Corrosivity of road tunnel microclimate

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Summary

The development of modern transport infrastructure, transport systems and vehicles belongs between fundaments of competitiveness. During last years the quickly degradation and service life decreasing of materials and surface treatments applied in tunnels occur. In frame of the European Tunnel Assessment Programme (EuroTAP) 150 tunnels in 14 European countries had been checked during 2005 to 2007. The conditions of 25 tunnels had been classified as „poor“ or „very poor“.

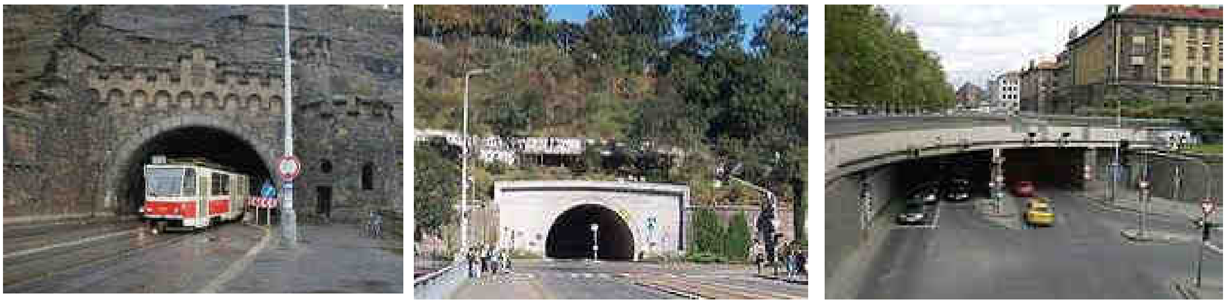
The road tunnel environment has its specific corrosivity due to climatic factors and extreme high air pollution from traffic. In tunnels there are exposed large number of materials including metals (painted steel, galvanized steel, stainless steel, copper, silver, aluminium, etc.) and their durability is affected by these specific conditions. There were evaluated corrosion attack of exposed material in two road tunnels in Prague after short-term service (Lochkov – 0.5, 1.0 and 1.5 years) and long-term service (Mrazovka – 6 and 7 years). The basis for choice and verification of materials and surface corrosion treatments long-term exposed to atmospheric environment is degree of corrosivity.

Key words: material degradation, corrosion protection, air pollution, traffic infrastructure, traffic emission

1 Introduction

Increasingly, road designers select tunnels as a good alternative, considering the ability of road tunnels to reduce some components of the environmental impact such as visual intrusion of infrastructures and noise pollution. Nevertheless some impacts remain or are even increased by such a choice. Road traffic and (consequently) vehicle emissions constitute a serious environmental concern particularly in confined spaces as tunnels. These emissions are characterized by the presence of various pollutants, which, at high concentrations, can cause adverse effects and consequences.

In the Czech Republic short road tunnels (24 to 40 m) had been sporadically built during 20th century, e.g. Vysehrad tunnel (1904, 35 m), Sec and Kokorin tunnels in 30ties. After 1945 year 2 road tunnels had been built on urban rings in Prague: Letná tunnel (1953, 423 m) and Tesnov tunnel (1980, 350 m). Since 1990 the number of road tunnels significantly increased together with their length. New 15 tunnels had been built on highways or urban rings (Prague, Brno, Ostrava) with length from 260 to 2116 m. Other 7 tunnels are in construction.



Vysehrad tunnel Letná tunnel Tesnov tunnel

Figure 1: The oldest Prague tunnels

Figure 2: Location of Prague tunnels

The increase in automobile tunnels is particularly evident from the fact that by 1996, reaching the length of the road network in the Czech Republic less than 1 000 m in 2008 however, the total length of automobile tunnels more than 11 km, being the tunnels that carry significant traffic volumes. In 2011 there were 27 road tunnels with total length 19 331 m in the Czech Republic including 14 tunnels with length 15574 on highways.

According to national requirements of RSD (Road and Motorway Directorate of the Czech Republic) the materials and surface corrosion protective treatment of metallic materials used in tunnel construction is tested according to EN ISO 12944-6 for corrosivity category C4. Even if the materials and protective systems past the tests, their durability in tunnel´s microclimate is significantly lower than suspected.

