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The method for selecting the best anti-graffiti protective coating for railway vehicles

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Highlights

- Utility – selecting the best coating available on the market.
- Reality – no reference in the selection to defined best (ideal) properies of coatings.
- Elasticity – user defined number of parameters and their significances (weights).
- Universality – possibility of using to select other materials used in the operation of devices.

Abstract

In recent years, the problem of vandalized graffiti damaging walls, facades, and railway carriages has been growing worldwide. This problem primarily affects users of historic buildings and railways. The article addresses the problems of removing graffiti from railway carriages, which has a significant impact on their exploitation and additional costs. To preserve or limit possible vandalism, special anti-graffiti coatings are used. Several types of coatings are typically available on the market for specific practical applications. This article presents an original, quantitative, easy-to-use, and universal method for determining the best coverage among those considered, taking into account the user-defined essential characteristics that the coating should meet and their importance (weight). The following parameters were chosen: adhesion, nanohardness, hardness, total surface energy, erosion resistance, corrosion rate, and material price. The method's application was demonstrated by comparing four anti-graffiti coatings from two manufacturers.

Keywords

anti-graffiti coatings, cost analysis, railway transport, selection method

1. Introduction

In recent years, the operation of railway carriages around the world has been plagued by the problem of vandalism in the form of graffiti painted on their side walls. This problem mainly affects passenger carriages. It is a global issue and poses a number of challenges from a social, managerial, economic, and technological perspective. From a social perspective, graffiti is associated with lawbreaking, social problems such as marginalization, unemployment, and social costs, which, although difficult to measure, are real. In addition, it poses a threat to passenger safety as a result of painting over windows or signaling elements, which causes fear and anxiety among passengers. Solving the problem of graffiti from a social perspective requires not only repressive measures, but above all edu-cational and preventive measures, effective social campaigns, and the designation of spaces for legal artistic expression. The management perspective requires an integrated approach to developing strategies to prevent and respond to the problem of graffiti by involving various departments of the company, such as those related to fleet maintenance and public relations, as well as cooperation with local law enforcement and

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local government services. In the article [1] is analyzed the operational efficiency of the city buses for different stages of their operational life and in the article [2] is presented the operational risk model of city buses incapacity, including costs of incidental repairs, unplanned downtimes and costs as results from potential user migration. The importance of operational vehicle quality measures as an important element used to evaluate the performance of transport services was highlighted in [3]. The possibility of using AI methods for this purpose, particularly artificial neural networks, was highlighted. The use of this approach requires a sufficiently large set of operational data for the network training procedure. To estimate readiness and reliability of individual elements as well as entire Markov systems and semi-Markov models are often used [4]. This is one of the random approaches to process analysis. In this case, too, sufficient data are necessary to proper random process description. In article [5] proposed a method of verification of the preventive renewal strategies, which makes possible a simulation evaluation of the effects of the application of a dedicated schedule of inspections of railway vehicles selected parts. Among such problems, the incidence of which is systematically increasing, and in particular applies to rail transport is the removal of the consequences of vandalism, which is the problem of destruction of train cars, especially passenger trainsets, by graffiti painting, which has become a challenge for many railway companies in Europe, including Poland, in the 21st century. The article [6] discusses the problem of costs generated by different rail carriers over the world (Australia, Belgium, Germany, Spain, the Netherlands). The articles [7,8] present an analysis of the costs incurred by rail carriers in Poland (PKP Rail-ways, Malopolska Railways, Mazovia Railways, Silesian Railways) and their comparison with Spanish RENFE Railways. Damage due to graffiti in Germany and with Deutsche Bahn AG is discussed in [9]. Many manufacturers of trains are now required to use anti-graffiti coatings on their products. Polish manufacturer PESA has been using such coatings since 2004 [10]. The paint coating of Elf2 railbuses ordered in PESA for Małopolska are covered with a special layer for the shortest period of 10 years [11].

Anti-graffiti coating is a protective layer applied to the surface to preserve or limit possible vandalism. It can be generally applied to all types of surfaces, especially cultural heritage and metallic objects (public places, historical walls, houses, trains). It creates a barrier layer between the substrate and graffiti, preventing the penetration of graffiti into the substrate and facilitating easy graffiti removal [12]. Initially, paint coating systems were designed to protect the external surface of structures (especially those made of steel) from aggressive external factors and to give them the appropriate color [13]. Over the years, protective paint systems have changed due to the development of paint application methods and the development of paint products themselves [13,14]. Paint coatings have been used to impart special effects and properties to the vehicles to which they are applied. One such system with special properties is the protective anti-graffiti coating system. The main purpose of coatings is to protect the structure's surface from corrosion. The use of filler allows for the improvement of the structure's shape due to heat transfer during welding during the production process. Providing the customer with the desired aesthetics – in the form of color, gloss, or special decorative effects (hammer effect, wrinkle effect). The final effect is protecting the vehicle from the end user in the form of a specialized anti-graffiti layer. Anti-graffiti paints are used not only for railway carriages or vehicles. Another broad area of application is the walls of buildings, where anti-graffiti products can protect surfaces against unwanted paints. Article [15] discusses the impact of the changing climate on anti-graffiti products and their related effectiveness. The study discussed in the article [16,17] explores the durability of two commercial coatings on concrete paving slabs under both natural and artificial aging tests. Generally, the problem of surface weathering was examined. The effect of usage of selected coatings applied to compact and porous calcareous stones, representative of building materials used in the Mediterranean basin, and their anti-graffiti ability has been analyzed in [18]. The application of anti-graffiti products to stones belonging to architectural heritage is discussed in [19]. Structures are sought that, by modifying previously known ones, acquire new properties, including an-ti-graffiti properties. An example is slippery liquid-infused porous surfaces (SLIPS), which have received significant attention for their potential applications in anti-icing and anti-fouling. After modification, they have achieved durability when subjected to mechanical impact and good anti-graffiti properties [20].

