CONSERVAR PATRIMÓNIO
Conservation of industrial and technological heritage
Conservação de património tecnológico e industrial
NOTE / NOTA

Comparative assessment of paint systems for use on heritage artillery at coastal forts in England: experimental design and interim report

Avaliação comparativa de sistemas de pintura para artilharia histórica exposta em fortificações costeiras em Inglaterra: projeto experimental e relatório intercalar

WILLIAM SMITH [1,2*]
DAVID WATKINSON [1]
NICOLA EMMERSON [1]
PAUL LANKESTER [2]
DAVID THICKET [2]
IAN LEINS [2]

1. Cardiff University, John Percival building, Colum Drive, Cardiff, CF10 3EU, United Kingdom

2. English Heritage, Rangers House, Chesterfield Walk, London, SE10 8QX, United Kingdom

*smithw6@cardiff.ac.uk

Abstract

This work aims to harmonise conservation practises for 20th century artillery housed in forts around the English coast by identifying a suitable protective coating for the nation-wide collection. Groups of analogue samples of five coating systems are undergoing 15 months of accelerated aging in the laboratory and three years real-time *in situ* exposure at two coastal sites in the UK. The impact of this on their chemical, physical, aesthetic and protective properties is being measured using pull-off tests, impact testing, colourimetry, FTIR, oxygen consumption and EIS. Results of the physical tests at three and six months accelerated aging and one year *in situ* exposure are reported in this paper. Based on set criteria and this data set, the Sherwin Williams 1 epoxy coating system is currently the best performing system.

KEYWORDS
Ferrous metals
Corrosion
Coatings
Conservation
Artillery
Analysis

Resumo

Este artigo visa uniformizar as práticas de conservação de artilharia do século XX exposta em fortes da costa inglesa, identificando um revestimento protetor adequado para a coleção nacional. Amostras com cinco sistemas de revestimento estão a ser envelhecidas artificialmente em laboratório, durante 15 meses, e naturalmente em dois locais costeiros do Reino Unido, durante três anos. O impacto do envelhecimento nas propriedades químicas, físicas, estéticas e de proteção dos revestimentos está a ser medido através de ensaios de adesão e de impacto, colorimetria, FTIR, consumo de oxigénio e EIS. O artigo considera os resultados dos ensaios físicos de três e seis meses de envelhecimento acelerado e de um ano de exposição *in situ*. Com base nos critérios estabelecidos e neste conjunto de dados, o sistema com melhor desempenho é o revestimento epoxídico Sherwin Williams 1.

PALAVRAS-CHAVE
Metais ferrosos
Corrosão
Revestimentos
Conservação
Artilharia
Análises

Introduction

The project aims to identify the most suitable coating system for the English Heritage collection of twentieth century artillery pieces exposed outdoors. Due to the proximity of these pieces to a coastline producing a C5M environment, as specified in ISO 12944 [1] (Table 1), the steel substrate is at significant risk of rapid corrosion [2]. Wet/dry cycles [3-4] and deposition of chloride ions create conditions ideal for formation of oxy-hydroxide corrosion products [2-4], preventing the formation of any protective patina [5] and favouring the chloride bearing corrosion product akageneite (β-FeOOH) [6] which drives further corrosion.

Developing a streamlined and efficient management system is essential for the care of a national collection comprised of large objects, situated in difficult to access locations along the full length of England's extensive coast line, A coating suitable for use across the whole collection must meet several requirements, including: 1) longevity; 2) retention of aesthetic properties; 3) damage resistance; 4) light resistance.

These characteristics are being investigated for selected coating systems during a programme of real-time and accelerated ageing to determine their suitability for use in the conservation of the collection.

Table 1. Categorisation of corrosion risk as a function of environment, as specified in ISO 12944 [1].

Category	Environment
C1 – Very Low	Environmentally controlled buildings
C2 – Low	Rural areas and non-environmentally controlled building
C3 – Medium	Average urban environment, or high humidity indoor environment
C4 – High	Industrial areas and medium salinity, indoor areas with liquids and high humidity
C5I – Very High (Industrial)	Industrial areas with high humidity, aggressive atmospheres, and constant condensation
C5M – Very High (Marine)	Inshore or offshore areas with high salinity or high condensation

Sample selection

A wide variety of coating systems are used in the conservation of metal objects, such as polysiloxanes, oil based paints, waxes, and fluoropolymers. Polysiloxanes ($[R_2SiO]_n$ where R is usually CH_3) would appear to be a good choice for a coating. They have greater resistance to the effects of ultraviolet (UV) radiation than organic polymers containing a carbon-carbon backbone, adhere well, resist abrasion, have good chemical and corrosion resistance, and do not pick up dirt easily [7]. Epoxy polysiloxanes are used as topcoats due to their hydrophobicity and are recommended for potential use over primers in marine environments [8]. Despite having stronger physical properties than many other coating systems, they become brittle with age and damage is not easily repaired, often requiring retreatment of larger areas [7]. Fluoropolymers influence surface energy to produce water repellent coatings, being difficult to apply and to repair means limits their use in marine environments. Oils and waxes are easy to apply, easily damaged and readily repaired but have aesthetic disadvantages, collect dirt, are temperature sensitive and unsuitable for public display where physical interaction might be expected.

Five systems were selected for testing (Table 2), based on a combination of manufacturer and conservator recommendations for the marine environment, as well as compliance with industrial standard ISO 12944 [1]. Four systems follow the industry standard of a high build zinc primer, a micaceous iron oxide (MIO) mid-layer bound by epoxy, and a polyurethane topcoat. A fifth system differed in being alkyd-based and was chosen due to its similarity to systems currently used on wrought iron cannons. Due to the length of time before the best performing system(s) will be introduced into practice following this experimental study, it was important to select products that are commercially viable and ongoing, hence established and currently available brands and systems were given preference over newer or more experimental systems.

Table 2. Coating systems used in this experimental study.

System name	Primer	Mid layer	Top layer
Sherwin Williams #1 (SW1)	Macropoxy L425	Macropoxy K267	Acrolon 7300
Sherwin Williams #2 (SW2)	Macropoxy C400	Macropoxy M905	Acrolon C237
Hempel (H)	Hempadur Avantguard 750	Hempadur Multi-500	Hempathane HS 55610
International (I)	Interzinc 52	Intergard 475HS	Interthane 990
Cromadex (C)	Cromadex 395	N/A	Cromadex 233

Sample preparation

The samples for the experiment were made from cold rolled mild steel, 2.5 mm in thickness, cut to the required sizes with a metal guillotine. The surfaces were prepared to a standard of Sa 2.5 [9], using grade 3 aluminium oxide (53-micron particle size) applied with a Texas Instrument Model AJ-1 abrasive machine. They were then placed in a sealed plastic box containing desiccated silica gel (3 % Relative Humidity – RH) prior to being coated.
The coatings were spray-coated by a contractor commonly used by English Heritage. A 2.5 mm hole was drilled in one corner to allow the samples to be suspended during coating. Cromadex was applied with a gravity fed pot using a B.E.N. Patents Ltd spray with a 1.3 mm jet size and polyurethane systems were applied with a Devilbliss GTI spray with a 1.8 mm nozzle from a Binks pressure pot, using manufacturer application guidelines.

