting in condensation. Water penetrates even through the tunnel lining if no special measures have been taken. Usually this should not result in drip formation (OEVBB, 2002; DAfStB, 2003). In many parts of the world frost attack will be possible in parts of the tunnel. This combined impact of water, frost or frost with de-icing salts should not reduce the lifecycle of the protective layer.

It is possible to replace protective layers after some years of service. But this should be avoided as far as possible due to the fact that our traffic tunnels need to operate to full capacity. In the references by Biennemann & Girnau (2005) and Haack (1994) it is suggested to replace protective layers 2 to 3 times over a 100 year service life. In Austria the specifications try to use only protective layers capable of 100 years of service life. One important advantage of protective layers is the possibility of replacing them easily after a fire disaster.

For the regular inspection of a tunnel for damage or changes in crack width it is beneficial to have a close look at the tunnel surface without any materials covering this surface. Especially for infrastructure which cannot be closed for inspection this work must be done in the most rapid way. Protective layers downgrade access to the structure. This can be resolved to some extent by "openings" in the protective layer and by proper inspection before application. Cement-based layers normally show cracks arising or widening in the substrate, as they are brittle too. Materials with a very low modulus of elasticity have to prove that underlying cracks will be visible on their surface.

3.2 *First experiences from preliminary tests*

In the course of a pre-qualification trial for a tunnel project in Austria (Tunnel Lainz), several protective layers were tested. Some of the constitutive materials and some properties are given below.

The binders used were cements according to EN 197-1 (2008) as well as high-alumina cement. As low thermal conductivity will result in thin layer thickness many protective layers are produced with lightweight aggregates or with air entraining agents (or binders or aggregates which release chemically bound water, when heated). Therefore normal aggregates, lightweight aggregates (shell sand, vermiculite, perlite, aluminosilicate hollow spheres and expanded glass granulate), or high temperature resistant aggregates (e.g. Olivine) are used. Ceramic fibres, cellulose fibres and glass fibres are used alone or combined with micro-synthetic PP fibres.

Mixtures incorporating such constitutive materials result in mortars with a bulk density of 420 kg/m³ up to 2200 kg/m³, resulting in a required layer thickness of 25 mm to 80 mm (when a maximum temperature at the interface of ≤350° Celsius and at the first reinforcement ≤250° Celsius is called for). In comparison the bulk density of plate-like protective layers is between 600 kg/m³ and 900 kg/m³, resulting in a layer thickness for use in tunnels of between 18 mm und 30 mm. Due to the very different bulk densities of the products the compressive strength of these layers may vary from 3 MPa up to the strength classes of normal concrete.

First fire tests were performed at maximum temperatures of 1200° Celsius or 1350° Celsius. Some products performed well at 1200° Celsius, while they started melting at 1350° Celsius (Figure 6).

Modifications of some products became necessary after having tested the protective layers subsequently to hosing with water. Even protective

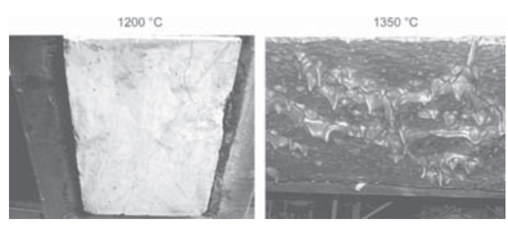

Figure 6. Example of a protective layer after a fire ingress of 1200 and 1350 degree Celsius.

layers can be damaged by explosive spalling under such conditions.

For overhead applications the owner required mesh reinforcement in addition to the bond of the material to the substrate. The use of reinforcement should help to avoid the formation of surface layers with inferior bonding that may loosen and endanger traffic passing by. The mesh should keep the protective layer in place until the next inspection.

For lightweight protective layers the mesh and the anchors have to be of stainless steel, for normal shotcrete ordinary reinforcement can be used. In any way it becomes clear that reinforcement and anchoring must be planned very carefully, as these are important safety and cost factors (Figure 7).