However there are known dedicated standards that can help in protection against graffiti [21] or in the selection of anti-graffiti coatings for use on concrete, masonry and natural stone surfaces by pressure washing [22], the article presents a new, original, quantitative method for selecting the best anti-graffiti coating for railroad cars from among the available options. When applying anti-graffiti coatings, railway companies must make decisions about which coating to use from among those currently available on the market. In the absence of other considerations, the proposed method can be used to support this decision. Importantly, this method selects the best available coating from among those considered, and compares the coating properties among them, not against a defined ideal standard. The number of coatings considered is not limited (from two to a few). Based on the group's experience and research, key operational factors and cost were selected. A simple formula was proposed that does not require determining the best or expected quantitative measures of selected features, but allows for a relative assessment of their value for the coatings under consid-eration. The method was implemented for four coating types: XPC 60012, XPC 60011, XPC 60036 produced by PPG, and BO100-AGR produced by BARWA S.A. The literature on the subject has identified a research gap related to the lack of a multi-criteria, comprehensive method that allows the end user to select the best coverage for their application. Methods presented in the literature typically focus on individual anti-graffiti coating features or the application technology itself.

2. Properties and parameters of protective coatings

Anti-graffiti coatings are dedicated surface protective coatings that offer a variety of properties, depending on the application. The coating properties which can be considered in practical applications are:

- Geometrical: thickness (deretmines properties as porosity, tightness, corrosion resistance, and mechanical resistance), stereometric structure of the surface (result of the technological process), unevenness (smoothness or roughness), defects of the coating (delamination, pitting, flaking, uneven coating thickness, blisters, brittleness, sagging, lifting of the coating, separation, spalling) [23].
- Physicochemical: surface energy, radiant parameters (re-emission, emissivity, radiation transmittance), catalytic parameters (acceleration or reduction of the rate of a chemical reaction), heat conduction ability, solderability, adhesion.
- Physical [24–26]: residual stresses, hardness, plasticity or elasticity, electrical and magnetic properties.
- Exploitation type [13,14,23,24]: corrosion resistance (two types of corrosion - chemical and electrochemical), erosion resistance (influence of e.g. aggressive media), porosity, swelling, permeability.
- Decorative [23]: color, spectrum, gloss, covering power.

3. Method of material selection

Proper selection of materials for the manufacture of protective anti-graffiti coating systems makes it possible to meet the expectations of the railway users. Therefore, a method was proposed to facilitate the selection process.

Let us assume that, from among N systems, the most advantageous one should be objectively selected for use as an anti-graffiti coating for railway wagons. Let us further assume that M parameters/features/properties are selected, which are important from the point of view of users (railway companies). For each coating, the quality parameter k_i (i = 1,…, N) will be determined. The key to the method is to provide a method for determining the criterion values d_{ij} for each of the assumed characteristics for each coating. The fundamental difficulty in determining the value of this parameter is that individual characteristics are described using parameters expressed in different units, which usually assume values of different orders. In such cases, a normalization procedure is usually used. However, this requires assuming the lowest and highest possible values for each characteristic. Given the multitude of available materials, adopting such limiting values is not obvious. The method proposes a different, universal approach, which results in a dimensionless quantity for a properly selected range of considered coatings. The value of the parameter dij is in the range $0 \leq d_{ij} \ll 1$, usually much less than one. The parameter d_{ij} is defined in the form (1), where $\bar{a}_i$ ~~a_i~~ is the average value of the given feature $\bar{a}_{ij}$ ~~a_i~~ for all coatings (2).

Let us further assume that the significance of the influence of each feature is described by a weighting factor α_j (j=1,…,M), and the coefficients satisfy condition (3). The sign of the coefficient is positive if an increase in the value of the parameter describing the j-th property has a positive effect on the expected properties of the coating, and is negative if it worsens the expected properties of the coating.

Finally, the relative quality index k_i (4) is determined for each coating under consideration. It is assumed that the coating with the highest value of this index is the most advantageous for use among those tested in terms of the adopted criterion and selected characteristics.

$$d_{ij} = \frac{\bar{a}_{ij} - \bar{a}_i}{\bar{a}_i} \tag{1}$$

$$\bar{a}_i = \frac{1}{M} \sum_{j=1}^{M} \bar{a}_{ij} \tag{2}$$

$$\sum_{j=1}^{M} |\propto_j| = 1 \tag{3}$$

$$k_i = \sum_{j=1}^{M} \propto_j d_{ij} \tag{4}$$

4. Laboratory tests

4.1. Investigated coatings

For verification of the proposed original method of selection three paint systems based on anti-graffiti coatings from PPG (the world's leading paint manufacturer) XPC 60012, XPC 60011, XPC 60036 and a paint system that included BO100-AGR developed in the laboratory of F.H. BARWA were taken into account. The general physical parameters of the used coating systems are given in Table 1. Weight proportion denotes the weight ratio of paint to hardener.