1 Material deterioration in road tunnels

Studies of materials´ degradation had been performed at France, Germany, Sweden, Switzerland and the UK [1 - 6]. These studies were focused mainly on stainless steels and copper.

The various metallic materials used in construction had been evaluated in detail in 3 road tunnels in the Czech Republic – Table 1.

Table 1: Tunnels and materials included in the study

tunnel	built	length (m)	trafic intensity	exposed materials
Mrazovka Klimkovice Lochkov	2004 2008 2011	1260 1088 1658	50 000 19 200 78 000	stainless steels, painted carbon steel, galvanized steel, aluminium, contact metals

The most intensive corrosion attack of materials used in tunnel construction is evaluated for stainless steels X5CrNi18-10 and X5CsNiMo17-12-2. These materials are used for SOS boxes, exit doors and various supporting constructions including fixing materials - screws and nuts (Fig. 3). The first sight of pitting corrosion was evident on stainless steel surfaces after 0.5 year of service (1 winter season) in Lochkov tunnel. After 1.5 years of service the critical attack was found on door surface in the 140 m distance from enter to tube (the higher chloride deposition) – Fig. 4d. The corrosion attack was more intensive on the other surface too in comparison to 0.5 year service evaluation.

SOS box | exit door | supporting construction

Figure 3: The examples of stainless steel application in the tunnel

There are used elements or products from galvanized steel for some application (Fig. 5); sometimes they are used as sublayer for duplex surface treatment. The intensive corrosion of galvanised steel, resp. duplex system, was found after 1.5 years in Lochkov tunnel. After 7 years of exposure the intensive corrosion of zinc coating was found (Mrazovka tunnel, Prague) – Fig. 5. There were found stainless steel screws on galvanized steel elements which create the conditions for galvanic corrosion.

The aluminium is used only in minor cases but its corrosion attack is very intensive (Fig. 6). There were found contact of aluminium and galvanized steel elements which create the conditions for galvanic corrosion. The corrosion of other metaling material or coating was found after short exposure too.

The failure of organic coatings applied on carbon steel, cast iron and galvanised steel surfaces/elements started after 0.5 years of exposure as corrosion of substrate metals on edges of elements and continue by blistering, filliform corrosion and peeling off after 1.5 years of exposure to massive rusting after 6 years of exposure (Fig. 7). The type and intensity of failure depends on type of coating and exposure conditions (location of exposure).