For inspection purposes it is essential to detect cracks and changes in cracks within the construction. Protective layers should not act as a crack bridging repair material. Tests were performed on slabs in bending (Figure 8). These tests demonstrated that cracks, which are in the substrate, are reflected on the shotcrete surface too, even if micro-synthetic PP fibres are used.

To achieve good thermal insulation many protective layers are based on mixes with high porosity (up to 60%). This often results in high water absorption (coefficient of water absorption 0.10 to 0.90 $kg/m^2\sqrt{h}$). If the layer is water-saturated, the risk of frost damage is very high. Up to now the degree of saturation of protective layers in tunnels is unknown.

Tests based on OENORM B 3303 (2002), without de-icing salt and with water on the tested surface (which is a very severe attack), showed frost damage material loss of up to 350 g/m^2 (the threshold value for concrete is usually 40 g/m^2). Frost resistance is therefore a hot topic regarding lightweight protective layers in central Europe. Frost resistance in combination with de-icing salts has not been tested yet in this research.

3.3 *Specifications in a technical bulletin of the Austrian Society for Concrete- and Construction Technology*

The bulletin "Protective layers for the improved fire resistance of underground constructions" published by the Austrian Society for Concrete and Construction Technology (OEVBB, 2006), has to be applied for all mortars and panels which are used as protective layers in underground constructions made of concrete in Austria.

The producer of the material has to declare the main constitutive materials, the manner of application, the layer construction and the necessary layer thickness. Grading, bulk density, tensile strength and water content serve as identification.

The fire test is performed on two large-scale test specimens measuring 1800 × 1400 × 500 mm (L × W × H) made from normal-strength concrete (Figure 9). The protective layers are applied on the centre part of one side of the panels. The RWS

Figure 7. Example of mesh reinforcement together with anchorage for overhead application of shotcrete (picture: Ruzicka).

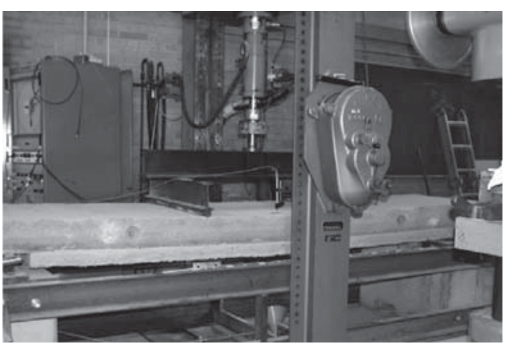

Figure 8. Bending test to demonstrate crack opening in protective layers (picture: Saxer).

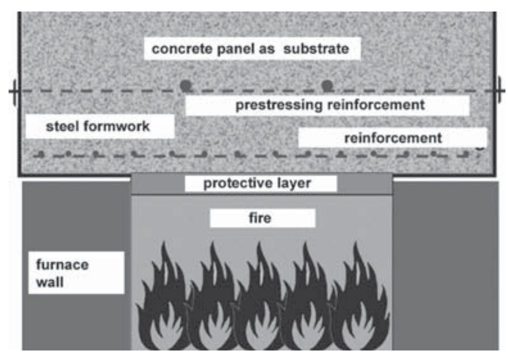

Figure 9. Cross section of a test specimen with protective layer on the oven.

time-temperature curve (Rijkswaterstaat) is used for the fire for 180 minutes (Tan, 1997). During the test it must be ensured that:

- the temperature at the interface to the concrete substrate does not exceed 350 degree Celsius,
- the temperature of the first layer of reinforcement in the concrete in 40 mm does not exceed 250 degree Celsius and
- no spalling occurs.

As there is no accepted testing procedure available for protective layers regarding their frost resistance, an existing testing procedure for concrete repair materials was used. The test for frost resistance with and without de-icing salts is always performed with de-icing salts using different threshold values. The test procedure follows the guideline "Maintenance and repair of structures made from concrete and reinforced concrete" ("Erhaltung und Instandsetzung von Bauten aus Beton und Stahlbeton") of the Austrian Society for Concrete- and Construction Technology (OEVBB 2003, Appendix 8, "Frost action with de-icing salts" ("Frost-Taumittel-Beanspruchung")).

