MATEC Web of Conferences **122**, 02007 (2017) DOI: 10.1051/matecconf/201712202007
GAMBIT 2016

Identification and analysis of factors affecting the durability of steel road safety equipment

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Abstract. Factors affecting the durability and life of steel road safety equipment have been reviewed. Based on a literature review and own experience, the following factors have been identified: corrosion, mechanical damage and abrasion during usage and maintenance. Corrosion factors have the biggest impact. Preliminary studies on the annual corrosion losses of selected metals and atmospheric corrosion taking into account regional divisions and roadsides show that the current relations do not apply to immediate surroundings with air pollution emitted by road transport. More research is required on that matter. Local corrosion induced by mechanical damage (gravels, stones impacts) to protective coatings and its impact on steel road safety equipment's durability have also been highlighted.

1 Introduction

The precise description of physical and chemical processes responsible for the phenomenon known as atmospheric corrosion is difficult due to the complex nature of the environment in which the climatic parameters and pollution of the atmosphere change periodically in a chaotic manner with parallel and simultaneous chemical and photochemical reactions [1–3]. The rate of these reactions depends on the type and concentration of pollutants emitted by different anthropogenic or natural sources, the presence of catalysts, change of climatic conditions such as air temperature, humidity, pressure, sunshine, direction and speed of wind. Atmospheric corrosion is usually treated as an electrochemical process, since most of the reactions proceed in aqueous solution and more precisely under a thin film of moisture [4,5].

Understanding the environmental effects of corrosion on materials plays an essential role in technical and economic decisions relating to serviceability of steel road safety equipment. The durability and life of road barriers, poles, sign posts, road fencing or anti-glare screens and other structures is used to qualify the life time of road safety equipment including recommendations for maintenance or even cost analysis.

The data needed for the evaluation, forecasting and empirical description of atmospheric corrosion comes from corrosion monitoring which is defined as a method of constant observation, description and/or measure of the progress of corrosion. A form of standardized monitoring of atmospheric corrosion relies on the use of coupons made from steel, zinc, copper and aluminium exposed in selected areas. In connection with weather and air pollution data collected during annual or long-term exposure the corrosion loss of coupons is determined according to PN-EN ISO standards [6–10]. This helps to classify the corrosivity

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of the atmosphere in accordance with PN-EN ISO 9223:2012 standard. There are five main categories of corrosivity connected with corrosion losses of metals exposed to selected environments and ranging from C1 (very low) to C5 (very high) with low, intermediate and high grades in between. These numbers serve as a recommendation of thickness for zinc coating for galvanized steel or type and thickness of a protective system for paint coatings. They also provide a valuable set of reference data for use in modelling of corrosion rates using dose-response equations. Equations given in PN-EN ISO 9223:2012 have been verified and adapted to the area of Poland during research done at the Institute of Precision Mechanics. An application of the spatial visualization software helped to assess a spatial distribution of atmospheric pollution concentration and corrosion losses across the country. Examples are given at [www.ck]. As a result it was concluded, that atmospheric corrosion of steel, zinc and galvanized steel in the county division did not exceed C3 category, which means medium corrosivity and in many regions was even lower (C2).

Taking into account the level of corrosion damage to infrastructure and new structures, especially steel road safety equipment, research on atmospheric corrosion in direct vicinity of streets, street canyons and highways has been undertaken. The aim of this paper is to present preliminary results, that are the starting point for a complex evaluation of operating conditions and an opportunity for optimising the technical and economic management of road safety equipment.

2 Air pollution in the area surrounding streets and roads

A special case of the environment of a complex chemical nature is the area of big cities where concentrations of pollutants emitted by different sources and temperature conditions are far more diverse and variable than in areas outside the city. This is also the case with roads with heavy traffic. In these areas the exhaust gases from transport are considered the main pollutant. Table 1 lists the content of chemical compounds and particular groups of compounds in total emission from vehicles.

Table 1. The contribution of inorganic and organic compounds released from transport, in 2013 [11].

Lp.	Type of contamination	Percentage in total emission,%
1.	SO_2	0.14
2.	NO_2	32.0
3.	CO	20.2
4.	NMLZO (non-methane volatile organic compounds)	22.0
5.	Particulate matter	19.0
6.	PM_{10}	7.7
7.	$PM_{2,5}$	11.0
8.	hexachlorobenzene	15.0
9.	Polychlorinated biphenols	8.0
10.	Polycyclic aromatic hydrocarbons	1.6

Substances originated from exhaust fumes, as well as those created during vehicle movement by tires and brakes are presented in Table 1. Among them the biggest contribution is from: NOx, CO and solid particles with average grain size of 10 µm and 2,5 µm, marked as PM10 and PM2,5, soot and organic compounds (aliphatic carbohydrates, formaldehyde, aromatic carbohydrates single- and polycyclic and their derivatives). Most of the solid

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particles are produced by tires and brakes. They are composed of aromatic carbohydrates and heavy metals such as Pb, Cd, Ni and Cu.

