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Experimental Evaluation of Structural Steel Coating Systems

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Abstract

Departments of Transportation currently use the conventional three-coat system as the predominant choice for the corrosion protection of steel bridge structures. Eliminating one step in the coating process could potentially save time and cost associated with lane closures and traffic control costs. This research paper evaluates several two-coat systems based on the zinc-rich primer and polysiloxane top coat technology. All samples were conditioned and coated in a state-of-the-art, climate-controlled paint booth, simulating common field <u>en</u>vironmental <u>con</u>ditions (ENCON) (ENCON 1: 25 °C/50% RH, ENCON 2: 10 °C/40%RH, and ENCON 3 :32°C/80% RH). Accelerated weathering tests were performed on 435 coated samples (scribed and un-scribed). Regardless of the ENCON considered, the performance of the two-coat system is very comparable to the three-coat system. This coating technology offers much improved performance with quicker set time and better adhesion to steel structures. Considering its durability and ease of application, this two-coat system can be attractive to other public and private agencies to enhance and extend the service life of steel structures.

Introduction

Over the last twenty years, most Departments of Transportation (DOTs) have used a three coat system based on Organic and Inorganic Zinc primer coat, Epoxy intermediate coat and Urethane finish coat (OZEU/IZEU) for the corrosion protection and aesthetic enhancement of structural steel members [1]. By eliminating one step in the coating process, the cost can be reduced through minimizing labor costs and lane closures. For this reason, the market developed the latest technology in structural steel coating based on a two-coat system, a zinc-rich primer coating and Polysiloxane top coat (OP/IP). The siloxane epoxy hybrid polymer combines the properties of organic and inorganic compounds in a new class of resins for protective coatings [2]. Hybrid systems based on polysiloxanes develop a high performance coating for the anticorrosive protection of metals. It is claimed that the Polysiloxane systems are able to provide a higher performance than traditional organic binders used in the heavy-duty coatings industry (e.g., epoxies or polyurethanes). A few important features of the Si-O bond in Polysiloxanes are the strength of the Si-O in comparison with the C-C bonds in epoxy-urethane [3, 4, 5]. The silicon is already oxidized and has more corrosion resistance than a carbon bond. In addition, the polysiloxane coatings have a low volatile organic compound (VOC) content (60 to 70 % less than urethane coating systems) and are made without any dangerous isocyanates. This coating technology could offer a much improved performance with a quicker set time and better adhesion to steel structures. However, each new coating system dictates its own particular requirement for surface preparation and application, related not only to its film-formation methodology and its mechanism of protection, but also to its resistance to moisture, sunlight, and exposure [6, 7]. Most suppliers' technical data sheets do not completely cover or list all essential qualification tests, and therefore, more comprehensive testing is required to quantify the performance characteristics. Such critical factors are the effect of temperature and humidity on the application and cure of this two-coat system. Hence, to specify an appropriate coating system that is known (through testing and validation) to perform well is more important than ever. Specification of coatings by generic type or using an equivalent approach can lead to disappointing results [8].

Despite the unique advantages of polysiloxane coatings, few field applications were translated to steel bridges. One of the earliest applications is the Peace Bridge, connecting the U.S. and Canada across the Niagara River in New York. This bridge was painted nearly 21 years ago using an earlier version of the two-coat system [5], and recently the Roosevelt Bridge in New York City (2008) painted using the two-coat system by International Paints Co [9].

To set the stage for any potential field applications, a comprehensive testing approach is presented and conducted in this paper. This experimental work highlights and evaluates various newly enhanced and hybrid two-coat polysiloxane systems. The three-coat system produced by Sherwin-Williams (OZEU) was selected as the control panel and provided the benchmark comparison data to score against other selected coatings.

Materials and Sample Preparations

Five different coating systems were selected. The three-coat system was supplied by Sherwin Williams and labeled as system A. All other two-coat systems with the polysiloxane top coat were supplied by PPG Industries, Carboline Co., International Paints Co., and Sherwin Williams. These systems were randomly labeled as B, C, D, and E, not necessary in the same order as listed in Table 1. Carbon steel grade 50 (A572 alloy) commonly used in steel bridge structural members was selected. All information related to sample size such as; steel grade, sample surface preparation, primer, intermediate, top coat, and thickness for each layer, are listed in Table 1. Steel surfaces of all samples were cleaned and abrasive blasted to SSPC SP-6. All samples and related coating components (primer/mid-coat/top coat) were placed and conditioned for 24 hours in the paint booth chamber for each environmental condition (ENCON). Three paint events occurred for all three ENCONs considered. These environmental conditions simulate common field temperature and humidity at time of coating or repair: ENCON1, 25°C /50%RH; ENCON2, 10°C/40%RH, and ENCON3, 32°C/80%RH. A conventional airless spray pump, Graco Airless Sprayer with 45:1 pump and 0.432 mm fluid tip, was used to coat all samples. All primers were allowed to dry for a 4 hour period in the climate controlled paint-booth chamber. The three coat system took an additional 4 to 5 hours depending on the ENCON. Temperature and humidity played a significant role in the drying time. In general, the higher the temperature is, the faster the curing time. Consequently, all samples sprayed under ENCON 3 cured much faster than other ENCONs. Drying tests were then carried out based on the ASTM D1640 [10] specification and then cured for 21 days under ambient temperature before testing.