Table 1. Physical parameters of the coating systems used in tests.

Material	Mass density [kg/m^3]	Weight proportion
XPC60011	990	1:1
XPC60012	980	3:1
XPC60036	1010	2:1
BO100-AGR	1020	2:1

The test specimens were made of S355 alloy steel with dimensions of 150 mm x 100 mm x 1 mm. The surfaces of the steel specimens were prepared by washing in Nitro solvent, then the surfaces were sanded with a rotary machine with P80 grit sandpaper and washed with XPA10003 solvent. The technology of the manufacturer supplying the coating materials, used by leading rolling stock companies, was strictly adhered to when performing the samples. The steel surface had a temperature at least 3 K higher than the dew point. Special attention was paid to the evaporation times between successive applied layers of the same product and the temperature regimes of the drying process.

In order to prepare the surface and apply the coating system, Festool rotary machines with sandpaper from this company, SATA guns with nozzles, and a Blowtherm spray booth were used. The booth had a function of extracting excess paint spray, and was covered with a film and protected by a gel that prevented dirt from settling on the surface of the applied coating in the form of dust. In addition, it was equipped with a thermostat to maintain a constant temperature, with the possibility of heating it to a temperature of about 323 K, required for drying larger samples. A WKL 64/70 climate booth from Weiss Umwlttechnik GmbH, with adjustable temperature and humidity, was used for drying smaller samples. Due to its small thickness and small impact on the results of operational tests, the anti-corrosion primer was not taken into account during the research work. Coating systems were made consisting of the following layers: anti-corrosion epoxy primer, putty, filler primer, base varnish and colorless anti-gaffiti varnishes XPC60011, XPC60012, XPC60036, BO100-AGR. Each layer was prepared and dried in accordance with the requirements of the technological cards. The produced coating systems were conditioned at a temperature of 296 K and a humidity of 50% in order to carry out dry coating strength tests. The following parameters for applying the anti-graffiti layer were used in the technological process: surface temperature 297÷299 K, working pressure 0.18÷0.2 MPa, evaporation between layers 15 minutes, dry film thickness 40÷60 μm, pneumatic spraying application technique, two layers application, drying temperature 323 K, drying time 60 minutes. The remaining layers were applied in accordance with the technical descriptions provided by the manufacturer of a given layer.

Results of mesurements of parameters of adhesion (j=1) and surface free energy (j=2) were statistically analysed including tests of significancy. Parameters of hardness (j=3), nanohardness (j=4), erosion resistance (j=5) and corrosion resistance (j=6) were staistically analysed if the number of experiments were enough. Parameter of resistance to UV radiation was analysed having in mind variation of chosen parameters over time.

4.2. Results of measurements

Adhesion (j=1)

Peel adhesion measurements according to PN-EN ISO 4624 [27] were performed using a DeFelsko PosiTest AT handheld adhesion meter. The measurements consisted of gluing a standardized punch to the surface of the coating system using epoxy adhesive. The punch was then removed using the measuring device and the force value was read, which was averaged over the punch surface. Aluminum punches with a diameter of 20 mm were used. The coating systems were applied to steel samples measuring 150 mm x 100 mm x 1 mm. Application parameters are presented in Section 2.3. Six measurement tests (*n*=1,…6) were performed for each coating system, which allowed for averaging the test results. The sample before and after the adhesion test for the XPC 60012 coating system is shown in Figure 1. A summary of the experimental results and the determined d_{i1} parameter values is provided in Table 2. The table presents the obtained adhesion values a_{i1}(n), mean values $\bar{a}_{i1}$ and standard deviations σ_{ai1} for the tested coatings (*i*=1,2,3,4).

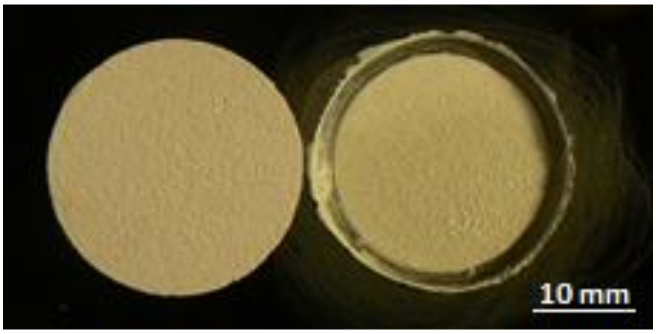

Figure 1. View of the sample beore after the adhesion test for the XPC 60012.

Table 2. Results for measurement of adhesion.

Material	XPC60011 *i=1*	XPC60012 *i=2*	XPC60036 *i=3*	BO100-AGR *i=4*
$a_{i1}(1)$ [MPa]	2.19	2.08	2.14	2.33
$a_{i1}(2)$ [MPa]	2.40	2.16	2.23	2.28
$a_{i1}(3)$ [MPa]	2.28	2.18	2.18	2.16
$a_{i1}(4)$ [MPa]	2.46	2.16	2.33	2.15
$a_{i1}(5)$ [MPa]	2.27	2.33	2.28	2.19
$a_{i1}(6)$ [MPa]	2.08	2.15	2.30	2.19
$\bar{a}_{i1}$ [MPa]	2.28	2.18	2.24	2.22
σ_{ai1} [MPa]	0.13	0.08	0.07	0.07
d_{i1} [-]	0.0228	-0.0236	0.0064	0.0259

The adhesion results for the coating systems are similar. The test results indicate that the XPC 60011 anti-graffiti coating system had the highest average adhesion value (2.28 MPa). The XPC 60012 paint system, which had the lowest average adhesion value (2.18 MPa), had 5% lower adhesion compared to the XPC 60011 coating system.