The requirements for maximum allowable decrease in mass when damage takes place at the surface of the specimen after 56 cycles are summed up in Table 1.

The amount of lost material estimated as mass per testing area is calculated as volume loss using the bulk density of the material. Thereby it is possible to compare the results of protective layers with different densities. As the toughest testing procedure is selected for all exposure classes, the threshold values regarding material loss are much higher for the exposure classes XF 1 and XF 3. The advantage would be that all materials can be tested with the same procedure. Practice will show if this is a suitable way of testing. In any case this testing procedure cannot be applied for layers consisting of materials which do not follow the same deterioration processes as concrete and lightweight concrete (e.g. delamination, swelling, upraising of fibres). In this case other testing procedures have to be applied (e.g. Fagerlund, 1977; Brameshuber et al. 2005).

Table 1. Requirements for protective layers regarding frost resistance (Bulletin "Protective layers for the improved fire resistance of underground constructions" published by the Austrian Society for Concrete- and Construction Technology) The requirements differ by exposure classes according to EN 206-1 (2005). XF is an European exposure class for freeze/thaw attack, 4 standing for the most severe attack. For panels the last column does not apply.

Requirement category	Decrease in mass cm^3/m^2 after 56 frost-cycles[1]	Bond strength in comparison to 28 day value
XF 4	≤70	≥70%
XF 2	≤300	≥60%
XF 1 = XF 3	≤600	≥50%

[1] max. depth of material loss shall not exceed 1 mm (XF 2) or 4 mm (XF 1) and the loss in volume shall not increase with time ($V_{42\text{–}56\,FC} \leq V_{28\text{–}42\,FC}$).

XF 1 = XF 3 for road tunnels with coatings and all railway tunnels with frost attack.
XF 2 for road tunnels with coating near the portal.
XF 2 for road tunnels without coating with frost attack.
XF 4 for road tunnels without coating near the portal.

Table 2. Requirements regarding bond strength versus bulk density of the protective layer (bulletin "Protective layers for the improved fire resistance of underground constructions" published by the Austrian Society for Concrete and Construction Technology OEVBB (2006)).

Oven-dry density ρ in kg/m^3	Bond strength f_B in MPa
$\rho > 2000$	$f_B \geq 1.5$
$2000 > \rho > 1000$	linear reduced from 1.5 to 0.4
$1000 > \rho > 400$	linear reduced from 0.4 to 0.2
$\rho < 400$	$f_B \geq 0.2$

The application of barriers onto the substrate of an existing tunnel requires preparation of the surface, normally a roughness equal to more than 1 mm, and bond strength that may vary with the bulk density of the protective layer (Table 2). "When applying shotcrete or gunite or any other lightweight mortar, mesh reinforcement for all overhead applications is required besides the proven bond strength. This mesh, together with anchors, has to be designed in that way that all regular loads during the life time do not lead to a local breakdown of the layer" (OEVBB, 2006).

For this anchoring system the following requirements are essential (condensed text from OEVBB 2006):

- The anchors have to keep the layer in place together with the mesh reinforcement without using the bond of the layer itself. Loads resulting from the dead weight of the layer and the maximal forces from suction have to be taken into account. The anchors have to be approved for use with the specific substrate. The partial safety factor for the action is $\gamma_S = 1.5$, for the anchor the partial safety factor for resistance fixed in the approval for a single anchor must be chosen.
- Resistance against corrosion must be proven.

- The mesh reinforcement must be fixed force-locked to the anchors. The mesh should not vibrate when embedded by shotcrete. Drilling the anchor holes must not damage the substrate or embedded reinforcement.

Plate-like protective layers are in contrast subjected dynamically to alternating stresses of suction and pressure caused by passing traffic over long periods. Their fastening to the lining must take the fatigue of the anchors into account.