Real-time weathering

Samples for real-time ageing (100 × 100 mm) were mounted in plastic u-shaped runners top and bottom within a custom-made rack angled at 30 degrees to the vertical. These were oriented southeast facing at two English Heritage coastal forts, Pendennis Castle in Cornwall and Dover Castle in Kent. The Pendennis Castle sample rack was 120 m from the sea at an elevation of 50 m and Dover Castle was 130 m from the sea at an elevation of 115 m. At each site, fifteen 100 × 100 mm samples of each coating system were mounted on the rack. Every 12 months for 36 months, five 100 × 100 mm samples of each system were removed for analysis in the laboratory.

Accelerated aging

The accelerated ageing is ongoing and has been set up in a Binder KBF 240 climate chamber set at 60 °C (±0.5 °C) and 70 % RH (± 2 % RH) [10]. Using the Arrhenius equation as an approximate guide, this elevated temperature would increase ageing by a factor of 16 when compared to 20 °C [11], while providing an RH typical of the coastal environment in which it will be displayed. Light banks within the chamber e continuously supply UV of wavelength 370 nm, with intensity of 0.5 mW/cm^2. Wavelength was recorded using a Konica Minolta CL-500A, and intensity was measured using a RTR 574H datalogger. This arrangement is limited in terms of alignment with in-situ performance of the coating systems, as exposure at coastal sites will involve variable RH, wet/dry cycles and a less UV intense light range. Accelerated ageing will therefore offer a worst-case scenario for UV exposure and may provide insight into how aged polymeric coatings perform.

Thirty samples 100 × 100 mm and 50 × 50 mm of each coating system were subjected to accelerated ageing. These were further divided into six groups of five for destructive testing at ageing intervals of 0, 3, 6, 9, 12, and 15 months. The 0 months sample set was tested unaged to act as a comparator. The remaining samples were removed after their respective ageing intervals and subjected to the appropriate experiments. A 40 × 40 mm sample set of all coatings was also included for the oxygen consumption tests. This was not destructively tested but was removed from ageing at the 0, 3, 6, 9, 12, and 15 months to record oxygen consumption values.

Data collection

The samples were exposed to a series of quantitative and qualitative tests to assess their performance (Table 3). This paper describes the methodology used for recording the thickness of the coatings and the changes in their colour, impact resistance and pull off values during the initial periods of in-situ exposure and accelerated ageing. Further reporting of data generated by these tests, along with descriptions of the methodology and full reporting of the Fourier-transform infrared spectroscopy (FTIR), Electrochemical Impedance Spectroscopy (EIS) and the oxygen consumption testing, will be provided in a later publication.

Testing involved either multiple samples or multiple test sites on one sample to offer a degree of statistical viability and to assess the value of averaging datasets. Where a single sample could provide more than one reading, data was recorded at the same locations on each sample to standardise data sets for comparison. The test sites were assigned Roman numerals, observing the sample as a square, site I is closest to the drill hole top left-hand corner, II top right-hand corner, III in the centre, IV bottom left-hand corner and V bottom right hand corner (Figure 1).

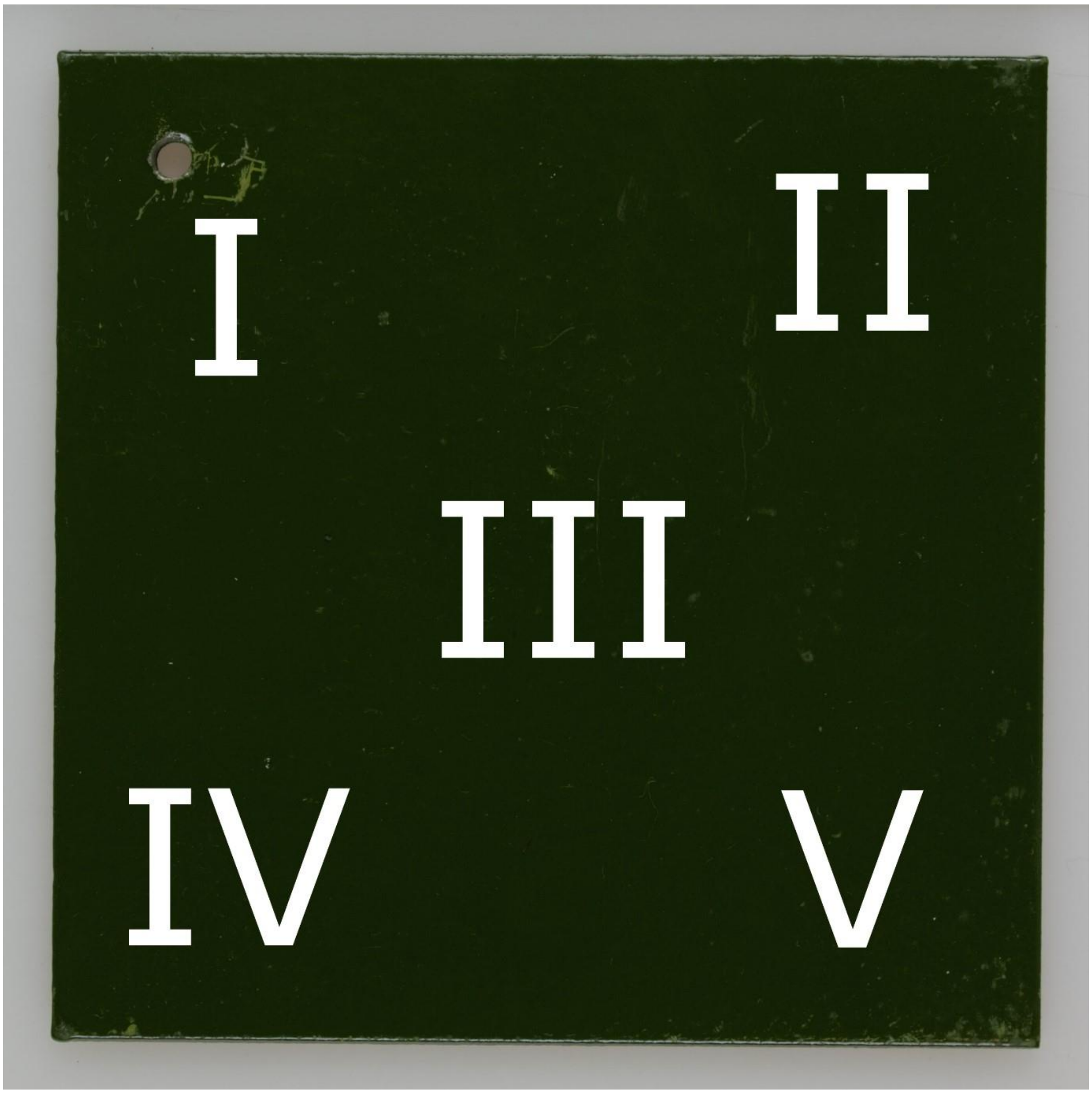

Figure 1. Standardisation of test areas on each sample.

