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Protective properties of various types of coating systems on selected bridge structures

Właściwości ochronne różnego typu systemów powłokowych na wybranych obiektach mostowych

On the basis of field studies, the protective properties of various coating systems on bridges in Poland after extended periods of operation according to PN-EN ISO 12944-1:2017 (approximately 15 years) are presented. The evaluation was carried out on the basis of visual damage assessment, tests of coating thickness and adhesion, while selected structures were tested for protective properties evaluated by impedance spectroscopy. The types of damage on the tested structures were compared. The results of the study can be used as a basis for discussion regarding the selection of optimum corrosion protection solutions for bridge structures.

Keywords: durability of corrosion protection systems, field tests of corrosion protection systems

Na podstawie badań terenowych określono właściwości ochronne różnych systemów powłokowych na obiektach mostowych w Polsce po około 15-letnich okresach eksploatacji (według PN-EN ISO 12944-1:2017 klasyfikowanych jako długie). Analizę przeprowadzono na podstawie wizualnej oceny zniszczeń, badań grubości i przyczepności powłok na wybranych obiektach, badań właściwości ochronnych, ocenianych metodą spektroskopii impedancyjnej. Porównano rodzaje zniszczeń zaobserwowane na poszczególnych obiektach. Wyniki badań mogą stanowić podstawę do dyskusji dotyczącej wyboru optymalnych rozwiązań w zakresie zabezpieczeń antykorozyjnych na obiektach mostowych.

Słowa kluczowe: trwałość systemów antykorozyjnych, badania terenowe systemów antykorozyjnych

1. Introduction

The corrosion protection of bridges is ensured by using various coating systems. The choice of system depends on the corrosive environment, the type of bridge structure, the required durability of the system and often the experience and practices of the country in which the system is used.

The largest amount of available data on the corrosion protection systems used comes from the USA, where state administrations have conducted extensive research in this area and make the data

available online [1–5]. Similar documents have been made available by Canada, Australia and China [1, 6–8].

Examples include the results of corrosion control systems applied in 1986–87 and evaluated after 20 years of operation on a bridge over a saltwater creek. Many studies of this type have been carried out on behalf of the Highways Agency, both on various selected bridges and in certified laboratories. The best results in the above tests were achieved by the metal coating system, with a zinc ethyl silicate primer system in second place and a zinc rich epoxy primer system in third place. Systems based on aluminium mastic and

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other epoxy coatings performed significantly worse. Two-coat systems also performed significantly worse than three-coat systems. What came as a surprise was the very good performance of ethyl silicate zinc rich primer systems on a poorly prepared surface. This system is also used as a restoration system, for example on the famous Golden Gate Bridge [3].

For many years, each state in the USA conducted its own research and had its own list of systems approved for use on bridges. Currently, testing is carried out by AASHTO (American Association of State Highway Transportation Office) according to an established programme. The tests are available to the relevant agencies in each state, which may adopt their acceptance criteria according to, for example, the prevailing corrosion conditions. The states of New England have their own NEPCOAT (North East Protective Coating Committee) requirements which are also available to all states.

There are reports available from many countries on the durability of polyurea (polyaspartic acid based) systems and systems with polysiloxane and polyfluoro top coats [9, 10]. Polysiloxane (epoxy) coatings are also used as interlayer coatings.

In Poland, the recommended systems for bridges can be found in the recommendations of the General Directorate for National Roads and Motorways [11] and the guidelines of the Ministry of Infrastructure WRM-31 [12]. For new structures, the approved (and used) systems include the following:

- thermal zinc sprayed coating, sealer, epoxy interlayer, polyurethane or polysiloxane top coat,
- zinc ethyl silicate coating, sealer, epoxy interlayer, polyurethane or polysiloxane top coat,
- zinc rich epoxy coating, epoxy interlayer, polyurethane or polysiloxane top coat,
- epoxy coating (with pigments other than zinc), epoxy interlayer, polyurethane or polysiloxane top coat.

It should be noted that in addition to the types of systems listed, all other systems that have passed the tests specified in the above documents are approved. In Poland there are no systematic studies comparing the protective properties of corrosion protection systems used on bridges. At The Road and Bridge Research Institute we have tested many structures as part of the renewal of technical approvals for many corrosion protection systems and as part of the DuraCoat project. Below we present typical results for the system type on a selected bridge structure. In Poland it is assumed that bridges are operated at a corrosivity class of C4/C5.