0.5 year | 1.5 years | 6 – 7 years

Figure 4: The details of stainless steel corrosion in the tunnels

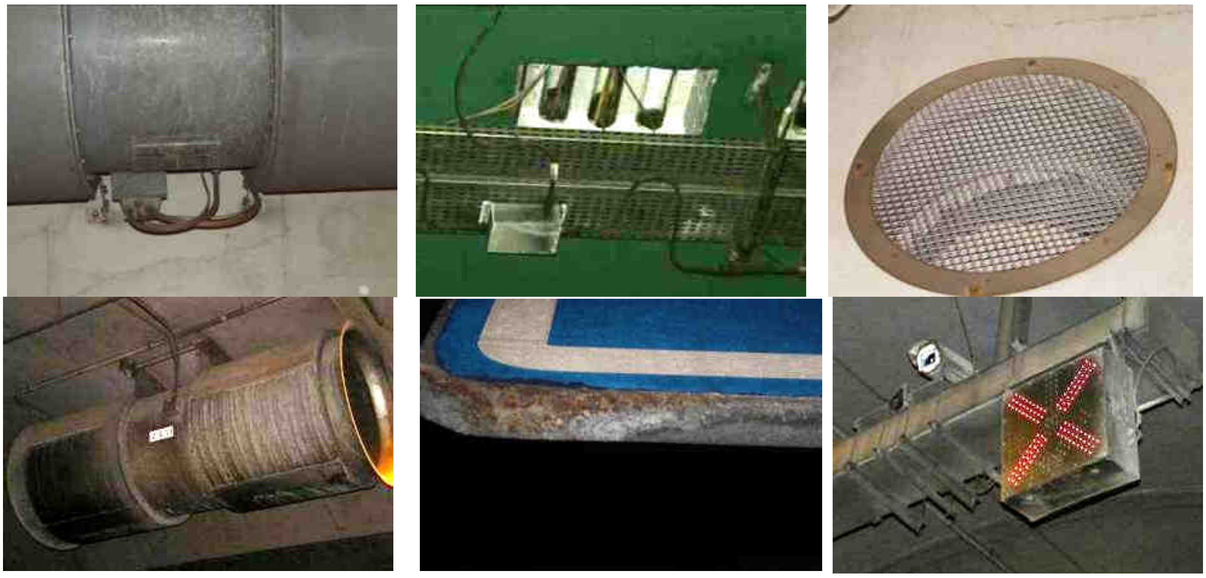


Figure 5: The examples of zinc coatings´ corrosion on the tunnel equipments after 1.5 years (above) and 7 years of exposure in tunnels

1.0 year 1.5 years 6 years

Figure 7: The examples of aluminium corrosion in the tunnels

0.5 year 1.5 years 6 years

Figure 8: The examples of coating failure

The total failure of cameras is reported in other highway tunnels in the Czech Republic after 2 years of exposure. Also they are corrosion problems with fixing of ligthening system on the tunnel celings – in few cases they are felt down.

2 Tunnel microclimate measurement and corrosivity estimation

The corrosivity in road Mrazovka tunnel, Prague is determined by environmental factors (climatic parameters, air pollution, particle´s deposition), corrosion resistance sensors (Fe, Cu, Ag) and according to corrosion loss of standard metal coupon (carbon steel, zinc, copper, aluminium).

The field study in tunnel started in 07/2011. The Mrazovka tunnel comprises two unidirectional tunnel tubes, each with a triple-lane profile, two-lane and single-lane sections, bifurcation chambers, 5 cross passages, a cavern for a transformer station and a cavern for ventilation plant, which is connected to a ventilation shaft. The tunnel is roughly 1.300 m long; the total length of the mined sections is about 2.200 m. The measuring locality in Mrazovka tunnel is in the west, slope down tube, approx. in 2/3 distance from enter to the tunnel (Fig. 9).

The climate data are continually measured in 1 hour intervals during whole exposure period. The survey of climate data is given in Table 2. Time of wetness (TOW) was calculated according ISO EN 9223 as a time when temperature is above 0℃ and relative humidity is above 80 %. During 14 freezing days in February 2012 the temperature below zero was measured for whole this period even inside the tunnel environment.

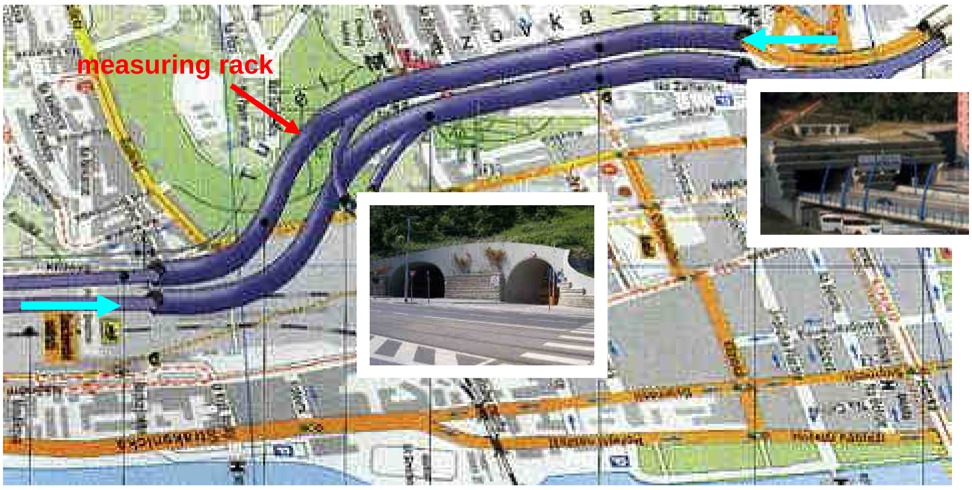


Figure 9: Mrazovka tunnel and measuring rack location

Table 2: Climatic parameters measured in road Mrazovka tunnel, Prague (period 07/2011-05/2012)

monthly values	T (°C)	RH (%)	TOW (hrs)
range	-11.4 to 24.3	22 to 100	33 to 384
average	6.1	67	141