The detection of cracks in the protective layer due to cracks in the substrate is carried out by flexural bending tests on two panels measuring 3.60 m × 0.80 m × 0.6 m, made from concrete C 25/30. Previous to the application of the protective layer both panels are cracked to 0.5 mm crack width by four-point loading. The cracks are marked and the panels unloaded. At the age of 28 days the protective layer (mortar or shotcrete) is applied together with the mesh reinforcement and anchorage with a length of 2.8 m between the supports. The shotcrete is cured and stored for a further 28 days. Then the bonded panel is tested and checked for deformation in a flexural bending test using a span of 3.0 m. The crack formation versus deflection in the substrate panel and the protective layer is observed continuously.

It must be demonstrated that a crack opening or crack widening of $\Delta w > 0.5$ mm in the panel leads to visible cracks at the surface of the protective layer. For cement mortars and shotcrete with bulk density of $\rho > 1000$ kg/m³ and bond strength >0.4 MPa no test is required, as the preliminary tests clearly demonstrated a positive result. For mineral mortars with a bulk density between 300 and 1000 kg/m³ specific agreements are suggested. Quality assurance matters together with the required tests are also addressed in detail in this bulletin.

3.4 *Availability and cost structure*

Sprayable protective layers are supplied by the producers of fire protection systems as well as premix producers and as polypropylene-fibre-reinforced shotcrete by ready-mix concrete plants. The application is performed by companies active in fire protection, but also by construction companies specializing in concrete repair work. The cost consists of the following elements:

- Substrate preparation,
- Mesh reinforcement and anchorage,
- Material and application,
- Site set-up and scaffolding.

As application in tunnels is quite new, only estimated costs can be given. Substrate preparation, depending on the site situation, without site set-up costs for undamaged concrete, is in the range 8 €/m² to 12 €/m². Lightweight gunite or polypropylene fibre reinforced shotcrete applied to the required thickness may be estimated vertically applied at between 90 €/m² and 120 €/m²; overhead application will raise the cost to 100 €/m² to 140 €/m² (Kusterle et al. 2006; Kusterle & Vogl, 2008) including application, reinforcement and anchors. Plate-like protective layers (construction boards) are provided by a limited number of companies. Costs are comprised of:

- Construction boards
- Anchorage
- Site set-up and scaffolding.

Evenness of substrate surface, orientation and structuring as well as required tolerances at joints will influence the costs. For the board 50–70 €/m² will have to be spent, depending on the type and thickness. For anchors 15–20 €/m² and for attachment about 45 €/m² have to be calculated. Site set-up and scaffolding may vary depending on the project.

4 APPLICATION OF PP- FIBRE-REINFORCED SHOTCRETE AS A PASSIVE PROTECTIVE LAYER IN THE TUNNEL LAINZ

4.1 *Project Tunnel Lainz*

The Tunnel Lainz is part of the new railway “entrance” to Vienna from the west. The part of the tunnel addressed here (LT22-LT25), was built using the cut-and-cover method (Vogl et al. 2006, Vogl 2007, Kusterle & Vogl, 2008).

The line passes built-up areas, crossing streets and rivers. An existing line is partly situated on top of the planned tunnel. Therefore an adequate passive fire protection of the structure is essential. In 2004 the Austrian Railway authorities (HL-AG, ÖBB-Infrastruktur Bau AG since 2005) issued an invitation to tender for covering the existing concrete structure with fire protective layers. The length of the tunnel concerned was about 1800 m, the total area about 43,000 m². Construction boards were applied in an area of 13,000 m², but most of the work was done with polypropylene-fibre-reinforced shotcrete.

Most of the shotcrete (about 23,000 m²) was applied in the LT23 section, where the tunnel has a span of 24 m and a height of 12 m. The slab beams in this area have a hammer-head cross-section, which made the application more difficult (Figure 10). To meet this challenge a specially developed control system was needed for the robot which was used for the spraying application.

Figure 10. Crossover in the Tunnel Lainz, LT 23, Austrian railways (picture: Vogl).

4.2 *Substrate preparation*

The preparation of the substrate prior to the shotcrete application was done by high pressure water jet at 2500 bar from special scaffolding. A bond strength of ≥1.5 MPa and a roughness equivalent of ≥1.0 mm had to be achieved.