Due to the number of tests performed for each material (six), it was possible to statistically analyze the differences between the obtained values for individual materials [28,29]. A null hypothesis was put forward that there were no differences between the means $\bar{a}_{i1}$. The hypothesis was verified using the F significance test [28,29]. The value of the test function F^0 determined using the analysis of variance was compared with the values of Snedecor's F statistic for the degrees of freedom resulting from the number of data, assuming significance levels equal to α=0.05 i α=0.01 The test value obtained as a result of applying the test was $F^0 = 7.92$, while the values of the F statistic were $F_{0.05} = 3.1$, $F_{0.01} = 4.94$. Since $F^0 > F_{0.01} > F_{0.05}$, at both considered significance levels, the null hypothesis of no differences between the effect of the type of coating on adhesion is rejected. Therefore, the adoption of the adhesion parameter for comparisons between coatings is not only justified by the research team's experience but also confirmed by statistical analyses.

Surface free energy (j=2)

Adhesive properties were determined indirectly by measuring the surface free energy using contact angle measurements with selected measuring liquids. Distilled water and diiodomethane (DIM) were used as measuring liquids to measure the contact angle. The view of the applied drops of measuring liquids is shown in Figure 2. A stereoscopic microscope with a camera and MicroScan v. 1.3 software were used to observe the droplets and measure the contact angle. A summary of the experimental results and the determined d_{i4} parameter values is provided in Table 3. The table presents the obtained total surface free energy values a_{i4}(n), mean values $\bar{a}_{i4}$ and standard deviations σ_{ai4} for the tested coatings (*i*=1,2,3,4).

To achieve reduced adhesion of contaminants to the protective layer, the aim is to minimize the surface free energy. The lowest surface free energy values were demonstrated by the XPC60011 and BO100-AGR coating systems. From the perspective of rolling stock and anti-graffiti protection, these two systems possessed desirable properties.

In the case of the surface free energy test, similarly to the adhesion test, the differences between the values obtained for the individual materials were statistically analyzed using the same methods. The test value obtained as a result of the test was

F^0 = 30.91, while the F statistics values were $F_{0.05} = 3.1$, $F_{0.01} = 4.94$. Since $F^0 > F_{0.01} > F_{0.05}$, at both considered significance levels, the null hypothesis of no differences between the effect of the type of coating on total surface free energy is rejected.

Figure 2. View of the applied drops of measuring liquids: diiodomethane (a) and water (b).

Table 3. Results for measurement of total surface free energy.

Material	**XPC60011** ***i=1***	**XPC60012** **i=2**	**XPC60036** **i=3**	**BO100-AGR** **i=4**
$a_{i2}(1)$ **[mJ/m^2]**	52.8	52.9	55.9	49.2
$a_{i2}(2)$ **[mJ/m^2]**	47.2	51.9	55.4	48.5
$a_{i2}(3)$ **[mJ/m^2]**	51.9	51.8	55.8	48.0
$a_{i2}(4)$ **[mJ/m^2]**	47.0	53.3	56.3	47.2
$a_{i2}(5)$ **[mJ/m^2]**	53.4	51.0	55.1	48.3
$a_{i2}(6)$ **[mJ/m^2]**	46.9	52.9	56.6	47.7
$\bar{a}_{i2}$ **[mJ/m^2]**	49.87	52.30	55.85	48.15
σ_{ai2} **[MPa]**	2.87	0.80	0.51	0.63
d_{i2} **[-]**	-0.0325	0.0147	0.0836	-0.0658

Hardness (j=3)

The hardness of a coating system describes its resistance to mechanical damage on a macroscale. Hardness measurement was performed based on the pendulum damping time measurement according to the PN-EN ISO 1522 standard [30] using a Koenig pendulum. The measuring device together with the pendulum used is shown in Figure 3. During the measurement, the number of oscillations during the pendulum damping was counted within the range of 6° to 3° from the vertical direction. Based on the obtained time values, the relative hardness was determined. A summary of the average values obtained from the experimental tests and the determined d_{i3} parameter values is provided in Table 4.

Table 4. Results for measurement of hardness.

Material	**XPC60011** ***i=1***	**XPC60012** **i=2**	**XPC60036** **i=3**	**BO100-AGR** **i=4**
$\bar{a}_{i3}$ **[GPa]**	0.4	0.3	0.4	0.5
d_{i3} **[-]**	0	-0.25	0	0.25

The XPC 60012 anti-graffiti coating system was characterized by the lowest pendulum damping time (83.7 s), compared to the BO100-AGR coating system, which had the highest pendulum damping time (120.8 s).