Table 1. Coating System Matrix (S/W: Sherwin Williams, CB: Carboline and IP: International Paint)

ENCON1;25°C/50%RH, ENCON2;10°C/40%RH, ENCON3; 32°C/80%RH					
Supplier (System)	**Substrate and panel sizes**	**Pretreatment**	**Primer**	**Intermediate**	**Topcoat**
S/W-3C Epoxy-Polyurethane	A572 Grade 50 Steel 76 X 152 mm 101 X 152 mm 100 x 100 mm Thickness of all steel samples 4.76 mm	Abrasive blast to SSPC SP-6	S/W Zinc Clad 200 (Organic Zinc) 3 components 75 - 125 µm	Macropoxy 646 FC 2 components 125-250 µm	S/W HP Acrylic 2 components 50- 75 µm
S/W-2C Epoxy-Siloxane			S/W Zinc Clad 200 (Organic Zinc) 3 components 75 -125 µm	N/A	S/W Polysiloxane XLE-80 2 components 125 - 175 µm
PPG-2C Modified Siloxane Hybrid			Amercoat 68HS (Organic Epoxy Zinc-Rich) 3 components 50 - 125 µm	N/A	PSX 700X 2 components 75 -175 µm

IP-2C Acrylic Polysiloxane	Interzinc 52 (Organic Epoxy Zinc-Rich) 2 components 40 µm Min	N/A	Interfine 979 2 components 100 -150 µm
CB-2C Modified Siloxane Hybrid	Carbozinc 858 (Organic Zinc-Rich Epoxy) 2 components 75 -125 µm	N/A	Carboxane 2000 2 components 75 - 175 µm

Note: 2C =Two-coat system; 3C=Three-coat system

Experimental Results

The experimental program included adhesion tensile strength, taber abrasion resistance, chipping resistance, cyclic accelerated weathering testing, salt and fresh water resistance testing and UV/condensation exposure testing. A total of 435 samples were tested in this research work. Following ASTM specifications and prior to testing, all samples were conditioned for 24 hours at 23±2°C and 50%RH ± 5% RH. The following are the procedures and devices used in this experimental phase of this program:

The Dry Film Thickness (DFT) of coatings on steel substrate was measured via a DFT gauge, a non-destructive technique using a combination of magnetic/eddy current probe [10]. Readings were performed on four points per panel for each coating system and the average is tabulated in Table 2 for each different ENCONs. All thicknesses ranged within the specified manufactures thickness recommendations (top coat, mid coat, and primer, Table 1).

Table 2. Average Thickness of Coatings

	Average DFT of Coating Systems(µm)				
Environmental Condition	**A**	**B**	**C**	**D**	**E**

Encon 1	317	247	248	133	160
	328	253	278	143	182
Encon 2	302	215	244	229	237
	294	217	227	216	234
Encon 3	366	167	248	229	243
	387	172	240	229	246

A total of 90 samples (18 samples per coating system) were tested in accordance with the Adhesion Tensile Strength ASTM D4541 Type IV [11]. The PATTI device (Quantum Gold Adhesion Tester F-6) was used for this purpose. Figure 1 shows the results of adhesion tests with a pull-off stud taped to the side of the panel, depicting the failure modes experienced for each coating system in different environmental conditions (for example A1, refers to system A coated and cured under ENCON1, and A2 under ENCON2, etc.). Most of failure modes experienced in ENCON1 were the cohesion and top coat failure. For ENCON 2 the failure modes switched to cohesion in the primer except for system A. ENCON 3 failure modes were in the cohesion break of the top coat except for system D which was primer cohesion failure.

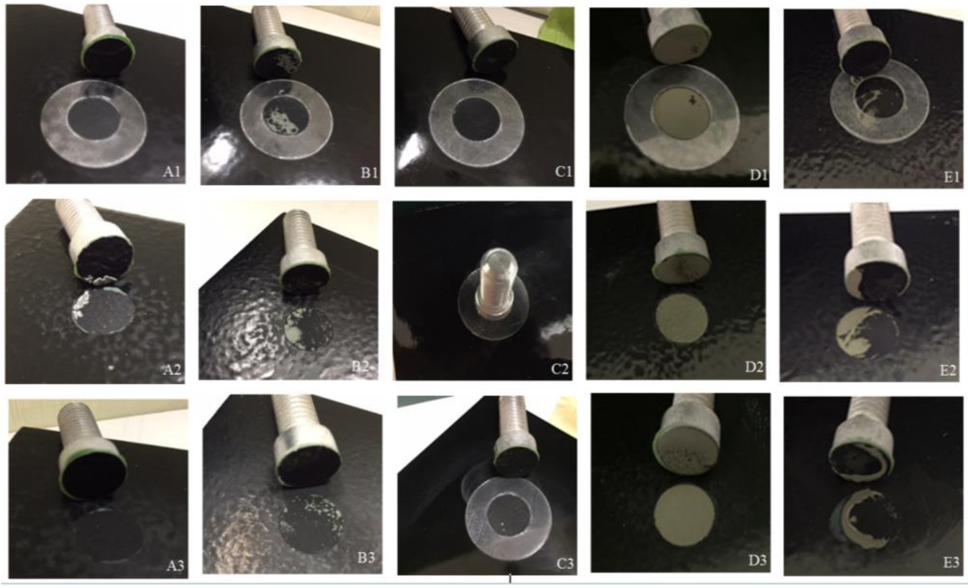

Fig.1. Failure Modes Post Adhesion Test (ENCON1: first row, ENCON2: second row and ENCON3: third row)

A total of 45 samples (9 samples per coating system) were performed in accordance with the Chipping Resistance of Coatings (ASTM D 3170) [12]. Three test panels (101 mm by 152 mm) for each coating system were sequentially tested by mounting in the target chamber of the Gravelometer and firing one pint of water eroded alluvial stones (passing 9.5 mm sieve) at the test panel using an air gun operating at 0.5 MPa. After the gravels impact the panel, the samples were evaluated for chipping by removing loose adhering paint with tough adhesive tapes and then comparing the samples to the transparent photographic chipping standards. This comparison is based on the size and number of chips and point of failure notation.