Table 3. Test procedures, equipment, and data outputs.

Test or variable measured	Aging		Data and context
	In-situ	Laboratory	
Mass – Mettler Toledo XS205 balance (±0.005 g)	✓	✓	Variable required for oxygen consumption calculations
Colour – Konica Minolta Spectrophotometer CM-700d	✓	✓	Colour change as aesthetic
Dry Film Thickness – Positector 6000 FNS3 DTF meter	✓	✓	ISO 12944 thickness compliance for coating systems and changes to physical properties with aging
Gloss – Rhopoint IQ-S Gloss Meter	✓	✓	Aesthetic and textural change
FT-IR – Perkin Elmer Frontier 400 FT-IR	✓	✓	Chemical changes in topcoats
Pull off tests – PostiTest AT-A Automatic Adhesion Tester	✓	✓	Inter-coating adhesion and adhesion to substrate
EIS – PARSTAT3000 Single Channel Potentiostat/Galvanostat 30V, 1A, 7MHz	✓	✓	Assess reduction in corrosion protection with aging
Oxygen consumption – PreSens OXY-1 SMA; OXY-4 SMA	×	✓	Detecting metallic corrosion to identify degradation of coating
Impact tests – 301 DuPont Impact Tester	×	✓	Changes in physical properties of coating such as embrittlement or softening

Dry film thickness

Three readings were carried out at each of the five test sites, on both the front and reverse face of all 100 × 100 mm samples using a Positector 6000 FNS3 DTF meter, which was recalibrated using a flat steel plate prepared to Sa 2.5 after reading five samples.

Colour

The Konica Minolta CM-700d spectrophotometer with MAV 3 mm attachment was used to collect colour data on the front and back of the samples. It was calibrated to record five consecutive readings at a test site and determine their average. The results are recorded as values which represent different dimensions of colour. These are L* (lightness), a* (red/green), b* (yellow/blue), C* (Chroma), and h (hue), which are then used to calculate Spectral Component Excluded (SCE) and Spectral Component Included (SCI) data using the Equations 1 and 2.

$$SCE\ (E*) = \sqrt{L*^2 + a*^2 + b*^2} \quad \text{(Equation 1)}$$

$$SCI\ (E*) = \sqrt{L*^2 + C*^2 + h^2} \quad \text{(Equation 2)}$$

SCE is an accurate reading of pigment colour but SCI offers a more accurate representation of how the human eye perceives colour, including the effect of surface texture in its measurement. Therefore, SCI values provide a more accurate measurement of how colour changes produced by ageing would be perceived by a viewer. Five test sites were used on 100 × 100mm samples but only a single measurement from the centre was taken on the 50 × 50 mm samples due to the size of the spectrophotometer aperture.

Pull off tests

Pull off tests were carried out at the five test sites on each sample. The sample surface was roughened with 240 grain emery paper and an alloy dolly roughened with wire wool was adhered to a test site using a cyanoacrylate adhesive (Loctite). To promote adhesion, pressure was applied to the dollies by resting a flat plate of mass 650 g on top of all five dollies simultaneously for a minimum of one hour. The coating around the circular edge of the dolly was scored down to bare metal using the PosiTest tool supplied and the PosiTest was attached to the dolly. A pulling force was incrementally applied until the dolly released free from the surface. The value at which this occurred and the residue of coating attached to the dolly, which must be 50 % or more for the test result to be considered valid, were recorded.

Impact tests – accelerated ageing

Impact testing determined the minimum force required to damage to the coating system. A single sample from the group being tested was used to determine the calibrate the impact tester. This involved placing the impact hammer on the sample, raising a 300 g weight 100 mm above the hammer, then releasing it so it transferred its kinetic energy to the impact hammer and the sample beneath. This was repeated incrementally raising the height by 25 mm until the impact produced visible damage to the coating. This was used as the initial test height for the next sample in the group, which was impacted five times at the initial test height, five from a height 25 mm higher (the high-end test height), and five from a height 25 mm lower (the low-end test height). An inspection process then determined whether damage had occurred to the coating and according to the outcome, the hammer was raised or lowered to increase or decrease the impact force and detect the minimum height at which damage occurs. This process informs impact test procedure for the remaining samples in the test group. The mass of the weight and its height is used to calculate force, which is used for intra and inter sample comparison, pre and post aging.

Results and discussion

Initial dry film thickness

Comparing initial dry film thickness using the average at each of the measurement sites I to V across the samples reveals a consistent trend across all the systems. Sites I, and III are consistently the thickest, closely followed by V, with sites II and IV the thinnest. This effect is likely due to the samples being suspended from the drilled hole during spraying. Hanging the coupon from the hole in the top left-hand corner creates a rhombus shape, which vertically aligns test sites I (top), III (centre) and V (bottom) during spraying, with sites II and IV at the edges of the horizontal drawn through the centre of the coupon.

Figure 2 records the spread of thickness measurements as box plots with the mean thickness recorded as X on the plot. Comparing average thickness of the five coating systems identifies that International produces the thickest layer and Cromadex the thinnest by a significant margin. Considering both the average readings and the spread of data, the Hempel and Sherwin Williams 1 and 2 systems return similar thicknesses. All coatings produce inconsistent thickness. Identifying the highest value recorded in a fourth quartile and the lowest in a first quartile for each coating system, indicates the thickest coatings have the greatest range. Representing these ranges as a percentage of the maximum thickness value recorded in a fourth quartile, reveals Cromadex (63 %) has the greatest range with the other four coating systems being similar (48-56 %). Cromadex has the most outliers (17), closely followed by International (16), with Hempel having the fewest (2).

Considering thickness, Cromadex can be discounted as performing significantly worse than the other four coatings. International may be the better choice of coating system simply because although its thickness varies over a greater range, it has a significantly higher average thickness and, despite having a high number of outliers, even the thinnest outlier lies within the fourth interquartile of Sherwin Williams 2 system.