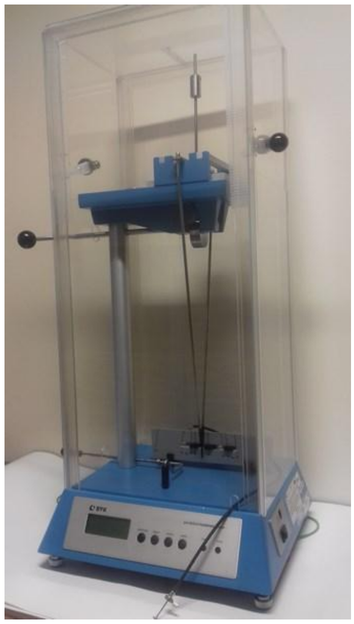

Figure 3. Measuring device together with the pendulum.

Nanohardness (j=4)

Nanohardness refers to the measurement of local hardness and primarily refers to the anti-graffiti paint layer itself. Nanohardness measurements were performed using a NANOVEA nanohardness tester for samples measuring 100 mm x 100 mm x 1 mm. The measurement involved indenting a diamond pyramid with an aperture angle of 65° (Berkovich indenter) into the sample surface while simultaneously measuring the force and penetration depth. The normal load value and the penetration depth of the indenter tip were continuously recorded during the loading-unloading cycle [31]. Example views of the indenter impressions during the nanohardness measurements on the surface of the BO100-AGR and XPC 60036 anti-graffiti paint coatings are shown in the Figure 4. The summary of averaged values obtained from the experimental tests and the determined d_{i2} parameter values is provided in Table 5.

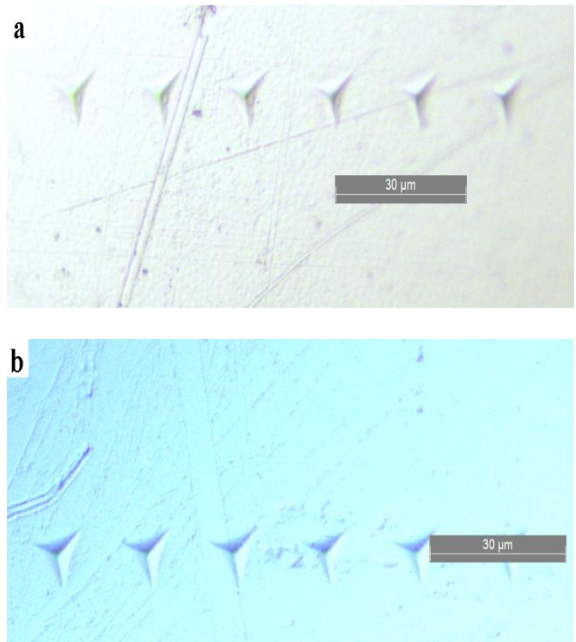

Figure 4. Views of the indenter impressions during the nanohardness measurements on the surface of the BO100-AGR (a) and XPC 60036 (b).

Table 5. Results for measurement of nanohardness.

Material	XPC60011 *i=1*	XPC60012 i=2	XPC60036 i=3	BO100-AGR i=4
$\bar{a}_{i4}$ [GPa]	0.23	0.26	0.27	0.26
d_{i4} [-]	-0.0980	0.0196	0.0588	0.0196

The nanohardness measured on the surface of anti-graffiti coatings was in the range of 0.229 GPa to 0.265 GPa.

Erosion resistance (j=5)

The erosive wear process is a very unfavorable phenomenon that causes degradation of machine components in a way that is difficult to predict at the design stage. Impact erosive wear tests were conducted in accordance with the PN-76/C-81516 standard [32]. The method involved abrading an elliptical hole in the tested paint coating using a jet of abrasive material. Erosion resistance was determined by the ratio of the mass of abrasive material used to abrade the paint coating onto the substrate, expressed in kg, to the average thickness of the tested coating, expressed in µm. Sample result of measuring the erosion resistance of the BO100-AGR anti-graffiti coating system is graphically presented in Figure 5. A summary of the average values obtained from the experimental tests and the determined d_{i5} parameter values is provided in Table 6.

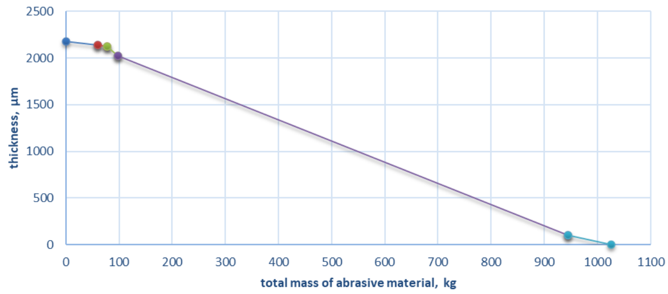

Figure 5. Sample result of measuring the erosion resistance of the BO100-AGR.

Table 6. Results for measurement of erosion resistance.

Material	XPC60011 *i=1*	XPC60012 i=2	XPC60036 i=3	BO100-AGR i=4
$\bar{a}_{i5}$ [kg/µm]	1.40	1.49	1.58	1.49
d_{i5} [-]	-0.0604	0	0.0604	0

The anti-graffiti coatings did not differ significantly in terms of erosion resistance, with results ranging from 1.40 to 1.58 kg/µm. The XPC 60036 coating demonstrated the highest resistance (1.58 kg/µm), while the XPC 60011 coating had the lowest (1.4 kg/µm). The remaining two anti-graffiti coatings, XPC 60012 and BO100-AGR, had the same erosion resistance of 1.49 kg/µm.