Figure 2 shows the chipping resistance results for all different environmental conditions. At the end of the test, all samples were characterized based on the size of chips, number of chips and point of failure notation.

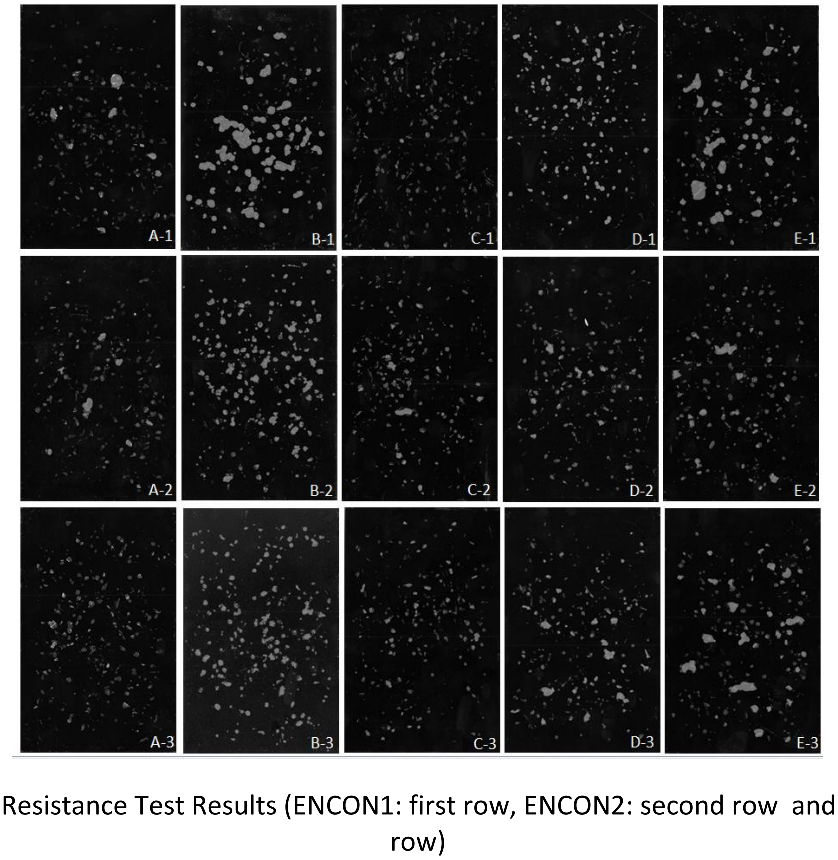

Fig.2. Chipping Resistance Test Results (ENCON1: first row, ENCON2: second row and ENCON3: third row)

To compare the area of chipping, all of the samples were scanned and evaluated using Image J software [13] to calculate the amount of chipped area. The result is shown in Figure 3. For ENCON1, most failure modes were in the top coat. However, this failure mode switched to primer/ top coat for ENCON 2 and 3. This trend is comparable to the adhesion test performed previously on all coating systems. This finding justifies the higher adhesion result for all coatings when sprayed under ENCON 2 and 3.This part will be discussed later in the following section of this paper.

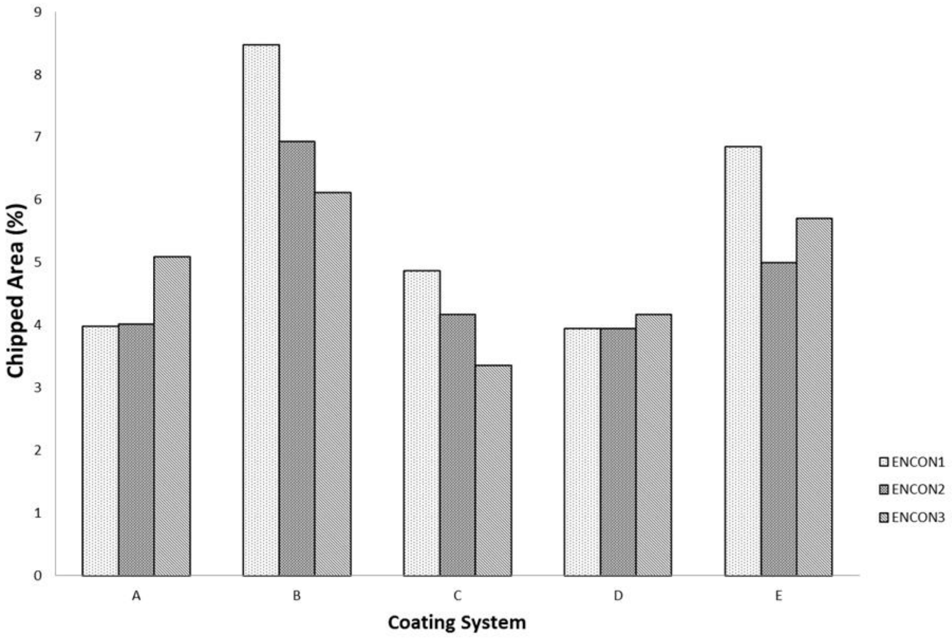

Fig.3. Calculated Chipped Area with Image J Software [17]

A total of 90 samples (18 samples per coating) were tested for Abrasion Resistance of coating (ASTM D4060) [14]. All coated test panels (100 by 100 mm) were weighed and then mounted on the turntable of a Taber Abraser (Model 5150 by TABER Industries). An auxiliary weight of 1000 g was applied on the abrasive wheel (CS17 wheel). The turntable rotated for a specified number of cycles (500-cycle increment) and then removed and reweighed (nearest 0.1 mg) to determine the wear index. The panels were then re-mounted on the turntable, and the cycles were counted until wear through to the primer was observed. The three-coat samples (system A) were tested until the topcoat layer was removed to expose the sub-coating layer.