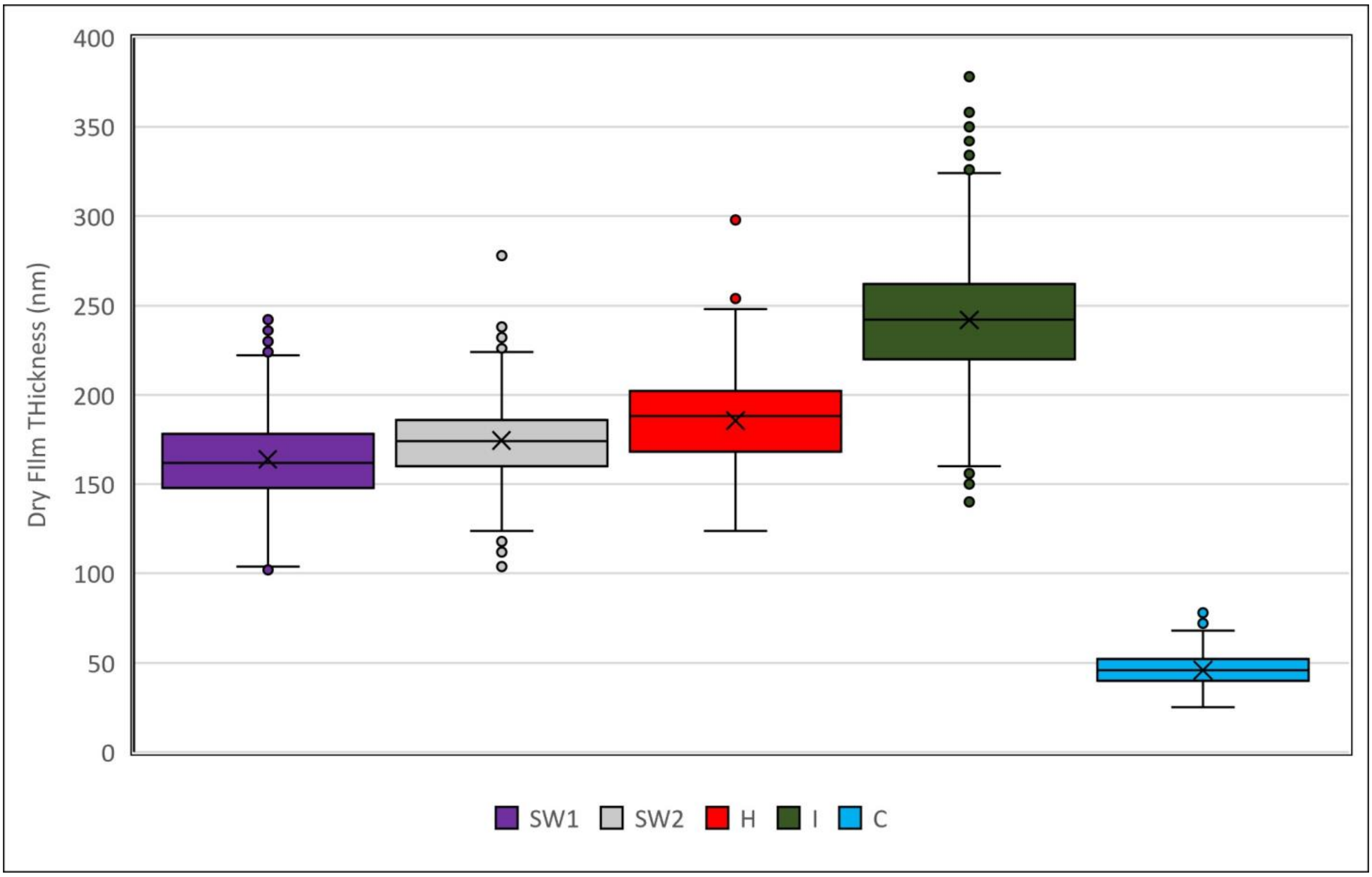

Figure 2. Dry film thickness of the five coatings. Box plots incorporate thickness readings taken from 60 (100 × 100 mm) samples of each coating at 5 measurement points (sites I to V) on each sample (total 300 measurement points per sample set).

The importance of the dry film thickness can be seen through the recommendations made by the manufacturers in their supporting documents. Almost all systems in a C5M environment are specified to be 320 nm thick [12-15]. The same or similar coating systems are recommended with reduced thickness requirements, typically 280 to 260 nm for less aggressive environments (C3 or C4 in Table 1), indicating systems are designed to withstand more aggressive environments by increasing their thickness, identifying this as an important characteristic. The failure of all these coating systems to reach the 320 nm specified for C5M environments that exist at Dover and Pendennis castles, may mean none are ideally suited to be used at those locations and are unlikely to reach their expected working life time. More quality control in application may be required, even when applying in accordance with manufacturers guidelines. Only International approaches C5M thickness (Figure 1) and Cromadex is far below it.

This data identifies the difficulty of obtaining consistent and even coverage over smooth flat surfaces hung vertically and sprayed in a standardised manner indoors. This will be compounded by the complex shape of the coastal artillery and the need to apply the coating in-situ for some pieces. Achieving manufacturer-specified thicknesses over the surface of a single piece of artillery is unlikely, hence longevity specifications may have limited meaning where thickness is one of the major controlling variables. This immediately makes definitive recommendations on performance, generated by any experimental study, difficult to provide for the English Heritage operational contexts.

Ranking the paints in terms of the resulting thickness of coating produced by following manufacturer instructions is difficult, as ranges overlap (Figure 1). International is the thickest but Sherwin Williams 1 and 2 and Hempel are all similar when the box plots are compared but Cromadex is the thinnest by far. Equal ranking was used for Sherwin Williams 1 and 2 and Hempel.

Ranking:

1. International
2. Sherwin Williams 2 + Sherwin Williams 1 + Hempel
3. Cromadex.

Colour change

SCI colour after ageing intervals is compared to the original colour reading of each individual sample before they were exposed to the ageing environment. It is considered that a change of 1.5 in the E value of SCI is visible to the naked eye [16]. Figure 3 records the change in ΔE values recorded at the specified test points on the accelerated ageing (3 and 6 months) and in-situ (1-year) samples, with the average ΔE recorded as X within the box plot.

Using average ΔE to compare the systems and considering the spread of data, the International coating system is the worst performer. It exceeds 1.5 ΔE by significant margins after in-situ exposure and accelerated ageing. The best overall performer is the Sherwin Williams 1 with all values below 1.0 ΔE except for two outliers within the accelerated ageing. Hempel and Sherwin Williams 1 were the best performing coating systems during in-situ ageing but Hempel exceeded 1.5 ΔE during accelerated ageing. Cromadex had a large spread of data but generally performed well in-situ. Sherwin Williams 2 performs poorly in-situ but well during accelerated ageing, which is the reverse of what is expected when extrapolating the accelerated ageing data. It indicates that short wavelength UV, elevated temperature and a damp 70 % RH are not the variables that cause it to change colour. Another variable such as time of wetness, pollutants such as salts or fluctuating or low temperatures may influence discolouration.