The highest concentration occurs in the case of nitrogen oxides. Reactions that take place in high temperature between oxide and nitrogen originated from the air and fuel compounds lead to nitrogen oxide (NO) synthesis. In the next stage NO is oxidized to nitrogen dioxide and other oxides with the participation of UV light and carbohydrates. Nitrogen oxide and dioxide concentration in fumes are thermodynamically and kinetically limited by reagent concentration, flame temperature and temperature in individual engine compartment combustion zones. Average annual NO2 concentration in different areas of Poland is presented in the diagram in Figure 1. During the last 15 years it has stood at a constant, characteristic level, being the lowest in rural areas, about 6 times higher in urban areas without transport. In the area located directly near streets and roads nitrogen oxides concentration is about 2-3 times higher than in urban areas without transport (Figure 2).

The research results including the analysis of nitrogen oxides concentration in urban areas show that quantitative composition of NO2, NO, O3 and organic compounds mixture is characteristic for given area during a specified time. A substantial contribution comes from concentration of oxidants and radiation energy as a direct trigger of photochemical reactions.

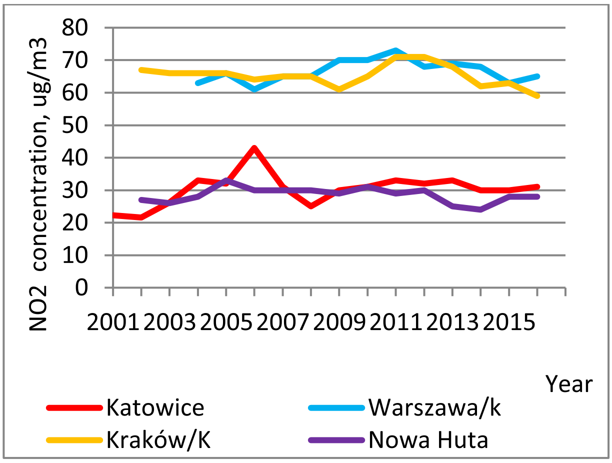
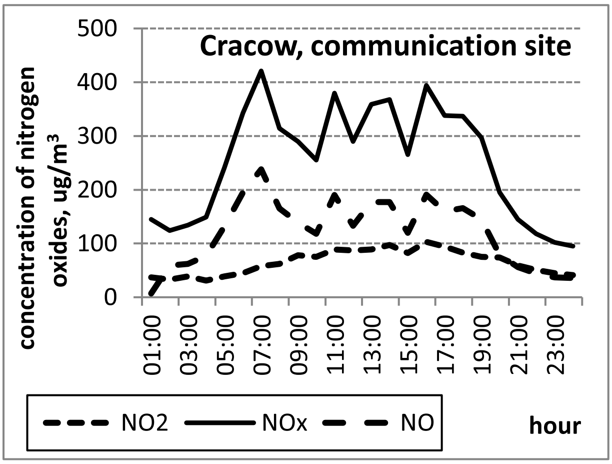


Fig. 1. The annual average concentration of NO2 in the years 2001-2016 for selected urban areas.



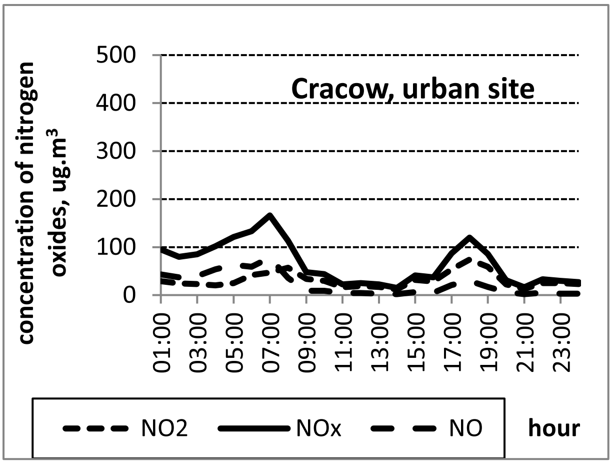
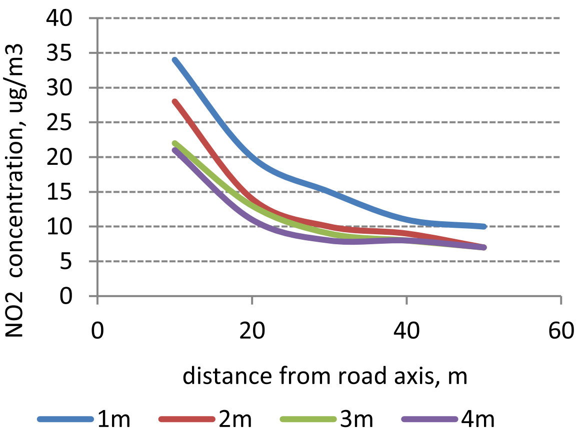