Equation (1) was used to calculate the Wear Index as follows:

$$\text{Taber Wear Index} = \frac{(A-B)\times 1000}{C} \qquad (1)$$

Where, A is the initial weight before abrasion, B is the final weight after abrasion, and C is the number of cycles to wear-through. Figure 4 shows the test results for all coating systems relative to each environmental condition.

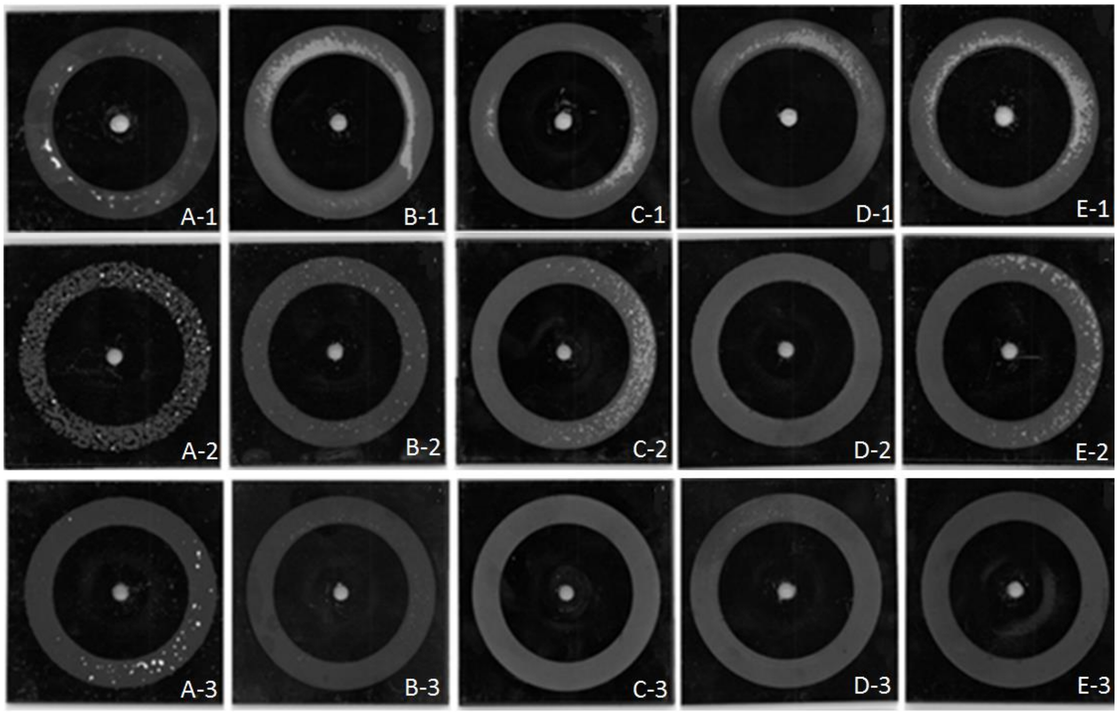

Fig.4. Taber Abrasion resistance-Failure modes (ENCON1: first row, ENCON2: middle row and ENCON3: third row)

A cyclic corrosion laboratory test (GMW 14872) [15], was carried out to assess the corrosion resistance of all coating systems (ENCON1 and ENCON2). This test provides a combination of cyclic conditions (salt solution, various temperatures, humidity, and ambient environment) to accelerate the metallic corrosion. It consists of four hand sprays of a 1.075% salt mist (0.9% NaCl, 0.1% $CaCl_2$, and 0.075% $NaHCO_3$) at ambient temperature, with each spray occurring approximately every 90 minutes. Then, all coated samples were placed in the fog-chamber for 8 hours of fog exposure at 49°C, followed by 8 hours of dry off at 60°C. After completing the 20 cycles, 6 panels (3 scribed and 3 unscribed) per coating system were evaluated for blistering, degree of rusting and rust creepage. The panels were inspected for corrosion in accordance with ASTM D714 [16] to evaluate blistering, ASTM D1654 [17] for evaluating undercutting (creepage from scribe), and ASTM D610 [18] to evaluate degree of rusting on painted surfaces.

Figure 5 and Table 3 show the acceleration weathering test results on scribed samples. None of the unscribed samples showed any type of rusting on the surface. The degree of blistering was also zero. For the scribed panels, most of the samples showed some rust creepage, specifically for C and D where loss of adhesion was less than 1.5 mm. An average percentage of rust was calculated on the scribed samples, system C and D showed 100% rusting for ENCON1, System E showed only 15% rusting (Figure 5).