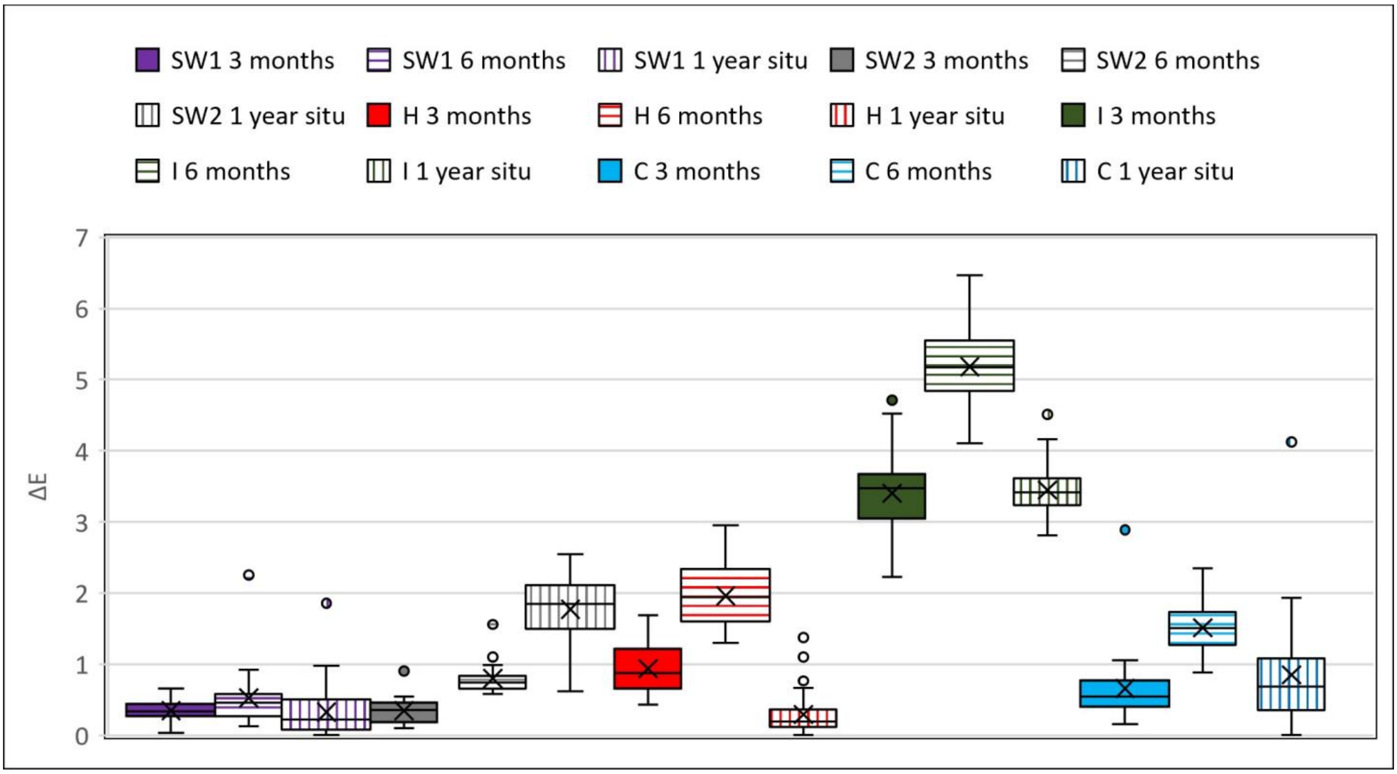

Figure 3. Box plots incorporating change in ΔE for accelerated aging (3 and 6 months) and 1 year in-situ recorded at five different points (sites I to V) on five (100 × 100 mm) sample coupons for each paint system (25 data points per box plot).

If this study was based only on accelerated ageing as a guide for choosing the coating likely to experience colour change in-situ, using data from this experimental study at this point in its progress, would favour choosing Sherwin Williams 1 closely followed by Sherwin Williams 2, which performed badly in-situ. Hempel would be rejected as exceeding ΔE 1.5 during accelerated ageing, yet it performed well in-situ. At present, accelerated ageing, as described here, is not providing suitable guidance for accurately identifying coatings resistant to colour change at coastal site environments in the UK. The importance of real time in-situ testing is evident when viewing this data. The coatings can be ranked for colour change on current data but with a further two years of testing ahead, new data may change this ranking (Table 4).

The results from pull off tests were returned in two forms: the force required to overcome the inter-coating adhesion of the system recorded in mega pascals for samples subjected to accelerated ageing (3 and 6 months) (Figure 4) and in-situ exposure (12 months) (Figure 5) and where the failure point in the coating system occurred (Table 5).

Table 4. Ranking of performance in colour change.

Ranking	In-situ 1 year	Accelerated ageing
1	Hempel	Sherwin Williams 1
2	Sherwin Williams 1	Sherwin Williams 2
3	Cromadex	Cromadex
4	Sherwin Williams 2	Hempel
5	International	International

Table 5. Pull off failure points within the coating systems.

	Initial failure	3-month failure	6-month failure	1 year in-situ failure
SW1	Within topcoat	Within topcoat	Within topcoat	Within topcoat
SW2	Between mid and topcoat	Between mid and topcoat	Between mid and topcoat	Between mid and topcoat
H	Within topcoat	Within primer and mid coat	Within primer	Within topcoat
I	Within topcoat and mid coat	Within primer	Within primer	Within all layers and at primer and substrate interface
C	Within mid coat and primer	Within mid coat	Within mid coat	Within mid coat and primer

Sherwin Williams 1 was the best performing coating system in terms of exhibiting no change in its adhesive properties. Overlap in the spread of data at all test points for both accelerated and in-situ ageing indicated no significant change in adhesion occurred (Figure 3 and Figure 4). The average values also indicated this and the failure point within the coating system remains unchanged (Table 4). It did not have the highest average initial adhesion value (5.9 MPa) but it exceeded Sherwin Williams 2 (3.5 MPa) and Cromadex (4.1 MPa) and was not much lower than the Hempel (7.2 MPa) and International systems (7.7 MPa). However, its spread data was wide (7.6 to 3.3 MPa for the in-situ sample) making the actual initial adhesion value hard to forecast accurately.

The Sherwin Williams 2 system had the lowest initial adhesion (3.5 MPa) but it is likely that it retains this value, as the accelerated ageing readings at 3 months appeared to be anomalous, being skewed to exceed the initial unaged starting value (Figure 3). This may indicate changes after 3 months that are not producing effects after 6 months accelerated ageing or that the readings were either a misapplication of the measurement system or a user error. Impact testing revealed the hardness of this coating increased significantly after 3 months accelerated ageing but then reduced at 6 months (Figure 5), potentially indicating a property change at 3 months that is not lasting. The in-situ range after 12 months reflected initial starting values and returned a similar average (Figure 4). Failure points in the system remain unchanged (Table 4).

The International and Hempel systems had high initial adhesion averages (7.7 MPa and 7.2 MPa) which reduced rapidly with accelerated ageing and after 12 months in-situ (Figure 3 and Figure 4). Hempel had the worst adhesion of all coating systems after 6 months accelerated ageing. The failure point changes from the topcoat to the primer for both these systems after 6 months accelerated ageing, which aligns with the major loss of adhesion and signifies a change in coating morphology (Table 4). Cromadex has the weakest initial adhesion, which reduces significantly following both accelerated and in-situ ageing (Figure 4).