Two approaches were chosen for tunnel microclimate pollution measurements. SO_2 and NO_x air pollution and chloride deposition in tunnel were measured by passive samplers in month intervals within the long term period. Other gaseous pollutants (O_3, NO_2, NO, CO, CO_2, H_2S) including also NO_x and SO_2 were measured in one week measuring campaigns in each year season using compact multi gas air quality monitoring system Airpointer (Recordum Messtechnik GmbH, Austria) in one minute intervals in continuous mode (Fig. 10). Particulate matter (TSP, PM_{10} and $PM_{2.5.}$) concentrations were also measured within these one week campaigns using Leckel MVS6 middle volume samplers (Sven Leckel Ingenierbüro, Germany). Results of passive sampling are summarized in Table 3 and data from winter active sampling campaign are shown in Table 4. The data show high concentration of H_2S, NO_x and chloride deposition. The average chloride deposition was ca 35 $mg.m^{-2}.d^{-1}$ in non-winter season, but during winter months the average chloride deposition was ca 200 $mg.m^{-2}.d^{-1}$. The SO_2 concentration measured by both methods are corresponding, but NO_x measured by active sampling were significantly higher (797 $\mu g.m^{-3}$). The NO represents 56 % of NO_x. High concentrations of suspended particles (TSP) were measured (555.9 µg.m^{-3}) with the dominant share of coarse particles larger than 10 µm (71 %). These particles probably originate due to resuspension of road dust or by abrasion of pavement or tires. Particles emitted from vehicles engines (usually smaller than 2.5 µm) represent only 13 % of total suspended particles. In period 12/2011 – 01/2012 the gaseous HNO_3 concentration was measured by passive samples by IVL, Sweden – the monthly average value was 0,05 µg.m^{-3}.

Table 3: Air pollution measured by passive samplers in road Mrazovka tunnel, (period 07/2011-05/2012)

monthly values	SO_2 (µg.m^{-3})	NO_x (µg.m^{-3})	Cl^- (mg.m^{-2}.d^{-1})
range	6.1 – 22.2	106.4 – 397.8	26.1 – 338.3
average	8.9	193.7	139.2

Table 4: Results of active air pollution measurement in the period 6.-13.12.2011

pollutant	TSP	PM_{10}	$PM_{2.5}$	NO	NO_2	NO_x	CO	CO_2	O_3	SO_2	H_2S
	[µg.m^{-3}]							[mg.m^{-3}]	[µg.m^{-3}]		
range	270.2 856.7	82.9 226.6	45.2 113.0	3.1 1469.6	3.5 336.5	22.4 2434.4	0.1 9.1	2.1 654.8	0.4 26.2	0.2 14.6	0.01 8.6
average	555.9	164.0	73.3	447.2	140.8	796.5	1.9	346.8	6.1	6.8	4.1

Figure 10: Location of field exposure and active sampling of air pollution in Mrazovka tunnel

On rack there are exposed the corrosion coupons of stainless steels X5CrNi18-10 and X5CsNiMo17-12-2, carbon steel, copper, aluminium, zinc and silver, too (Fig. 11). These metals represent the most exposed materials found for tunnel infrastructure (see above). The silver coupons are made as electrodeposited coating on copper substrate. The corrosion attack was visually evaluated in monthly intervals and corrosion mass loss will be estimated after 1 year exposure.

The resistance sensors of iron, copper and silver were exposed too, but the aggressivity of tunnel environment was so high they failured very quickly:

- resistance sensor Fe failured after 2 months and had been replaced (details of surface see Fig. 13a); the second resiatnce sensor failured after 4 months;

- resistance sensor Cu failured after 4 months and had been replaced (details of surface see Fig. 13b); the second resitance sensor failured after 2 months;
- resistance sensor Ag failured after 9 months.