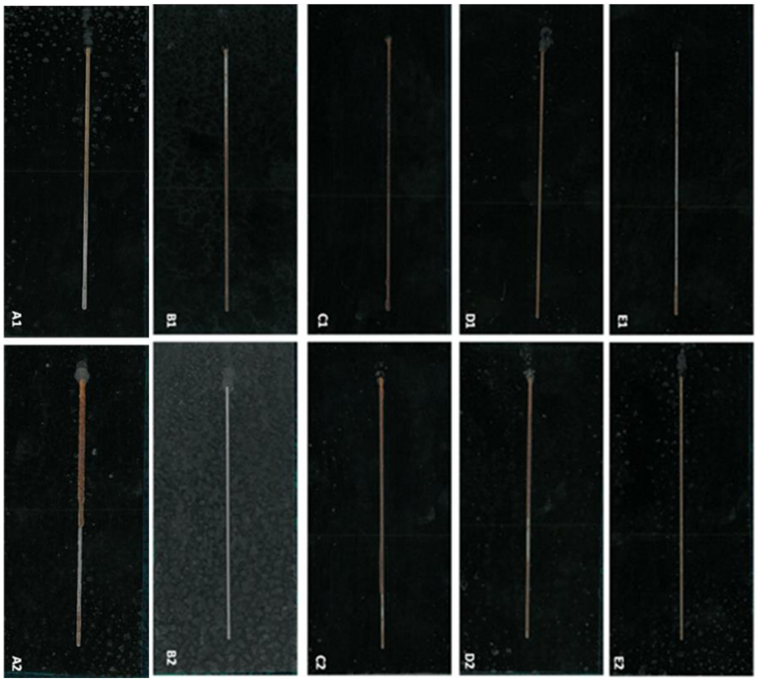

Fig. 5. Rust in Scribed Samples after 20 Cycles of Exposure (ENCON1: first row, ENCON2: second row)

Table 3. Results of Corrosion Weathering Test

	Average percent of rust on scribe		**Rust Creepage Rate* for scribed Samples**	
Coating System	**ENCON1**	**ENCON2**	**ENCON1**	**ENCON2**
A	35	70	0	0
B	25	0	0	0
C	100	40	1	1
D	100	80	1	0
E	15	85	0	0

* Rate of 0 = No lifting of coating, and 1=Lifting or loss of adhesion up to 2 mm (1/16") away from the scribed surface

A Fresh and Salt Water Resistance Test (ASTM D870) [19] was performed on all samples conditioned and coated under ENCON1. Two coated steel samples (for each coating system) were fully immersed in two mediums of distilled water and 3 wt.% NaCl solution in a glass container with three different exposure period of 7, 14, and 30 days. Glass containers were stored in a controlled chamber under 38°C and 98% relative humidity. All of the samples were checked for any sign of corrosion, blistering, or softening after 7, 14, and 30 days of exposure. No effect of any sign with respect to blistering or softening was observed in all five coating systems. Following this immersion test (30 days exposure), an adhesion test was conducted on all exposed samples (6 adhesion tests for the dry or unexposed samples and 4 tests for each of the DI water and saline exposed samples). Average results are shown in Figure 6. As observed, system C shows a significant change in adhesion loss (66% drop) after 30 days exposure, both in the distilled water and saline solution. This indicates some swelling in the coating/softening. Meanwhile, system D and A demonstrated a significant performance (16% increases in distilled water) with respect to good stability and adhesion.

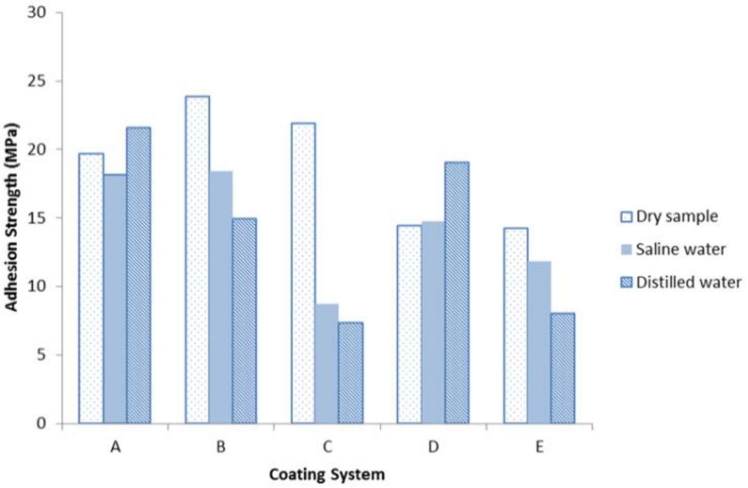

Fig. 6. Tensile Adhesion Strength– Post 30 days Exposure in Saline Solution and Distilled Water

To evaluate the UV effect on the coated samples, 9 samples of each system were prepared and applied under ENCON1 conditions and then exposed to 3000 hours in a UV/condensation chamber (ASTM D4587-11) [20]. The QUV condensation chamber subjects all samples to a constant temperature and moisture, UV wavelength and irradiance levels. Measurements were then taken after each 1000 hours increment. Initial values for the color and gloss were recorded based on the ASTM method for specular gloss (ASTM D523-05) [21]. A BYK Gardner Spectro-Guide Sphere device was used for calculation of gloss index and color retention. The measurements of gloss index were calculated at three different angels (20°, 60°, and 85°). The average values of six measurements on each panel were reported as the gloss index value for that panel. To assess changes in the colors of the coated samples, the CIE LAB (International Commission on Illumination) color indexing model/standard was used in this study. As depicted in figure 7 and 8, systems A and D show promising stability in gloss with respect to other systems. For color retention, system C had the most noticeable color change in comparison to other systems. System D showed a reasonable resistance in gloss and color change after 3000 hours.