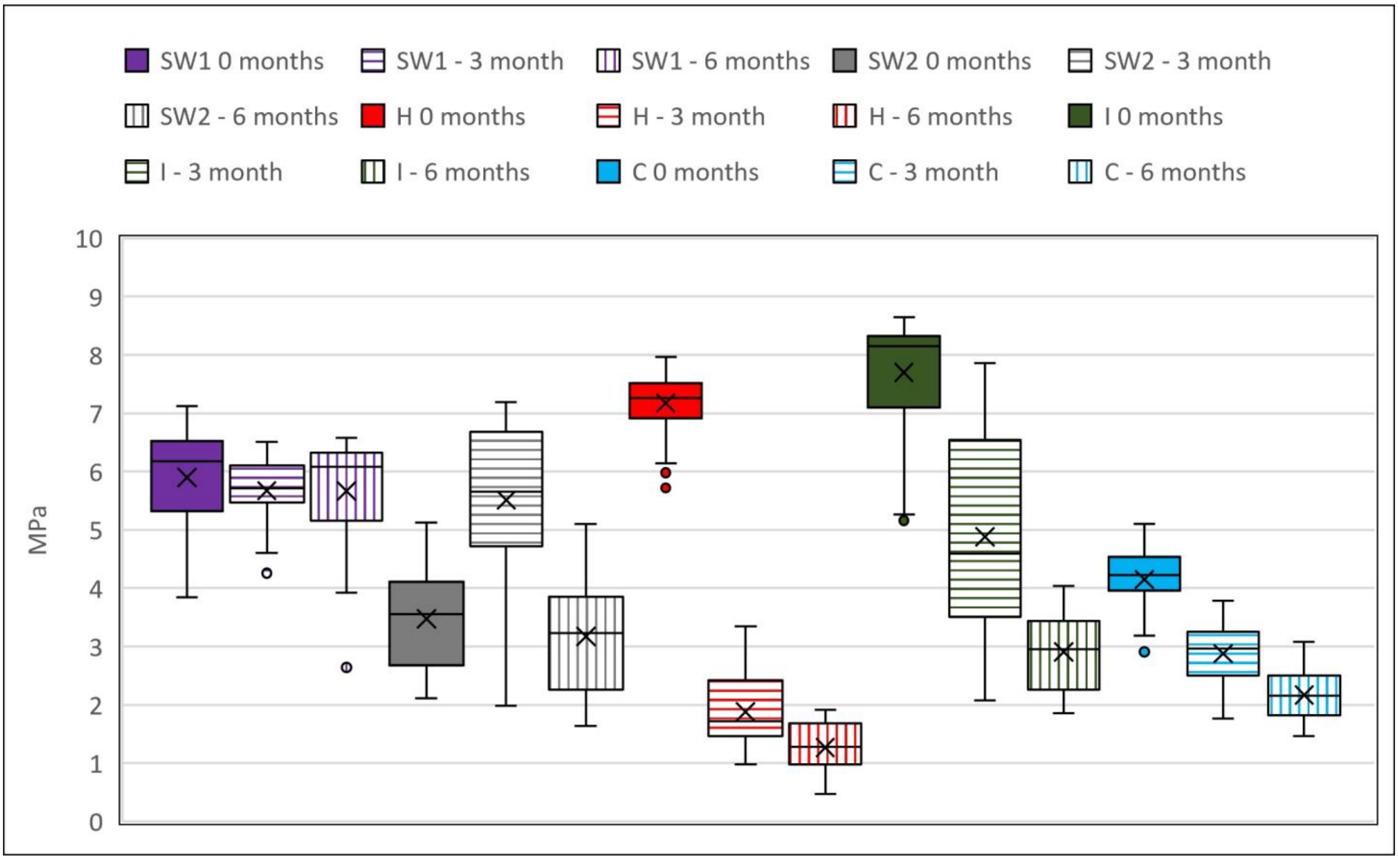

Figure 4. Box plot of pull off test data for samples subjected to accelerated aging (3 and 6 months). Five samples and five pull off values per sample.

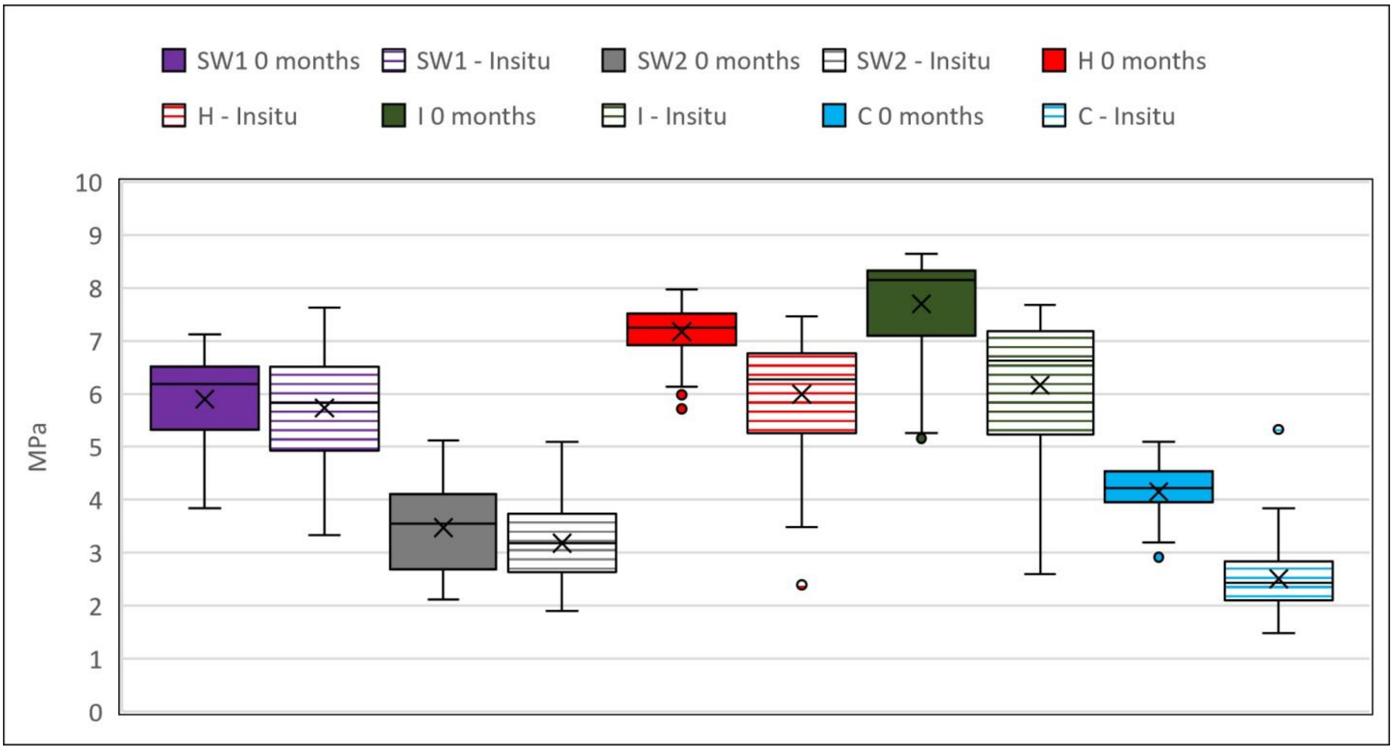

Figure 5. Box plot of pull off test data for samples exposed in-situ (1 year). Five samples and five pull off values per sample.