4.3 *Polypropylene-fibre-reinforced shotcrete*

The tender for the application of protective layers was the first for such a tunnel in Austria. The use of lightweight mortars was possible as well as the use of shotcrete with polypropylene fibres. Both had to meet tough requirements regarding frost action (the bulletin of the OEVBB (2006) was not published then, resulting in somewhat different requirements). Lightweight protective layers were not able to fulfil the requirements in the short term.

Therefore shotcrete with a layer thickness of 80 mm was envisaged for most of the work. Only the ceiling between the beams was covered to a thickness of 60 mm. If a lightweight mortar could have been used the thickness could have been reduced to 40 mm.

For safety reasons a mesh reinforcement was included as part of the protective layer. Due to dead weight and suction, together with the safety factor, loads of 8.0 kN/m^2 must be carried. Anchors tested for use in cracked concrete had to be used. When drilling the anchor holes it was not permitted to damage the existing reinforcement. The anchors should only be loaded by tension loads. Even the connection between anchor and mesh had to be designed for the applied load. Approval was received following the performance of special tests on the individual members and an enhanced testing programme.

The fibre-reinforced shotcrete complied with the Austrian class FRSpC 20/25/III/BB2G/HZ1,5 (Novimontan produced by Schretter & Cie, strength class 20/25, class III for permanent use, fire resistance class BB2G, bond strength >1.5 MPa). Polypropylene fibres with a diameter of 18 µm and 6 mm length were used at a dosage of 2.0 kg/m^3. The fibre had been tested according to the Guideline for Fibre Reinforced Concrete by the Austrian Society for Concrete and Construction Technology using an RWS fire (OEVBB, 2008). This product was chosen after several trials with reference to the throughput, surface appearance and application by robot. The dry-mix process was used. A control-chamber shotcrete machine was used as a shotcrete gun. About 20 to 30 tonnes of dry mix were sprayed during one shift. Compressive strength reached 31 MPa. Water penetration tested in accordance with Austrian standard B 3303 (OENORM, 2002) was 25 mm. Testing bond strength was somewhat difficult, as the layer thickness was 60 to 70 mm and reinforcement was present in the layer and the substrate. The required 1.5 MPa could always be reached.

4.4 *Shotcrete robot*

When preparing this work it became clear that the process had to be automated in some way. For an automated shotcrete application a robot was the first choice. Smooth surface, constant cross sections, high shotcrete throughput and uniform quality were the crucial factors. Advantages in the construction sequence and good experience with the automation of high water pressure jet processes for concrete demolition were other decisive factors.

The catalogue of requirements was only met by one robot from MEYCO, Type Logica 15. This system allows scanning of the substrate by a laser and subsequent fully automated application of the shotcrete. Overriding the process is possible.

In cooperation with the producer of the system a full scale model of the hammer-head beams was set up in the producers' premises. This model was used to test the software and optimize the rows and row gaps followed by the nozzle. The scaffolding was designed following the robot producer's requirements to provide a rigid platform. A stiff platform was necessary to achieve exact rows of sprayed concrete (Vogl et al. 2006).

The main problem was to find a way of spraying the hammer-head beams with the robot using an automated process. Due to the geometry of the cross section, the operation of the laser scanner was limited. Therefore this method became uneconomical. For use with the Logica system the robot was upgraded by angle and distance sensors. With eight degrees of freedom, the robot can be used in manual, semi-automatic or fully automatic mode.

For this special application a programme was adapted which is similar to the software used with machine tools. The starting point of the control system was the exact dimensions of the application areas and the correlating angles. The starting point, angularity, and nozzle distance as well as kinematics have to be defined on the laptop using this software. In the course of trial applications the nozzle feed rate, the shotcrete throughput and the nozzle oscillation had to be adjusted for final optimization of the shotcrete (Figure 11).

When shotcreting in the automatic mode the nozzle head moves in rows with a constant speed over the receiving substrate. By adjusting the speed and row gap the required layer thickness is achieved. Other parameters influencing the layer thickness, such as throughput, nozzle distance and nozzle oscillation, are presumed to be constant. The application is done automatically in the area of the scanned 3-dimensional grid, by measuring the distance from the laser head to the receiving surface. Using the remote control, it is possible to override the automatic spraying at any time. Following use of the manual mode the process will continue automatically.