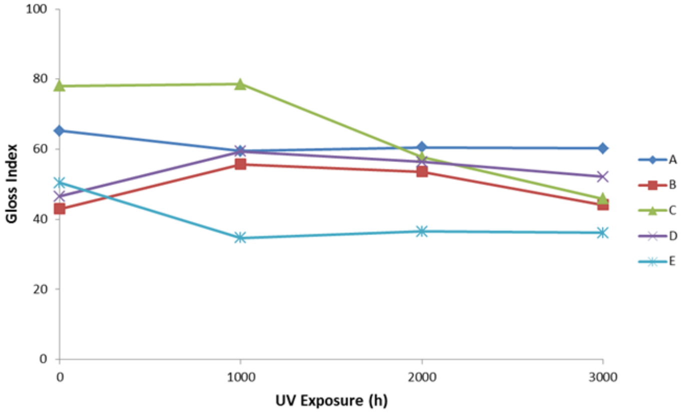

Fig. 7. Change in Gloss Index after 3000 hours UV/condensation Exposure

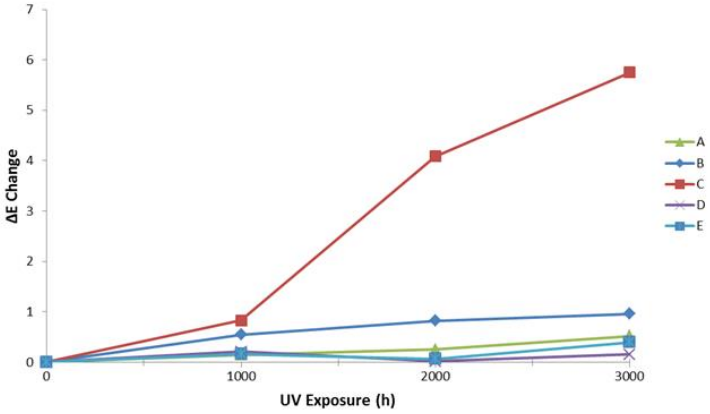

Fig. 8. Change in color after 3000 hours UV/condensation Test

Examining Figure 7, system C shows a substantially high gloss retention after 1000 h (highest value); however, its gloss retention significantly dropped after 2000 h. Systems A, B and D exhibited a very stable trend; also system E showed a good stability after 3000 h. Color stability retention for system A, D and E are shown in Figure 8.

Discussion and Statistical Results

Figure 9 shows the individual value plot of adhesion (y-axis) with respect to Exposure and System (x-axis). The means are shown as bold dots with 95 % confidence interval for all categorical factors. This data presents the adhesion in (MPa) for all coating systems using the PATTI test.

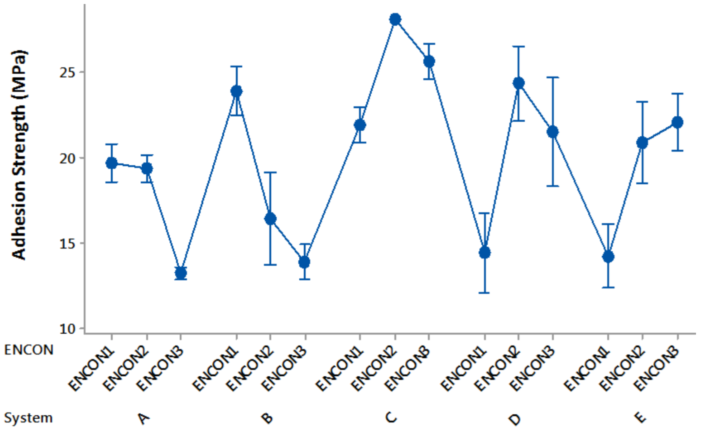

Fig. 9. Adhesion Strength of Systems versus ENCON (Environmental Condition)

System A and B showed very good adhesion strengths (18.5-24 MPa) when applied under ENCON 1. For ENCON 2 and 3, System C reached a range of 24 MPa to 28 MPa. These are considered excellent values in comparison with coated steel samples. All coating systems (except system E) when applied in a humid environment (ENCON 3), had their adhesion capacity dropped by at least 10%. Investigating the statistical significance among all coating systems, a two way ANOVA (analysis of variance) was conducted using Minitab 17 software [22], where both ENCON and System are assumed to be fixed as per the experiment. Based on data obtained, strong evidence indicated that both factors, Exposure and System, influence the adhesion capacity. The ANOVA results (for $\alpha = 0.05$) concluded that a significant interaction exists between exposure and system. With R-squared of 0.88, about 88% of the variability in adhesion is explained by the exposure, the system and the exposure-system interaction.

Figure 10 and Figure 11 show the main effect plot and interaction for adhesion using the fitted means. These plots are categorized by System and Exposure. Systems C and D show a significant increase in adhesion at ENCON 2, while almost all coatings (except system E) show a minor drop in adhesion at ENCON 3. Overall, irrespective of the ENCON conditions applied, the two-coat polysiloxane systems (system B, C, D and E) outperformed (adhesion strength) the three-coat system A. Statistically, all coatings are predicted to perform at their best in adhering to the steel substrate if applied under the ENCON 2 condition.

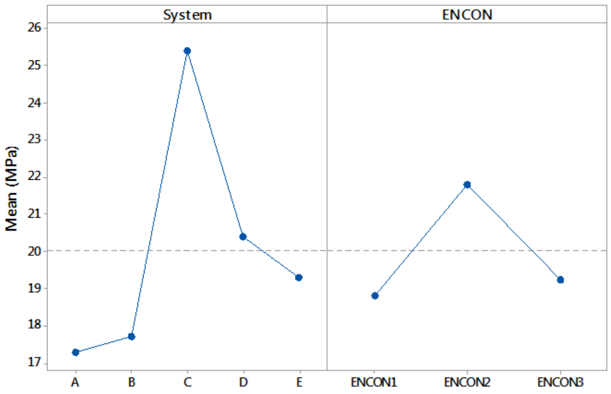

Fig. 10. Comparing Mean of Adhesion for Different Systems and Environmental Conditions