2. Protective properties of various types of coating systems after a service life of approximately 15 years

2.1. Coating systems evaluated

The following most commonly used coating systems on bridges in Poland were selected for the evaluation:

- zinc rich epoxy primer, epoxy interlayer, aliphatic polyurethane top coat,
- zinc phosphate epoxy primer, epoxy interlayer, aliphatic polyurethane top coat,
- epoxy mastic with aluminium filler, aliphatic polyurethane top coat,
- thermal sprayed zinc coating, epoxy sealer, epoxy interlayer, aliphatic polyurethane top coat,
- thermal zinc coating, epoxy sealer, epoxy interlayer, aliphatic polyurethane top coat – with white efflorescence,
- zinc ethyl silicate primer, sealer, epoxy interlayer, aliphatic polyurethane top coat,
- old-generation thermoplastic system with mini-silicate primer.

As this is a review work and not a planned research project, not all surveys are done for all systems and the service lives differ by

several years from each other. The photographs 1–7 show illustrative pictures of the condition of the structures.

2.2. Field tests carried out on the structures

2.2.1. Coating thickness tests

The thickness of the coatings on the bridges was measured using a non-destructive, electromagnetic method. An Elcometer 456 gauge was used for the measurements. The measurement was carried out in accordance with PN-EN ISO 2808:2020-01 method 7B.2 at a temperature and humidity of $T = 15\text{--}22^\circ\text{C}$ and $RH = 35\text{--}71\%$. The thickness values were corrected by a value of $25\ \mu\text{m}$ according to the requirements of PN ISO 19840 as for an unknown roughness profile. A series of 1,000 measurements was taken for each structure and the average was calculated.

2.2.2. Coating adhesion tests

Adhesion tests were performed in accordance with PN-EN ISO 16276-2:2008. The cross-cut adhesion test was performed using a single-edged knife. Tesa 4024 adhesive tape was used and three values were defined for a single determination. The evaluation was carried out according to the norms included in Appendix A of the cited standard.

2.2.3. Coating damage assessment tests

A visual assessment was carried out under natural light, without the use of a magnifying glass. Damage was compared according to the standard values contained in the individual standards. Individual corrosion damage was assessed according to the standards described below:

- blistering – according to PN-EN ISO 4628-2:2016-03,
- rusting – according to PN-EN ISO 4628-3:2016-03,
- cracking – according to PN-EN ISO 4628-4:2016-03,
- flaking – according to PN-EN ISO 4628-5:2016-03.

2.2.4. Coating condition tests using the EIS method

Measurements were made using an Ivium high-impedance circuit tester. The amplitude of the measurement signal was 20 mV. Measurements were made using a two-electrode system, in a 3% sodium chloride solution, over the frequency range $10^3\text{--}10^{-2}$ Hz. The results are presented in the form of a logarithm of the impedance modulus obtained for the minimum measurement frequency (0.1 Hz) and the variation of the phase angle, and a logarithm of the impedance modulus as a function of the frequency logarithm. The value of the impedance modulus logarithm indicates the sum of the protective properties of the coating system, i.e. the higher the value of the impedance modulus, the greater the barrier properties of the system. Logarithmic values of the impedance modulus for frequencies of 0.1 Hz below 6 indicate low barrier properties.

2.3. Testing of thermal sprayed zinc, sealant, epoxy coating, polyurethane coating systems showing white efflorescence under a scanning microscope with an EDS attachment

Observations of the coating systems studied were made using a JEOL JSM-6010LV scanning microscope equipped with an EDS X-ray energy dispersive spectrometer for micro-area chemical composition analysis (Oxford Instruments). The study was carried out in high vacuum with an acceleration voltage of 15 kV and a WD working distance of 15 mm. The chemical composition analysis carried out is qualitative (indicating the presence of the elements in question) and semi-quantitative, due to the specificity of the methodology and the fact that the characteristic X-rays emitted by the sample at the point of measurement come from a certain depth (of the order of a few μm).