The retention of initial adhesion values by the Sherwin Williams systems during accelerated ageing and in-situ exposure under accelerated ageing indicate they are less prone to light and heat ageing than the other coating systems. Despite not having the best initial pull off values they remain unchanged, making their performance predictable and hence the coatings to choose. In contrast, the other coatings significantly degrade in light ageing and in-situ. Whether they reach values as low as Sherwin Williams 2 initial adhesion value remains to be seen. Even if this does not occur, the changes that caused adhesion loss and changes to the separation point in these systems likely make these coatings worse and unpredictable performers. All the coating systems recorded wide ranges within their data sets, making it difficult to offer a precise value for their adhesive ability but trends in adhesion are evident. Sherwin Williams 1 and 2 are good coating choices for retaining their initial adhesion to substrates in high UV environments. In this instance, accelerated ageing offers useful information on coating performance.

Ranking of retention of adhesive properties of coating systems: 1 – Sherwin Williams 1; 2 – Sherwin Williams 2; 3 – International; 4 – Cromadex; 5 – Hempel.

Impact test

The impact resistance of each coating system subjected to accelerated ageing is reported as average values of successful impact tests on four samples in each paint group (Figure 6), with the fifth sample determining the initial starting height for the test (Figure 6).

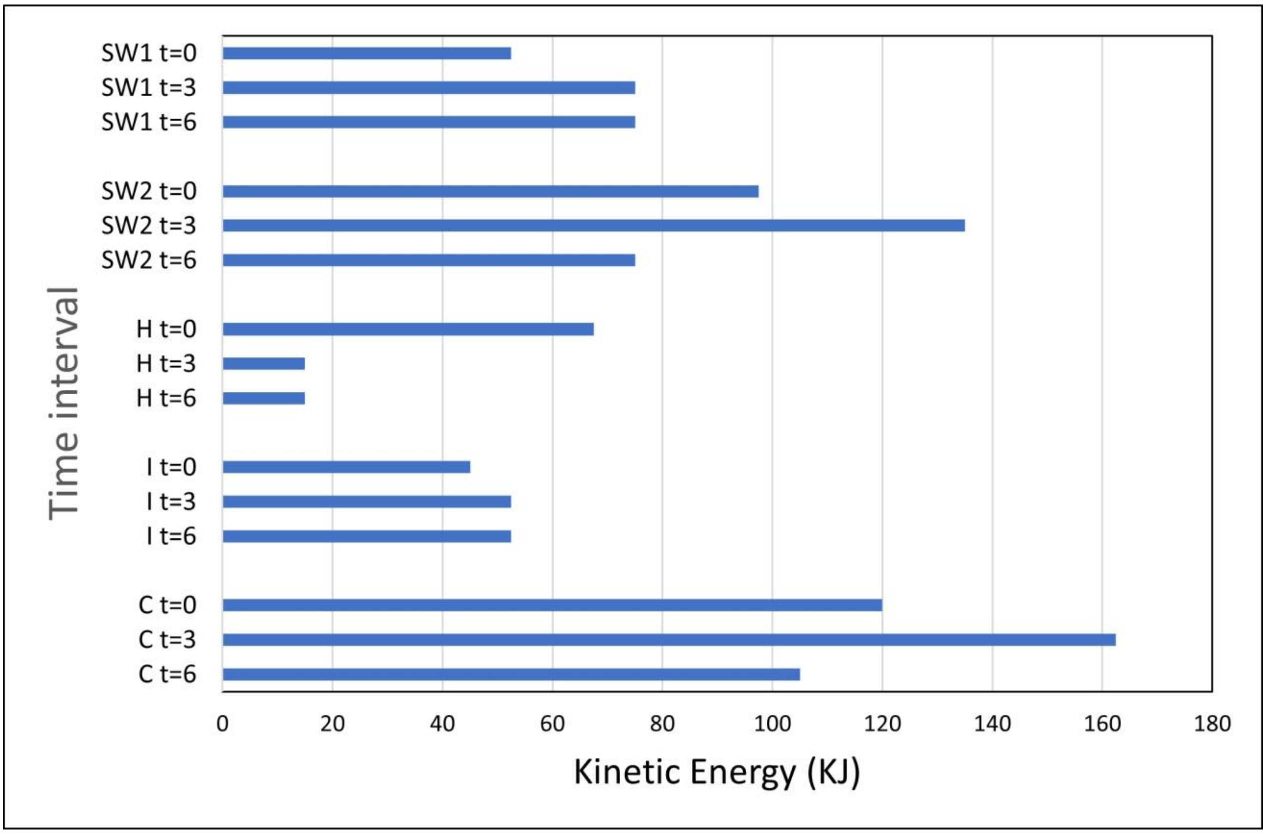

Figure 6. Bar chart showing the force required to compromise the surface of the coatings via impacts after aging periods.

Table 6. Ranking for performance in impact tests.

Ranking	In-situ 1 year	Accelerated ageing
1	Cromadex	Sherwin Williams 1
2	Sherwin Williams 2	International
3	Hempel	Cromadex
4	Sherwin Williams 1	Sherwin Williams 2
5	International	Hempel

Six months accelerated ageing significantly embrittled the Hempel system and Sherwin Williams 2 and Cromadex lost some resistance. At 3 months, all paint systems except Hempel either retained or increased their impact resistance beyond their unaged values. At 6 months, only Sherwin Williams 1 and International systems retained this value, both Sherwin Williams 2 and Cromadex fell below their initial starting value after 6 months ageing. Considering all the paint systems, Cromadex had the highest initial and 6 month impact values, although its degradation during ageing suggests that this is unlikely to persist after the full 15 months of exposure. Its high impact resistance may relate to its alkyd base, as the polyurethane topcoats on the other systems are often considered to be quite brittle, particularly after ageing [7]. Hempel was consistently damaged at the lowest force that the testing equipment would allow and its resistance to heat may be a problem since occasionally its surface blisters during accelerated ageing.

Ranking impact resistance of coatings is difficult. Is a coating with a low but unchanging impact resistance preferable to one with a much higher initial impact resistance value that diminishes with age? It may not resist damage sufficiently well to fulfil a long-term performance brief. A simple ranking is offered in Table 6 but with the above reservations.