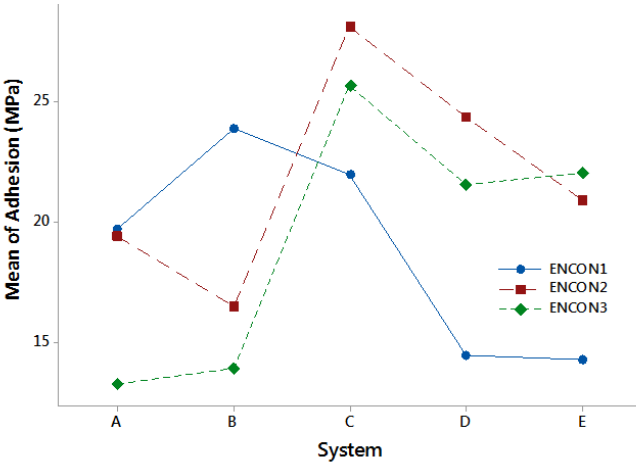

Fig. 11. Interaction Plot for Adhesion Test

Performing a Tukey simultaneous pairwise comparison of the differences of means for adhesion, shows that ENCON 1 is significantly different than ENCON 2. ENCON 3 is considerably different than ENCON 2. Statistically, all coatings performed relatively similar when compared individually between ENCON 3 and 1. Minitab 17 (Figure 12) gives the results in terms of intervals. If zero is contained in an interval, then those two means being compared are not significantly different from each other.

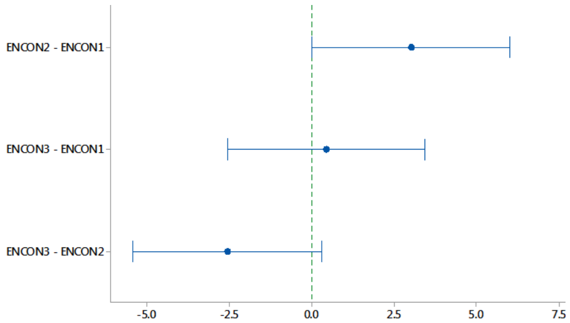

Fig. 12. Tukey Simultaneous 95 % Confidence Intervals of Coating Systems vs. ENCONs

As for the coating systems, when all ENCON conditions are considered, the Tukey procedure indicates that all pairs of the coating systems means are similar, except for coating system C (See Figure 13, in particular, system E similar to D, A similar to B, and coating system E similar to B). These predicted similarities can be explained as if two coating systems E or B were used to coat a steel girder in any environmental conditions; then one would predict the same performance (adhesion) for both coated steel surfaces using these two systems (Figure 13).

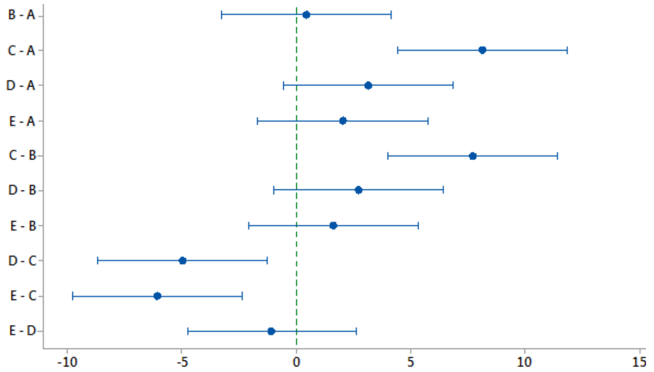

Fig. 13. Tukey Simultaneous 95 % of Different Coating Systems (y-axis) Based on Adhesion Test Results

Analysis of variance and interaction study were performed on the wear index for Abrasion Resistance. Figure 14 shows the individual value plot with mean (bold dot) and 95 % confidence interval for all categorical factors, Exposure and System. This data presents the abrasion resistance of each coating system using the Wear-Index as the response. The higher the Wear-Index, the more cycles will sustain reaching the primer while abrading the surface of the samples. System A and B (containing epoxy resin), if applied in a very humid environment (ENCON 3), show an almost negligible abrasion resistance (200 cycles). This shows sensitivity to hygrothermal effect (temperature and moisture) at the time of application of the coating. However, system C, D and E showed very stable results, irrelevant of ENCON 1, 2, and 3. In fact, high temperature and humidity at the time of application improved the abrasion resistance of these systems (ENCON3). From the two way ANOVA (Figure 14), Exposure and System influence the abrasion resistance/Wear-Index. Clearly, the interaction effect (for α = 0.05) between exposure and system influence the response (Wear-Index). One can also conclude that a significant interaction exists between exposure and system. With an R-squared of 0.96, about 96 % of the variability in the Wear-Index is explained by the exposure; the system and the exposure-system interaction.

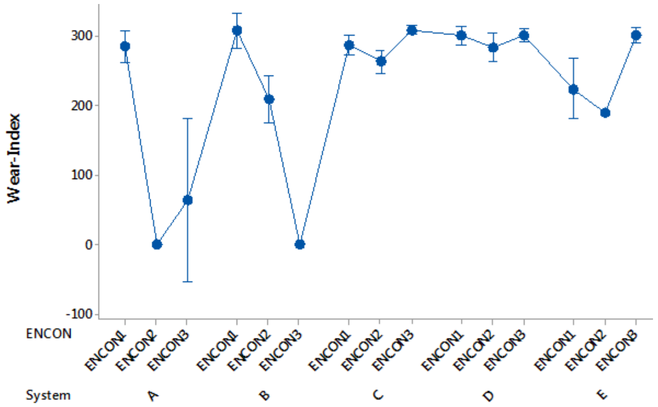

Fig. 14. Wear-Index vs. ENCONS and Coating Systems

Figure 15 shows the interaction between system and exposure. All systems showed some increase in the Wear-Index at ENCON 3, except system A and B. System A and B are predicted to perform at their best in abrasion resistance if applied under an ENCON 1 environment.