Fig. 2. Changes of daily concentrations of NO, NO2 i NOx for urban and communication corrosion sites in Cracow (25 June 2012 r.) (www.krakow.pios.gov.pl.)

A distribution of pollutants near roads and highways proves that the concentration of gases and solid particles significantly decreases with distance from the centre of a road (Figure 3 A). It also depends on the height of the emission source. Emission size at a given point or on a road section depends on vehicle velocity, engine and fuel type. As can be seen in Figure 3B the same trend is observed for both nitrogen concentration and corrosion loss of zinc.



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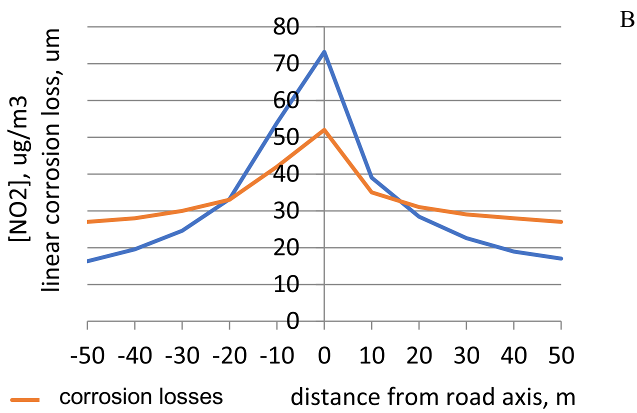

Fig. 3. A) a change of NO2 concentration with distance from the road axis and height of emitter (data related to vehicles driving at 110 km/h), B) a change of NO2 concentration with distance the road axis and related change of corrosion loss of zinc coating.

3 Preliminary results and discussion.

Test specimens of dimensions 150 x 100 x 1 mm were made of the following materials:
- low carbon steel sheet according to PN EN 10139:2016-04, grade DC05
- zinc sheet according to PN EN 988 / PN EN 1179:2005, min. zinc concentration 97.7%
- hot dip galvanized low carbon steel sheet coated in batch process.

Experimental racks were assembled at a distance of 0.5 m to 4 m from the edge of the carriageway next to streets with different traffic levels (115/5000 vehicles per hour). Corrosion losses were determined after annual exposure of the samples according to PN-EN ISO 9224 and atmospheric corrosivity categories were established according to PN-EN ISO 9223: 2012. The results are presented in Table 2.

Table 2. Changes of atmosphere corrosivity at selected sites in the vicinity of roads for steel and zinc determined in annual exposures in the years 2014 – 2016.

Exposure site	**Zinc**			**Steel**		
	2014	**2015**	**2016**	**2014**	**2015**	**2016**
Niepodległości Av.	C3	**C5**	-	C2	C2	C3
Gen. Maczek St.	C3	C3	**C5**	-	C2	C2
Skłodowska-Curie Bridge	**C4**	C3	**C5**	C3	C3	C3
Czerniakowska St.	C4	C3	**C5**	C3	C3	C3
Siekierkowski Bridge	C5	C3	**C4**	C3	C3	C3
Viaduct at Central Station	C4	C4	**C5**	C2	C3	C3
Primate of Millenium Av.	C4	C3	**C5**	C3	C3	C3
Toruńska Route	-	**>C5!**	**>C5**	C3	C4	C3
Tunnel at Wisłostrada	C4	**>C5!**	**>C5**	C2	C4	**C4**

Wisłostrada/Bielany	C4	C3	**C4**	C3	C4	**C4**
Wisłostrada/Cytadela	-	C3	**C5**	-	C3	C3
Łazienkowska Route	-	**C4**	**C5**	-	C3	C3
Katowice/A4	**C4**	**C4**	C3	C3	**C4**	C3
Katowice/ Urban	C3	C2	C3	C3	C3	C3
Cracow/Nowa Huta	C3	C2	C2	C3	C2	C2
Cracow/ communication route	**C4**	C3	C3	C3	C3	C2

It is notable, that corrosion categories determined from corrosion losses of steel are lower than those of zinc. This is because of a greater susceptibility to corrosion of zinc in the presence of nitrogen oxides and nitric acid in the air. As an example, there are very high zinc corrosion rates in tunnels (tunnel at Wislostrada) and under roofing (Torunska route, viaduct near CS) where the corrosivity category reached C5 and above its upper limit. In areas outside any transport routes (Cracow/Nowa Huta) the corrosion rate of zinc and steel corresponds to C2 and C3 category, which is in compliance with atmospheric corrosivity determined across the whole country.