General discussion

Tests are ongoing and so data reported here cannot provide a comprehensive view of coating performance and longevity. Discrepancies between in-situ and accelerated aging results indicate data interpretation will be complex and its extrapolation to context difficult. Will the current excellent performance of the Sherwin Williams coating systems in UV light and high temperatures translate to its performance in-situ?

Specific factors may carry more importance for the end user and will skew its importance in a ranking system. Decisions must be made on a contextual basis. For example, whether significantly better initial adhesion that reduces with time is preferred to a lower initial value that does not change over time. Colour change may not affect the degree of protection afforded by a coating, but it may be a critical priority for an end user who is prepared to sacrifice longevity for colour retention. Similarly, resistance to impact may be considered the number one requirement to avoid application of unsightly inpainting repairs that spoil the aesthetic of an object and to avoid the cost of frequent maintenance. With a differing balance of criteria, a coating system may become unfit for purpose before its protective ability is degraded to the point of requiring replacement. Stating which of the five coatings tested here is currently offering the 'best' performance relates to context, which is for English Heritage to decide.

Balancing the extent of failure within any one of these test procedures makes a holistic assessment of 'best performance' difficult, if not impossible and the extent of failure in a single category, may eliminate a coating as an option. Current data based on best performance in a specific test (listed at the close of the discussion of each test) indicates Sherwin Williams 1 as the best overall performer.

Conclusion

Data from real time in-situ testing and accelerated ageing, using short wavelength UV, 60 °C and 70 % RH to test selected properties of five coating systems identified the challenges of using accelerated ageing to predict the working environment. One coating system produced the best results in most of the tests and a ranking process identified it as the best overall performing coating based on film thickness, colour change, adhesion to substrate and resistance to impact. This was the Sherwin Williams 1 coating system.

The timeframe for testing is only one third completed and some tests are not reported here. The data here reports only physical properties. EIS and oxygen consumption will examine protective properties of the coatings and FTIR will explore chemical change. Increasing data may change the ranking of reported here. The final decision on the best coating to use on their coastal artillery lies with English Heritage, aided by this data set.

REFERENCES

1. BS EN ISO 12944-6:2018, *Paints and varnishes. Corrosion protection of steel structures by protective paint systems* (2020), https://www.iso.org/standard/51378.html (accessed 2023-08-19).
2. Alcántara, J.; de la Fuente, D.; Chico, B.; Simancas, J.; Díaz I.; Morcillo, M., 'Marine Atmospheric Corrosion of Carbon Steel: A Review', *Materials* **10**(4) (2017) 406, https://doi.org/10.3390/ma10040406.
3. Alcántara, J.; Chico, B.; Díaz, I.; de la Fuente, D.; Morcillo, M, 'Airborne chloride deposit and its effect on marine atmospheric corrosion of mild steel', *Corrosion Science* **97** (2015) 74–88, https://doi.org/10.1016/j.corsci.2015.04.015.
4. Asami, K.; Kikuchi, M., 'In-depth distribution of rusts on a plain carbon steel and weathering steels exposed to coastal–industrial atmosphere for 17 years', *Corrosion Science* **45** (2003) 2671-2688, https://doi.org/10.1016/S0010-938X(03)00070-2.
5. Chico, B.; Alcántara, J.; Pino, E.; Díaz I.; Simancas, J.; Torres-Pardo, A.; de la Fuente, D.; Jiménez, A.; Marco, J.; González-Calbet, J. M.; Morcillo, M., 'Rust exfoliation on carbon steels in chloride-rich atmospheres', *Corrosion Reviews* **33**(5) (2015) 263-282, https://doi.org/10.1515/corrrev-2015-0025.
6. Rémazeilles, C.; Refait, P., 'On the formation of β- FeOOH (akaganéite) in chloride-containing environments', *Corrosion Science* **49**(2) (2007) 844–857, https://doi.org/10.1016/j.corsci.2006.06.003.
7. Jarman, J.; Salvatin, J., *Comparison of Polyurethane and Polysiloxane coating systems in marine environments*, Bachelor dissertation, Department of material engineering, California polytechnic state University, San Luis Obispo (2013), https://digitalcommons.calpoly.edu/matesp/87/ (accessed 2023-06-24).
8. Arukalam, I.; Oguzie, E.; Li, Y., 'Nanostructured superhydrophobic Polysiloxane coating for high barrier and anti-corrosion application in marine environment', *Journal of colloid and interface science* **512** (2018) 674-685, https://doi.org/10.1016/j.jcis.2017.10.089.
9. BS EN ISO 8501-1:2007, *Preparation of steel substrates before application of paints and related products* (2007), https://www.iso.org/obp/ui/#iso:std:iso:8501:-1:ed-2:v1:en (accessed 2023-08-19).
10. Binder, Model KBG 240, Constant climate chamber with large temperature/humidity range, in *Technical data sheet* (2022), https://www.binder-world.com/uk-en/product/asset/180638?cHash=701d3078ba34b5ecc1edd17bcce81618 (accessed 2023-08-07).
11. Hemmerich, K. J., 'General ageing theory and simplified protocol for accelerated ageing of medical devices', *Medical Device and Diagnostic Industry Ind Qual Assur*, (1998), http://www.mddionline.com/article/general-aging-theory-and-simplified-protocol-accelerated-aging-medical-devices (accessed 2023-08-07).
12. International, ISO 12944, *Corrosion protection of steel structures by protective paint systems* (2019), https://international.brand.akzonobel.com/m/5f44067b30402a97/original/ISO12944_UK_LR.pdf (accessed 2023-08-07).
13. Sherwin Williams, *Iso 12944, Systems Guide 2020 edition*, online (2020), https://protectiveemea.sherwin-williams.com/Documents/InformationCentre/iso-12944_coatings-system-guide.pdf (accessed 2023-08-07).
14. Hempel, *How to select the right paint system: Guidelines for corrosion protection in accordance with ISO 12944*, online (2019), https://asset.source.thenbs.com/api/pdf/78cc1a4a-2ae7-4615-b787-7e29fa790a3f (accessed 2023-08-07).
15. *Steelkote by Baril*, Product brochure (2017), http://www.baril.cz/dokumenty_ostatni/17_1-01112017_SteelKote_Brochure_WEB_EN.pdf (accessed: 07/08/23).
16. Pretzel, B, 'Now you see it, now you don't: lighting decisions for the Ardabil carpet based on the probability of visual perception and rates of fading', in *Proceedings of ICOM-CC 15th Triennial Meeting*, vol. II, Allied Publishers, New Delhi (2008) 759-765, file:///C:/Users/CHAM/Downloads/ICOM-CC_2008_New%20Delhi_122.pdf (accessed 2023-06-24).

RECEIVED: 2023.1.10
REVISED: 2023.3.10
ACCEPTED: 2023.6.19
ONLINE: 2023.9.24

This work is licensed under the Creative Commons
Attribution-NonCommercial-NoDerivatives 4.0 International License.
To view a copy of this license, visit
http://creativecommons.org/licenses/by-nc-nd/4.0/deed.en.