Corrosion resistance (j=6)

Accelerated corrosion tests are conducted in test chambers in an artificial corrosive atmosphere. This atmosphere intensifies the corrosion processes of metals, metal alloys, and other materials used for corrosion protection. The corrosion resistance of anti-graffiti protective systems was tested using a WKD SC450 salt spray chamber from Weiss Umwelttechnik GmbH. Samples with anti-graffiti coating systems, measuring 150 mm x 100 mm x 1 mm, were prepared for testing, and cut into them. A set of samples of each anti-graffiti coating system was placed in the salt spray chamber, where a nozzle sprayed a 5% sodium chloride solution in demineralized water (pH = 6.5). An example sample before and after exposure in a salt spray chamber coated with the XPC 60011 coating system is shown in Figure 6. The samples were then removed from the salt spray chamber and cleaned with diammonium citrate. The corrosion current density was measured as a function of the exposure time to the brine solution, and the corrosion rate was calculated. The summary of averaged values obtained from experimental tests and the determined values of d_{i6} parameters is presented in Table 7.

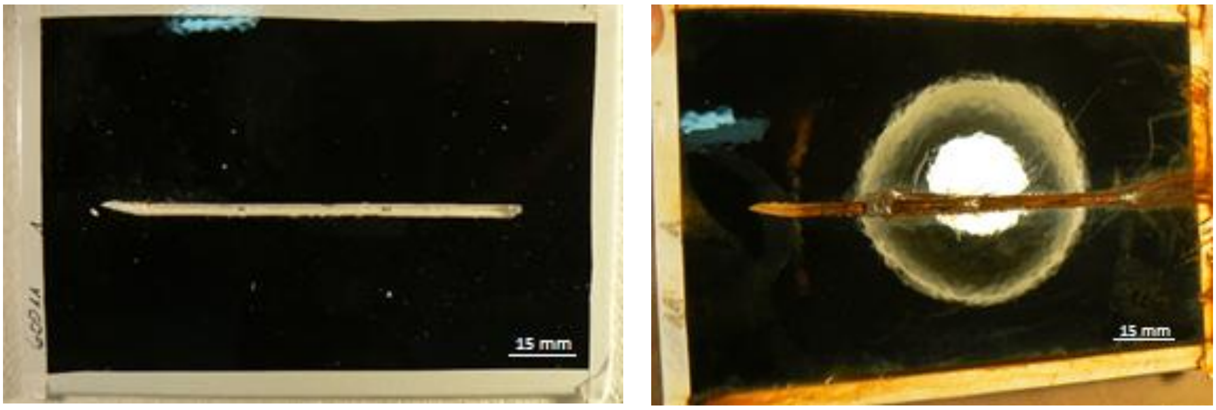

Figure 6. Sample before (left) and after (right) exposure in a salt spray chamber coated with the XPC 60011 system.

Table 7. Results for measurement of corrosion resistance.

Material	XPC60011 *i=1*	XPC60012 i=2	XPC60036 i=3	BO100-AGR i=4
$\bar{a}_{i6}$ [mm/year]	0.0120	0.0241	0.0237	0.0288
d_{i6} [-]	-0.4582	0.0880	0.0700	0.3002

Two anti-graffiti coating systems, XPC 60011 and XPC 60036, exhibited similar corrosion rate trends when tested on the substrate material. After the appropriate exposure time for the aforementioned systems (approximately 500 hours for XPC 60011 and approximately 700 hours for XPC 60036), the corrosion rate began to decrease. The remaining two paint systems tested, XPC 60012 and BO100-AGR, exhibited an increase in corrosion rate throughout the entire test period. The XPC 60011 anti-graffiti coating system exhibited the lowest corrosion rate after the total exposure time.

Resistance to UV radiation

The changes between the tested anti-graffiti systems were compared based on the gloss change assessment in accordance with PN-EN ISO 2813 [33] using a BYK-Gardner glossmeter. The tested anti-graffiti coating systems were placed in a QUV light chamber with installed UVB-313Lamps and exposed to UV-B radiation. The samples were tested in the light chamber according to a test program that included repeated twelve-hour chamber operation cycles: exposure at a continuous irradiance of 1.23 W/m2 at 60 °C (8 hours), misting (15 minutes), and water condensation on the coating surface at 50 °C (3 hours 45 minutes). Before testing, the paint systems were characterized by high gloss with values over 90 gloss units (GU). The variation of the gloss parameter over time during the 2100-hour tests for the tested coatings is shown in Figure 7.

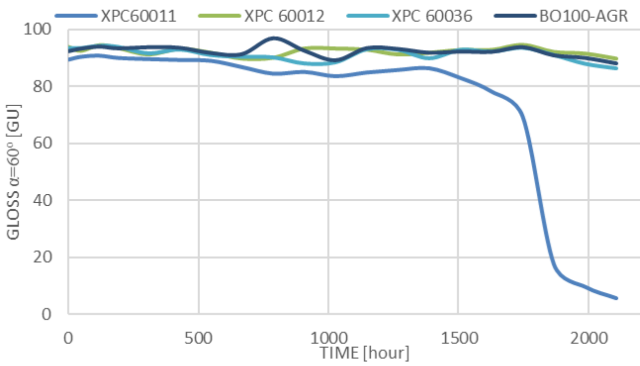

Figure 7. Gloss variation over time after UV-B irradiation.