The question arises about the correlation between causes and effects. The results collected from 58 traffic corrosion sites are expressed by Pearson's correlation coefficients and presented in Table 3. The correlation between the average annual NO2 concentration measured at test sites and the average daily traffic volume for vehicles for two different time periods remain at moderate levels.

Table 3. Pearson's correlation coefficients (r) between traffic intensity and NO2 concentration, as well as corrosion losses of zinc or steel.

No. of sites/ Time of exposure		$[NO_2]$, μg/m^3	Corrosion losses Zn, μm	Corrosion losses Zn coating, μm	Corrosion losses of steel, μm
1 (+N=26) 2 years	Traffic intensity vehicles/h	0,58	0,59	0,34	0,17
2 (+N=58) 3 years	Traffic intensity vehicles/h	0,63	0,26	0,42	0,17

Correlation coefficients between traffic and corrosion of zinc or zinc coating exhibit moderate linear dependence for the time period of 2 years and poor for 3 years, indicating that the corrosion rate can be influenced by local factors not taken into account in the analysis, e.g. wind speed and direction, type of vehicles and fuel, vehicle speed etc. Another reason may be an insufficient population of test sites and too short period of observations.

As it was stated at the beginning of this paper the spread of pollutants is mainly influenced by many agents and parameters which in turn affect corrosion rates of materials. The most important are type of pollutant and volume of emission, type and the origin of emitter and its parameters, shape and topography of the area characterized by roughness of terrain, meteorological conditions including circulation type of atmospheric content, atmospheric equilibrium, wind direction and velocity, air temperature and its vertical gradient, size and type of precipitation near the emission source and near the receptor, intensity of sunlight, cloudiness and humidity.

To find a solution to the possible relations between local road factors listed above and corrosion losses of structural materials would require extremely intensive research which would be very difficult to complete in a reasonable period of time. At least for financial and logistic reasons. Taking into account a phased approach, the most urgent studies should focus on a more precise explanation followed by relevant equations of the relation between corrosion rate of road safety elements and the intensity of traffic. This will lead to the development of a software as a tool for the adequate prediction of corrosion behaviour of infrastructure at local sites. Consequently, it will help to formulate practical recommendations to extend the durability and life of road safety elements.

4 Conclusions

1. A comprehensive review of scientific and technical literature supported by the authors' own research revealed that pollution emitted from heavy traffic affects to a greater extent corrosion of metals than many other industrial corrosion agents. The origin of chemical compounds comes from exhaust gases, tires and brakes. In order to achieve an optimum durability of road infrastructure a determination of corrosivity of the atmosphere in the vicinity of highways and roads seems to be the most serious and urgent problem to solve. This kind of research has not been carried out in Poland.
2. It is proved that dose – response equations for modelling the atmospheric corrosion rate developed for relatively large administrative areas and proposed in PN EN ISO standards do not apply to the local sites where the number of parameters can be greater and the dynamics of events is much more intense in comparison with regional area. This conclusion shall be assumed as the genesis of this work devoted to the determination of corrosivity of atmosphere in the vicinity of roads and highways with special attention paid to the characteristics of sources of corrosion agents and traffic intensity in particular.
3. The corrosivity of local atmosphere along roads is more aggressive towards zinc than steel. Zinc is the major protective material against corrosion, usually applied as zinc coating on steel. It is confirmed that corrosion rate of zinc is 3 – 5 times faster within a road area than in a regional division which poses additional requirements for surface finishing of structures exposed to local corrosion.
4. Corrosion category in big cities is the highest for zinc and zinc coatings located in sheltered and/or screened sites, e.g. in tunnels but one may find similar areas across the country. Therefore a new exposure started in 2016 as part of this work. It is located in environments containing sheltered and un-sheltered conditions with a diversified corrosion load.

Acknowledgements

This work was supported in part by the National Centre for Research and Development and General Director for National Roads and Motorways – research programme „The Development of Road Innovations, project RID 3B (agreement nr TZP/RID-I-64/12/NCBR/2016) NCBiR and GDDKiA in the frame of LifeRose Project.

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