Figure 11: Rack with passive samplers and exposed metal coupons, resistive sensors and PCB with SMD attachements

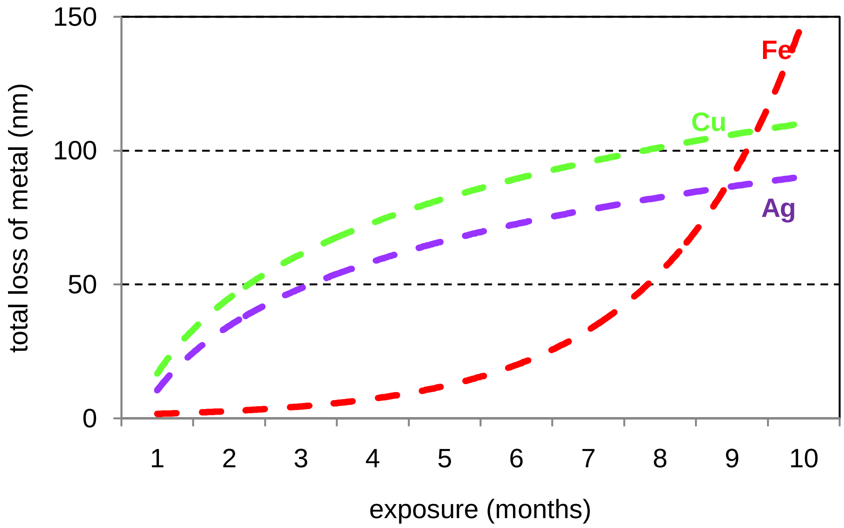


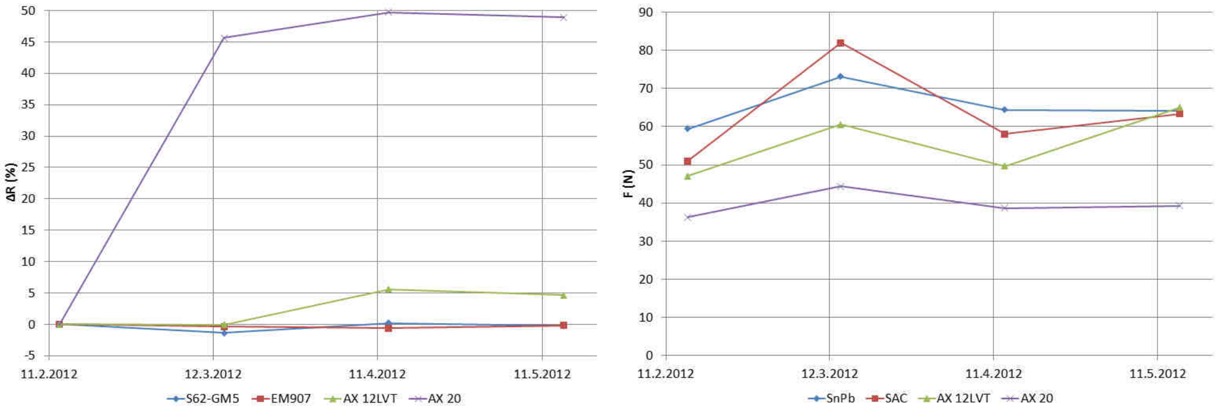
Figure 12: Corrosion loss measured by resistance sensors

The results of measurement are given on Figure 12. According to ISA Standard S71.04 reactivity monitoring the tunnel environment can be classified as class C3 for copper (moderate) – corrosion loss average value was 223 Å/30 days, but during some most corrosivite months even to C4 (harsh) – 335 Å/30 days. The class S3 was estimated for silver (moderate) - corrosion loss average value was 114 Å/30 days and 170 Å/30 days during some most corrosivite months.