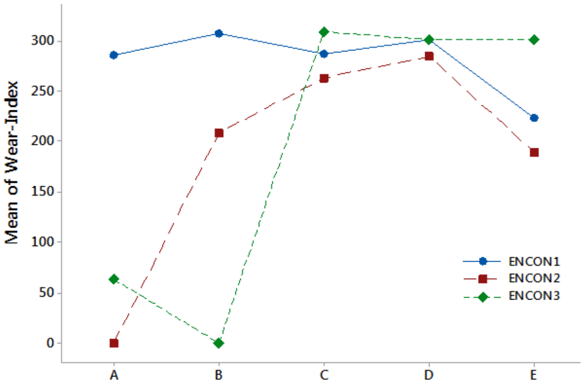

Fig. 15. Interaction Plot Based on Wear-Index Results

Investigating the fitted means of the main effect factors (Figure 16), the two-coat systems (system B, C, D, and E) demonstrated better performance and flexibility than the three coat system (system A) when applied at ENCON 1, 2, and 3. For instance, if system B or C were coated in different environmental or geographic locations, their predicted Wear-Index values would be much higher than system A. Obviously, under ENCON 2 (sprayed and initially cured at cold temp.) all coating systems means dropped slightly in abrasion resistance versus ENCON 1.

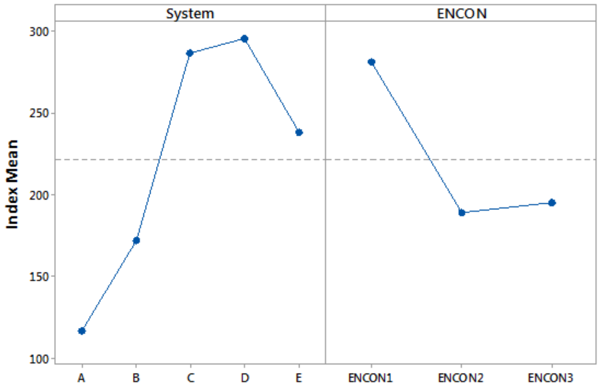

Fig. 16. Main Effect of Wear-Index on System and Exposure

Performing a Tukey simultaneous pairwise comparison of the differences of means for Wear-Index, we conclude that ENCON 1 is significantly different than ENCON 2 and 3. While all coatings performed relatively similar when compared individually between ENCON 2 and 3, Figure 17 shows the results in terms of intervals.

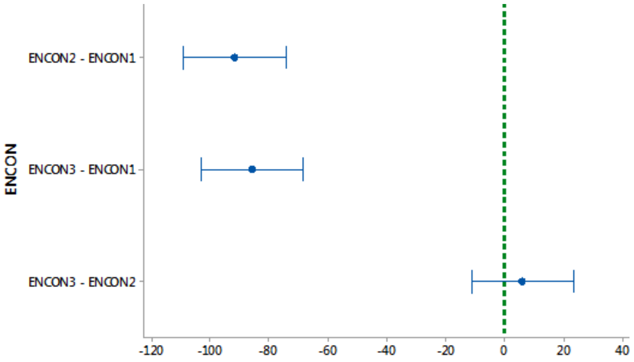

Fig. 17. Tukey Simultaneous 95 % Confidence Intervals for Abrasion Resistance

Conclusion

This experimental work considered five steel coating systems, a conventional three-coat system (baseline organic zinc/epoxy/polyurethane) and four other two-coat systems based on a polysiloxane top coat. A total of 435 steel samples were prepared, characterized, and coated in a state-of-the-art climate-controlled paint booth, controlling temperature and relative humidity. Three different environmental conditions were considered, ENCON 1: 25° C/50% RH, ENCON 2: 10° C/40%RH, and ENCON 3:32 °C/80% RH. These environmental conditions simulate different weathering conditions where common spray events and the curing of structural steel bridge components are likely to experience in the field. Within the scope of this investigation and considering the materials tested, the following conclusions can be drawn:

- Based on the test results, the zinc-rich primer Polysiloxane top coat system can replace the conventional three-coat system.
- Regardless of the environmental condition considered (ENCON), all two-coat systems showed better adhesion strength than the three-coat system.
- Regardless of the environmental condition, all two-coat systems sustained a significant number of cycles in the taber abrasion test than the three-coat system.
- When conditioned and applied under a humid environment (ENCON3:32 °C/80% RH) the three-coat system tested for adhesion and taber abrasion showed lesser values in comparison with the two-coat systems.
- The chipping resistance of the two-coat system is very comparable to the three-coat system.
- Overall, the corrosion resistance in terms of blistering and rust creepage (acceleration corrosion test GMW14872) was comparable among all scribed coated panels, except for one system labeled as system C. Temperature and humidity at the time of application of the coating can affect the corrosion resistance of the scribed samples.
- All five coatings passed the fresh and salt water resistance immersion test when exposed to 7, 14, and 30 days.

- All coatings showed a similar trend with respect to color and gloss retention when exposed to 3000 hours of UV/condensation. Two systems, system C and B revealed lower color/UV retention than the other coating systems.
- All weathering accelerated tests executed in this work validates the quick cure set of the two-coat Polysiloxane coating without compromising the corrosion protection, durability, and gloss retention of the structural steel members.

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