Photo 1. System with zinc rich epoxy primer, epoxy coating, polyurethane coating

Fot. 1. System z wysokocynkowym gruntem epoksydowym, powłoką epoksydową i powłoką poliuretanową



Photo 2. System with zinc phosphate epoxy primer, epoxy coating, polyurethane coating

Fot. 2. System z gruntem epoksydowym z fosforanem cynku, powłoką epoksydową i powłoką poliuretanową

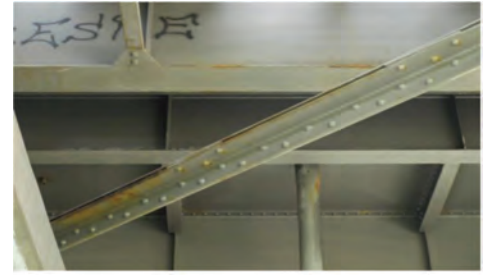


Photo 3. Epoxy mastic system with aluminium filler, epoxy coating, polyurethane coating

Fot. 3. System z mastyką epoksydową z wypełniaczem aluminium, powłoką epoksydową i powłoką poliuretanową



Photo 4. System with thermal sprayed zinc coating, sealant, epoxy coating, polyurethane coating

Fot. 4. System z powłoką cynkową natryskiwana ciepłnie, uszczelniaczem, powłoką epoksydową i powłoką poliuretanową

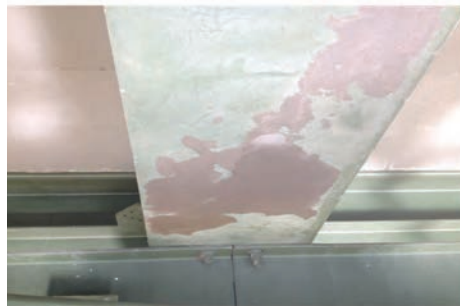


Photo 5. System with thermal sprayed zinc coating, sealant, epoxy coating, polyurethane coating showing white efflorescence

Fot. 5. System z powłoką cynkową natryskiwana ciepłnie, uszczelniaczem, powłoką epoksydową i powłoką poliuretanową, na którym widać białe wykwity



Photo 6. System with zinc ethyl silicate primer, sealer, epoxy coating, polyurethane coating

Fot. 6. System z wysokocynkowym gruntem etylokrzemianowym, uszczelniaczem, powłoką epoksydową i powłoką poliuretanową



Photo 7. Old-generation thermoplastic system with primer pigmented with minium and chromium compounds

Fot. 7. System termoplastyczny starej generacji z gruntem pigmentowanym minią ołowianą i związkami chromu

2.4. Comparison of the protective properties of the systems tested

Table 1 shows a comparison of the protective properties of the previously mentioned coating systems. The results of field tests such as coating thickness, degree of adhesion, amount and type of damage and logarithm of impedance modulus were compared with each other.

Figures 1 and 2 show examinations made using a scanning microscope

Table 1. Results of field tests

Tabela 1. Wyniki badań terenowych

Coating system	Thickness range/average thickness [μm]	Adhesion [degree]	Damage*	Log Z value range
Zinc rich epoxy primer, epoxy interlayer, aliphatic polyurethane top coat	218–322/283	2	Ri0, local peeling of the top coat 2 (S5), chalking 2	7.5–9.1
Epoxy zinc phosphate primer, epoxy interlayer, aliphatic polyurethane top coat	176–357/304	1	Ri0, local peeling of the top coat 2 (S5), chalking 2	9.2–9.3
Epoxy mastic with aluminium filler, aliphatic polyurethane top coat	270–567/389	1	Ri1–Ri2, chalking 2	8.7–12.5
Thermal sprayed zinc coating, epoxy sealer, epoxy interlayer, aliphatic polyurethane top coat	261–562/356	2	Ri0, chalking 1	6.3–7.9
Thermal sprayed zinc coating, epoxy sealer, epoxy interlayer, aliphatic polyurethane top coat – system with white efflorescence	270–528/386	0–2	Ri1, local flaking 2 (S2), chalking 1	not assessed
Zinc ethyl silicate primer, sealer, epoxy interlayer, aliphatic polyurethane top coat	212–407/282	0	Ri0, chalking 1	not assessed
Old-generation thermoplastic system with minium primer	120–200/172	0–2, locally 3–4	Ri3, small cracks in the top coat visible under 10 \times magnification, local flaking of the top coat 5 (S4–S5), chalking 3–4, rust spots on edges, welds, rivets, nuts and bolts, on bracing surfaces, near drains	not assessed

* If the table does not indicate the degree of damage as defined in ISO 4628, the degree is deemed to be 0.