In 02/2012 the samples of 2 types of soldered joints and 2 types of electrically conductive adhesives were exposed (see Fig. 11b):

- sample 1 – solder S62-325GM5 (traditional Sn62Pb36Ag2 solder),
- sample 2 – solder EM-907 (Sn96.5Ag3.0Cu0.5),
- sample 3 – one-component electrically conductive adhesive AX 20 (epoxy-phenolic hybrid type resin with silver flakes),
- sample 4 – two-component conductive adhesive AX 12LVT (phenolepoxy resin with silver flakes).

These samples are withdrawn in month intervals and the basic characteristics of their properties are measured (electrical resistance and shear-off strength test). After 2 months of exposure the electric resistance of metallic solders are without changes but for both adhesives shows decreasing of electric conductivity, especially one component conductive adhesive AX 20 – Fig. 13.



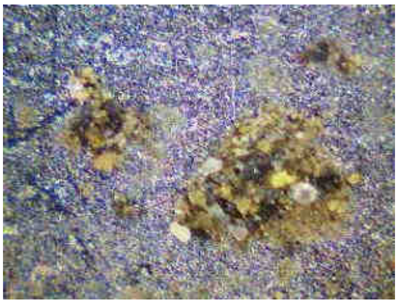
electrical resistance shear-off strength test

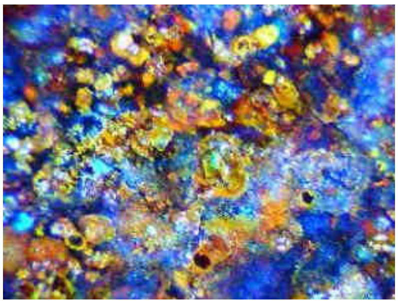
Figure 13: Corrosion loss measured by resistance sensors

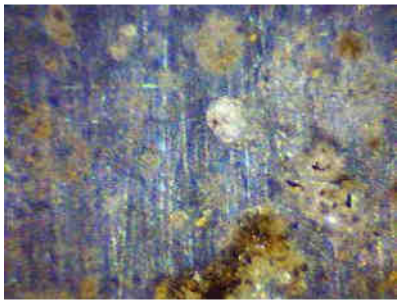
3 Analysis of corrosion products

The corrosion attack of exposed corrosion coupons is very intensive for all exposed metals. The surfaces of them are covered by deposition of different particles and corrosion products. The most intensive corrosion attack occurred on carbon steel, copper and zinc (Fig. 14).

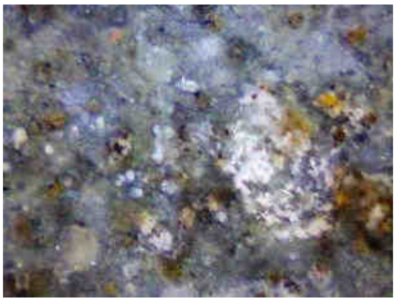
The corrosion product layer of carbon steel and copper is shown after 2 months, resp. 4 months of exposure. on Fig. 15. There are evident black carbon particles and particles of salt on the surface of metals. The chemical compositions of exposed metallic surfaces of carbon steel, copper and silver (exposed for 9 months) are given in Table 5. The analysis confims the effect of chloride onto corrosion attack of exposed metals. As the silver sensor had been exposed for 9 months the corosion products and deposits contain higher concentration of corrosion stimulators (Cl, S).


stainless steel 316


carbon steel


aluminium


copper


zinc

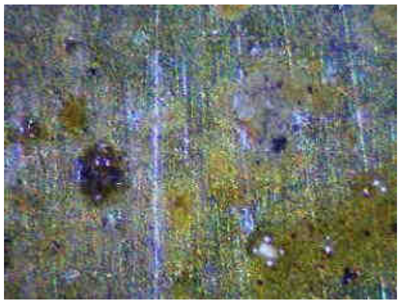

silver

Figure 14: Corrosion products and deposited particles on metal surfaces after 10 months exposure