4.5 *Experiences from this application*

For the job at the Tunnel Lainz LT22-LT25 the 30,000 m² of PP-fibre-reinforced shotcrete application was successfully realized between July 2005 and September 2006. Different problems had to be solved when applying PP-fibre-reinforced shotcrete for the first time (Vogl, 2007). The problems were intensified by the short construction time, the limited space and the complicated geometry of most of the receiving substrate. PP-fibre-reinforced dry mix shotcrete proved to be difficult to handle. The following problems occurred:

Figure 11. Shotcrete application at the hammer-head beams in the Tunnel Lainz, LT 23, Austrian railways (picture: Vogl).

- Blocking of the dry mix when filling the silos,
- increased wear and tear of equipment,
- reduction in throughput by more than 50%,
- hampered working conditions,
- damage of equipment due to blocked filter and intake by fibres (Vogl, 2007).

As this was the first application of this type of protective layer, a dense control and test programme was necessary. The use of PP microfibres resulted in adaptations in the production process, especially the silo, the shotcrete gun and the application. Due to the close cooperation of all the people involved, the final result was nearly perfect. Regarding durability and quality, use of a micro-synthetic PP-fibre-reinforced shotcrete as a fire protective layer is in the contractor's view the optimum solution. But there is still quite a big potential for improvements. In future the wet mix process will be favoured, as less fibres will be lost in the overspray with this method. In recent years the following areas of tunnel linings have been covered by protective layers in Austria:

- PP-fibre-reinforced shotcrete 63,000 m²,
- lightweight mortar about 20,000 m²,
- construction boards 220,000 m².

In the same period 38 km of new tunnels were built using micro-synthetic PP-fibre-reinforced inner linings in Austria.

5 SUMMARY

Currently the following advantages may be listed for the use of sprayable protective layers (PP-fibre-reinforced shotcrete, sprayable lightweight mortars) in comparison to other measures (e.g. micro-synthetic PP-fibre-reinforced concrete inner lining).

The advantages include: thermal isolation of the structure; excellent fire protection, which can be tailored by adapting the layer thickness; longer fire resistance than with other possible methods; application on any geometrical form of receiving surface; excellent durability in the case of PP-fibre-reinforced shotcrete; fast and easy rehabilitation subsequent to a fire disaster; no special concrete or reinforcement necessary for the tunnel lining; existing tunnels with durability problems can be upgraded by increasing concrete cover (this additional value requires a dense normal weight shotcrete); simple bond Quality Control by knocking with a hammer on the surface and by mapping cracks. The disadvantages include: for lightweight mortars it is difficult to prove the same durability as concrete inner linings; no direct access to the structure; profile reduction; surface treatment and anchoring is time-consuming and costly; complex site set-up and high cleaning expense.

Plate-like protective layers (construction boards) differ in the following aspects from sprayed products: generally they need no substrate preparation except local deburring; dry, mortarless construction without any overspray from shotcrete work; boards are easily replaced if local damage occurs; smooth surface of prefabricated boards but curvature of the tunnel, keeping straight joints within small tolerances and inspection openings as well as mounting parts increase application costs; high cycle fatigue strength requirements coming from alternating stresses due to suction and pressure lead to a closer pattern of anchorage then in housing; cracks and defects are hidden for a long time.

6 CONCLUSION

Due to recent fire disasters passive fire protection in traffic tunnels is a hot topic. One of the possible measures for improving fire resistance, especially reducing explosive spalling, is the application of protective layers which thermally isolate the structure from fire ingress. The bulletin "Protective layers for the improved fire resistance of underground constructions" published by the Austrian Society for Concrete and Construction Technology gives for the first time guidance regarding the application of protective layers. Shotcrete reinforced by polypropylene microfibres is an excellent material for this purpose. The first lightweight sprayable mortars are also available for tunnel application. But frost and durability aspects are still under development for this type of material. Their superior insulation properties result in thinner layers than for shotcrete.

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