For the XPC 60012, XPC 60036, and BO100-AGR anti-graffiti coating systems, gloss remained high throughout the exposure period. Minor variations in the measurement results during the test were due to different locations where the gloss was measured on the test sample. After two thousand hours of testing, a decrease in gloss values was noticeable for the above-mentioned systems. The BO100-AGR coating system (final value 79.6 GU) experienced the fastest gloss reduction, while the XPC 60012 coating system experienced the slowest (final value 89.7 GU). However, the XPC 60011 coating system experienced a steadily decreasing gloss value starting after 308 hours of exposure. Initially, this change was not noticeable to the human eye. After 1750 hours of exposure, a significant change occurred, resulting in the coating system's top layer irreversibly losing its gloss. The cause of this effect was the degradative effect of UV radiation on the layer binder in the form of polyurethane resin, which leads to the gradual disintegration of polyurethane bonds.

The second parameter that allows for the assessment of UV resistance is the color difference parameter ΔE. The tests were conducted in accordance with the PN-EN ISO 7724 standard. A Konica Minolta spectrophotometer was used to determine the values of individual color parameters. The color difference parameter ΔE (5) was then calculated, where: L*, a*, and b* are the parameters of color coordinates [34]. Figure 2 shows the change in the ΔE parameter value over time for the tested coatings.

$$\Delta E = \sqrt{L^* \cdot a^* \cdot b^*} \tag{5}$$

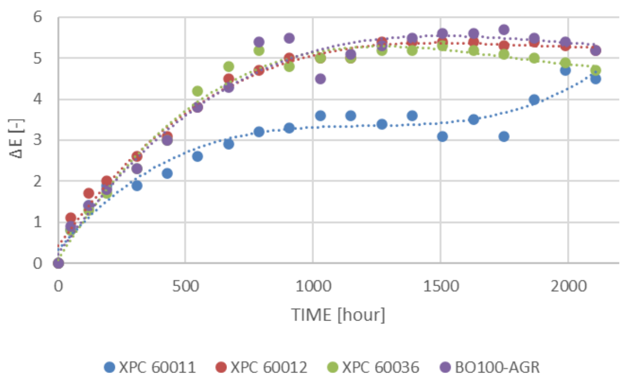

Figure 8. Color difference parameter variation over time after UV-B irradiation.

The change in the color difference parameter ΔE over time for the coating made of XPC 60011 differed from the changes for the other coatings during exposure to UV-B radiation. However, the parameter ΔE values after 2100 hours of exposure did not differ significantly for the tested coatings (see Figure 8). According to the authors, it is difficult to consider one of the parameters determining UV resistance as a parameter in the presented assessment method, as it is not clear what exposure time should be used. Furthermore, after a sufficiently long exposure, the values for these parameters for the tested coatings become close to each other (see Figures 7 and 8) except for the coating made of XPC 60011 (gloss parameter). Therefore, it was decided not to take into account the influence of the UV resistance to UV radiation of coatings as a parameter in the proposed formulation of the discussed method.

5. Application of the method – case study, discuusion

Based on the results of a series of research studies and experience, among the previously discussed geometric, geometric-physicochemical, operational, and decorative parameters, the following parameters were assumed as input variables of the model: adhesion (d_1), nanohardness (d_2), hardness (d_3), total surface energy (d_4), erosion resistance (d5), corrosion rate (d_6). Moreover the important parameter is cost (price) of anti-graffiti material. The cost of technology and application are omitted.

Price (j=7)

Price is an important parameter for users when selecting a coating. Price data was collected. The price per liter of coating was based on the prices of the base, hardener, and solvent, and their different proportions for the tested coatings. These values, along with the determined d_{i7} parameter values, are presented in Table 8. The painting efficiency (covered surface) using the considered coatings is approximately the same per kilogram of coverage.

Table 8. Price of 1 kg of coating.

Material	XPC60011 *i=1*	XPC60012 i=2	XPC60036 i=3	BO100-AGR i=4
$\bar{a}_{i7}$ [PLN]	82.78	52.56	53.86	69.89
d_{i7} [-]	0.2780	-0.1885	-0.1685	0.0790

The XPC60011 coating system has the highest purchase price, while the XPC60012 coating system has the lowest purchase price, close to the price of the XPC60036 system.

Based on the determined values of the d_{ij} criteria, the relative quality index k_i was can be determined for each tested coating. The selection of weight values α_j becomes crucial in the analysis. If multiple parameters are included in the proposed selection method, weight values can be adopted arbitrarily or after applying selection methods known in the literature, such as the expert method or pairwise comparison. The expert method requires expert consultation, which does not preclude its use, but was not used in the presented case study due to its exemplary type. A disadvantage of using the pairwise comparison method in the evaluation of anti-graffiti coatings is the incomparability of the parameters used for evaluation. In the analyzed case study, with the exception of the cost parameter (j = 7), the remaining parameters refer to physical properties that determine the coating's durability. The weight values were adopted arbitrarily. It is known from the literature that the surface free energy value is a key parameter considering the deposition of the graffiti paint layer. Therefore, in the case study, a weight value of α_2 = 0.25 was assumed for this parameter. From the customer's perspective, the material cost is also important, so a weight value of α_7 = 0.25 was assumed for this parameter as well. The remaining parameters are evaluated with the same weight as for the module, equal to $|\alpha_j| = 0.1$ (j=1,3,4,5,6). The values of all weighting factors α_1, α_2, α_3, α_4, α_5, and α_7 are positive, because a higher value of the determined parameter corresponds to a better feature. Only in the case of corrosion is a lower value of the corrosion rate parameter desirable. Therefore, the weighting factor α_6 is negative. The obtained values of the quality index k_i are summarized in Table 9.