Table 5: EDAX analysis of surface layers of failured resistance sensors

metal	element concentration (wgh. %)										
	Fe	Cu	Ag	O	Cl	S	Si	Al	N	Pb	Ni
iron	29,1	-	-	33,6	1,6	0,3	13,9	0,4	12,1	0,2	2,0
copper	0,4	15,2	-	44,9	3,8	0,5	4,3	1,0	13,5	0,2	0,5
silver	1,3	0,2	31,2	21,0	8,7	2,7	8,9	3,0	1,9	0,5	0,1


carbon steel, 2 months in tunnel

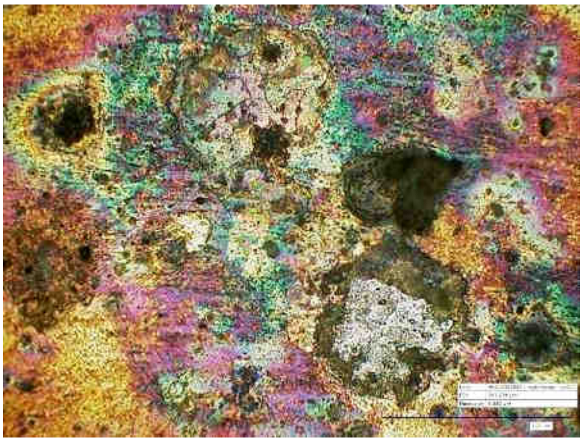

copper, 4 months in tunnel

Figure 15: Corrosion products and deposited particles on metal surface

Conclusion

The corrosivity category is a general term that describes the corrosion properties of atmospheres based on knowledge of atmospheric corrosion and may be used for prediction of metallic materials and surafce treatment durability and service life. The periodical assessment of damage of construction materials in tunnel microclimate proved its high corrosivity. High concentrations of pollutants important for corrosion processes e.g. NO_x, SO_2 and H_2S were measured in tunnel microclimate. Also high concentrations of particulate matter together with extremelly high chloride deposition measured within this study could negatively affect the service life of materials. Guiding values of corrosion rate of structural metals help to predict the service life of metals and protective systems in long-term exposures. The one year corrosion values for standard and others metals will give some first important data for this prediction.

Classification of pollutants in respect to corrosion of electronic materials are given in Table 6 - the limits are based on results from the Nordic research project, 1989. In case the combination of pollutants affects the environment the most concentrated pollutant is used for classification, so in the case of Mrazovka tunnel the category is P5.

Table 5: Classification of pollutants in respect to corrosion of electronic materials

category	Pollutants ($\mu g.m^{-3}$)				
	SO_2	NO_2	H_2S	Cl^-	TSP
P1	< 10	< 25	< 3	< 1	< 2
P2	10 - 30	25 - 150	3 - 10 [1] 3 - 20 [2]	1 - 5	2 - 20
P3	30 – 100	150 – 500	10 - 50 [1] 20 - 100 [2]	5 – 10	20 – 75
P4	100 - 300	500 - 1000	50 - 100 [1] 100 – 200 [2]	10 - 50	75 - 150
P5	> 300	> 1000	> 100 [1] > 200 [2]	> 50	> 150

Note: [1] limits if silver is used; [2] limits for other materials than silver

Many risk analyses for road tunnels have been worked out in previous years, a number of models have been established and a lot of literature has been written about the issue. A good overview can be found in the PIARC document [7] and Czech TP 229 [8]. Some of the applied programs are based on standard spreadsheet programs, which are not particularly useful for this type of application [9]. An example of a suitably applicable tool is TURAM [10], which is a sophisticated standardised program for the assessment of road tunnels which has been used for the assessment of many tunnels in Switzerland and Germany [11]. But all these risk assessments are focused on risk of collision and risk of fire, the risk of corrosion is not fully implemented in any of these documents. In current guidelines, there are no requirements for the quality assurance of safety equipment in road tunnels.

In the Czech Republic the TP 154 *Specifications - Operation, Administration and Maintenance of Road Tunnels* defines requirements for operation, administration and maintenance of road tunnels. Beside good technical design for a tunnel, also the tunnel's subsequent operation is of essential importance for safety of operation. Good or bad operation has an impact not only on the traffic attributes of the tunnel, but also on operational costs. The effect of corrosivity of tunnel microclimates on materials degradation and safety of operation are not included into this document, too.

Acknowledgements

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