Fig. 1. Structure 1, external surface of the top coat: a) surface appearance at $\times 1,200$ magnification, b) chemical composition analysis sites, c) chemical composition histogram of site 33

Rys. 1. Obiekt 1, zewnętrzna powierzchnia powłoki nawierzchniowej: a) wygląd powierzchni w 1200-krotnym powiększeniu, b) miejsca analizy składu chemicznego, c) histogram składu chemicznego miejsca nr 33



Fig. 2. Structure 2, external surface of the top coat: a) surface appearance at $\times 1,400$ magnification b) chemical composition analysis sites, c) chemical composition histogram of site 10

Rys. 2. Obiekt 2, zewnętrzna powierzchnia powłoki nawierzchniowej: a) wygląd powierzchni w 1400-krotnym powiększeniu, b) miejsca analizy składu chemicznego, c) histogram składu chemicznego miejsca nr 10

with an EDS attachment of fragments of the top coat that fell off the structures with the system: thermal sprayed zinc coating, sealant, epoxy coating, polyurethane coating, on which white efflorescence was visible.

3. Discussion

Most of the types of corrosion protection systems tested could only be repaired locally due to defects caused by application errors. No corrosion pits affecting the stability of the structure were found on any of the structures tested.

The highest level of corrosion was found on the bridge protected by an old generation system with a minium primer (Ri3), but it should be borne in mind that this structure had been in service for 31 years and that the cracking of the top coat, typical of this type of coating after such a long period of use, meant that it no longer acted as a barrier to corrosive media.

The second most damaged system was the aluminium-filled epoxy mastic and aliphatic polyurethane top coat system. This confirms the results of a US study [2]. However, the damage was not very high for such a long service life (Ri1–Ri2) and, according to EN ISO 12944-5: 2018, does not yet require a complete renovation, only a local one. The damage is mainly located at edges, welds, rivets, bolts, struts, i.e. areas that are difficult to secure. It is suspected that thick coatings of this type may have poorer penetration and edge coverage properties. The barrier properties of these coatings on undamaged areas tested by EIS are still very high and the coatings continue to provide excellent barrier protection against corrosive media.

Other systems have a corrosion status of Ri0, similar to that reported in US publications. These include not only systems with a zinc coating or high zinc pigment content, but also a system with an epoxy primer containing zinc phosphate. Localised delamination of the top coat has been observed on some of these systems, but this is likely to be related to application errors and not to the properties of the coatings. When evaluating systems with thermal sprayed zinc coatings, localised sacrificial protection is still present (rather low $\log [Z]$ value), but on two structures the phenomenon of white residue on the top coat, not described in the literature, was observed. These were found to be zinc compounds after examination under a scanning microscope with an EDX attachment. They caused delamination of the coatings in many places. The penetration of zinc compounds through thick organic barrier coatings is puzzling. At present, we are unable to explain the causes and mechanism of this phenomenon. Research is ongoing.

By analysing the results obtained, it can be concluded that all the systems used are capable of protecting bridges against corrosion in a C4/C5 environment over a long period of time. Looking at the condition of the coatings, it can be assumed that the systems will have protective properties even after the very long required service life of over 25 years, if the protection is maintained. It is therefore important to consider what characteristics of the corrosion protection system, other than longevity, should be taken into account when selecting a protection system.

Ecological and health concerns are paramount. This applies both to the conditions of use and to the harmfulness of waste during application and renovation. Systems with a zinc ethyl silicate

primer and a thermal zinc sprayed coating (if zinc penetration in this system proves to be an artefact) are valuable in this respect as they can be left on the steel surface during refurbishment (this also reduces the carbon footprint by limiting the scope of work!), although thermal zinc sprayed coatings are not safe and environmentally friendly during application.

With all coatings, attention should be paid to the VOC content and other components that are increasingly considered to be harmful, such as isocyanates. Other factors include ease of application, the range of atmospheric conditions in which the coatings can be used, speed of drying and many others. Last but not least is the price, which is beyond the scope of our analysis.

4. Conclusion

All the corrosion protection systems presented provided good protection for bridges operated in a C4/C5 corrosive environment over a period of about 15 years, not only in the sense that they did not allow significant corrosion of the steel leading to a reduction in the strength of the structure, but also in the sense that they still do not require significant repairs and some of them do not require any repairs at all.

Further observations of structures protected with different types of corrosion protection systems will allow an assessment of their behaviour over the very long term (more than 25 years) required by many investors when selecting a system. Field observations are the most reliable of all the corrosion tests used. When selecting a corrosion protection coating system, attention should be paid to all features that are useful in the application and operation process and not just to the projected longevity of the protection system.

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