Table 9. Values of the quality indices for the tested coverings.

Material	**XPC60011** *i=1*	**XPC60012** **i=2**	**XPC60036** **i=3**	**BO100-AGR** **i=4**
k_i [-]	0.0936	-0.0777	-0.0157	-0.0003

The analysis results show that, considering the adopted criteria, the XPC60011 system is the best performing system, while the XPC60012 system is the worst performing system. The XPC60036 and BO100-AGR systems are comparable according to the adopted criteria. It is worth emphasizing that the quality factor values differ significantly, despite relatively small differences in the values of the individual parameters quantifying the tested features.

The case study demonstrates the practical application of the proposed method. The question of the feasibility of using other methods for this purpose becomes important. First and foremost, it is important to address the possibility of comparing coatings using the methodology specified in the ASTM D6578/D6578M-13 standard [22] (ASTM D7089-06 standard [23] applies to concrete, masonry, and natural stone surfaces removed by pressure washing). In this case, testing is performed on specially prepared samples. The surface is assessed for residual graffiti, color change, and gloss change using visual observation or instruments. Graffiti is removed using a series of cleaners (ranging from mild to aggressive), often combined with mechanical action (wiping, rubbing). The advantage of this method is the direct comparison of coating quality after the same cleaning procedure with increasing aggressiveness. However, the main disadvantage of this method when selecting commercially available coatings is the need to conduct tests for these coatings. The proposed method involves determining a single scalar parameter, the value of which indicates the best coating, essentially without the need for additional testing, intentionally based on known material properties, which should be available as data from the manufacturer. Multi-criteria decision-making methods, known for years, can also be used to select the best coating based on the values of selected parameters. Among them, the AHP (Analytic Hierarchy Process) method [35,36] deserves special mention. This method involves decomposing the problem into component elements and analyzing the decision-makers' assessments [37] by comparing them pairwise. For example, the article [38] presents practical applications of the AHP method in transportation issues. The main disadvantage of this approach is the need to conduct complex pairwise comparisons, which increases the reliability of the analysis but also increases the time and cost of implementation. Arbitrarily adopting weight values, taking into account the knowledge and experience of the person in the subject matter, is the quickest, lowest-cost, and fastest approach. Other decision-making methods known in the literature include the decision tree method [37], the Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) [39], and the Preference Ranking Organization Method for Enrichment Evaluation (Promethee) [40]. These methods are characterized by their complexity and relatively high workload required in their construction and application compared to the proposed method, resulting from, for example, the need to perform pairwise comparisons (AHP) or define a subjective ideal solution (TOPSIS). However, in the case of the Promethee method, all the parameters to be defined have an economic meaning. The proposed method is original, easy to use, and is a proposal for practical application.

6. Conclusion

This article addresses a current problem requiring resolution: the destruction of exterior surfaces by graffiti and methods of protection against this phenomenon. This particularly applies to the operation of railway carriages and the destruction of building walls, especially historic buildings that constitute cultural heritage. Technologies and coatings are available on the market that provide protection against this undesirable phenomenon, primarily by providing coatings with specific physical properties that enable relatively easy removal of graffiti from the structure's surface. The range of products available on the market includes many types of coverings from many manufacturers. Therefore, the user is faced with a choice. In this context, the question arises about the correct decision to choose the best covering. The economic criterion (lowest price) alone is not always the right approach. The selection process should also consider physical and operational properties relevant to the user. When considering the operation of vehicles used in transportation, it is also necessary to pay attention to factors that have an economic dimension and are related to broad issues of management, law, aesthetics, and in many aspects are related to the implementation of the concept of sustainable development [6,41].

The article proposes an original, quantitative, comprehensive, multi-criteria, universal method for identifying the best coverage among those considered. The primary advantage of the method is the identification of the best product among those considered. An ideal (exemplary) product meeting specific characteristics is not constructed here. The approach to this problem is original and is based on determining the average value of measures of a given characteristic and taking into account the differences for each coverage. The universality of the method lies in the user's ability to individually select the characteristics that the coverage should meet (the number of acceptable characteristics in the method is arbitrary). It is also possible to individually increase the importance of specific characteristics by adopting appropriate weighting coefficient values.

The method's application was demonstrated by comparing four anti-graffiti coatings from two manufacturers. This required thorough laboratory testing to determine the values of parameters describing selected coating characteristics using the same laboratory test and under the same conditions (this does not apply to the price parameter). The laboratory methods for determining the analyzed parameters, often referring to standards, were discussed. The results showed that despite usually small differences in the values of parameters describing individual characteristics for different coatings and their completely different natures, a single resultant parameter can be provided, the value of which varies for each tested coating, and which allows for the selection of the best coating for use, with characteristics (proportion of the importance of features) that can be individually defined by the end user.

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