FINAL REPORT

APPLIQUÉS FOR THE MAINTENANCE OF LEAD-BASED PAINTED BRIDGES: A LABORATORY ASSESSMENT OF FIELD-PERFORMANCE CHARACTERISTICS

S. Ray Taylor, Ph.D.
Faculty Research Scientist

Christopher R. Standridge
Research Assistant

Michael M. Sprinkel, P.E.
Associate Director

Virginia Transportation Research Council
(A Cooperative Organization Sponsored Jointly by the
Virginia Department of Transportation and
the University of Virginia)

Charlottesville, Virginia

July 2004
VTRC 05-R4

DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Virginia Department of Transportation, the Commonwealth Transportation Board, or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

ABSTRACT

Approximately 3,500 bridges in Virginia having steel superstructures are coated with lead-based paints. Many of these bridges are in need of paint maintenance. This research evaluated appliqué technology, an alternative to the conventional paradigm of bridge paint maintenance in which the lead-based paint is removed and the structure repainted.

The results indicate that the barrier properties, self-cleaning characteristics, chemical stability, and thermal stability of the 3M 5004 Paint Replacement System are superior to those of conventional industrial maintenance paints. In addition, its use as a method to refurbish lead-based painted bridge structures reduces the quantity of lead introduced into the environment and the lead exposure of workers.

The cost of the 3M system in pre-production is approximately $10.41 per square foot. Recent costs to remove lead-base paint and repaint typical bridges are approximately $8 per square foot. As a consequence, the project was terminated before the proposed work was completed. The report provides test results that should be useful should the system become economical.

FINAL REPORT

APPLIQUÉS FOR THE MAINTENANCE OF LEAD-BASED PAINTED BRIDGES: A LABORATORY ASSESSMENT OF FIELD-PERFORMANCE CHARACTERISTICS

S. Ray Taylor, Ph.D.
Faculty Research Scientist

Christopher R. Standridge
Research Assistant

Michael M. Sprinkel P.E.
Associate Director

INTRODUCTION

The corrosion protection provided by industrial maintenance paints has historically been augmented by the introduction of heavy metal salts (e.g., chromate, lead salts), which act as corrosion inhibitors. Of the 200,000+ steel bridges in the National Bridge Inventory, 80 to 90 percent are covered with lead-based paint.[1,2] Although lead-based paints are extremely effective in mitigating corrosion in these steel structures, the U.S. Center for Disease Control has established that lead uptake by children is the most common and devastating disease in modern society.[3,4] The lead compounds used in traffic paints have been tangibly contributory to the lead contamination and exposure cycle.[5]

Legislation passed within the last two decades under the Clean Air and Water Act; Resource Conservation and Recovery Act; and Comprehensive Environmental Response, Compensation, and Liability Act now regulates lead exposure levels. This legislation mandates that the owner of a structure that contains heavy metals or heavy metal compounds (e.g., lead, lead oxide) is responsible for this toxic material from "cradle to grave." Thus, a bridge owner would be liable as the "generator" of toxic materials if lead from lead-based paints entered into the environmental chain (e.g., groundwater, air).

The Construction and Safety Standard on Lead established by the U.S. Occupational Safety and Health Administration (OSHA) must now be followed by contractors to protect the health and safety of workers who maintain the 3,000+ steel bridges in Virginia with lead-based paints.[6] Compliance with these regulations resulted in significant cost increases associated with multiple factors, all tied to lead maintenance. These factors included:

- The costs associated with controlling lead dispersal during surface preparation.
- The costs associated with the containment of lead during paint removal to protect workers and the site environment. (Both the paint and the abrasive that may have been used to remove the paint are considered lead-bearing and thus toxic substances.)

- The costs associated with the handling and disposal of a toxic substance.

- The costs associated with environmental and worker health (e.g., blood tests) monitoring.

The cost breakdown for these facets of maintenance for a structure with lead-based paint versus for the same structure with a non-lead paint is shown in Table 1. The increased costs for repainting lead-based painted structures have led to a significant effort to find alternate cost-effective strategies that would reduce worker and environmental exposure to lead.

The economic climate and market factors that led in the prices listed in Table 1 have changed considerably since 2003. A more recent assessment placed the total cost associated with re-painting lead-based painted bridges between $2.30 and $7.50 per square foot,[7] rather than the earlier estimate of $4.00 to $18.00 per square foot. Prices have come down because of at least two factors:

1. the earlier overcompensation in cost budgeting by paint contractors to accommodate as yet unrealized maintenance issues during the lead-maintenance procedure

2. a change in the market demand based on the transition from an extremely strong to a fragile economy.

This project was initiated under the economic considerations of the late 1990s. As with many other commodities, the reduced costs for repainting using present-day methods may resurge as the economy cycles up. In addition, and perhaps more important, current methods of repainting do not eliminate the lead exposure to the workers or the environment. There is certainly room for improvement.

To defray costs, many state departments of transportation (DOTs) have resorted to practices of zone repainting, maintenance overcoats,[8] or even planned procrastination.[9] These methods are effective at reducing short-term costs. However, they have the disadvantages of being short-term repairs; producing an aesthetically displeasing result; or placing the bridge owner in a position to encounter future liability, since the generator of toxic waste is responsible for the material *in memorium.*

Table 1. Costs for Maintenance of Lead-Based vs. Non-Lead Painted Steel Structure[1]

<table>
<tr><th rowspan="2">Item</th><th colspan="2">Lead-based Paint</th><th>Non-Lead Paint</th></tr>
<tr><th>Range
$\$/m^2$ ($\$/ft^2$)</th><th>Average
$\$/m^2$ ($\$/ft^2$)</th><th></th></tr>
<tr><td>Surface preparation</td><td>21.50-43.00 (2-4)</td><td>27.00 (2.50)</td><td rowspan="6">Surface preparation $10.80 (1.00)
Paint application 9.70 (0.90)
Materials 3.80 (0.35)</td></tr>
<tr><td>Containment</td><td>10.75-54.00 (1-5)</td><td>21.50 (2.00)</td></tr>
<tr><td>Disposal</td><td>0-32.00 (0-3)</td><td>5.40 (0.50)</td></tr>
<tr><td>Environmental monitoring</td><td>0-21.50 (0-2)</td><td>5.40 (0.50)</td></tr>
<tr><td>Worker health monitoring</td><td>10.75-21.50 (1-2)</td><td>16.15 (1.50)</td></tr>
<tr><td>Overhead/miscellaneous</td><td>0-21.50 (0-2)</td><td>5.40 (0.50)</td></tr>
<tr><td>Total</td><td>43.00-193.00 (4-18)</td><td>80.50 (7.50)</td><td>24.30 (2.25)</td></tr>
</table>

Although the exact performance figures (life extension) may vary, numerous surveys confirm the deficiencies of conventional paint maintenance methods for lead-based painted bridges and echo the need for better alternatives.[1, 9,11] One method under development minimizes worker exposure by eliminating blasting and grinding using the principle of cathodic disbondment.[12] Many paints can be effectively removed by this method; however, significant time is needed for electrode assembly and actual film disbondment. In addition, considerable energy may be required.

Another area of development has been in the identification of more benign blast media. Since the actual abrasive and its airborne fragments formed during blasting can in themselves create health risks (e.g., silica can induce silicosis and also becomes a toxic substance once in contact with lead-based paints), alternative blast media such as frozen CO_2 (dry ice), cornstarch, sodium carbonate, and high-pressure water[13] have been used. Although these media are themselves more benign, they are limited in their paint removal rate and have similar subsequent limitations in terms of worker exposure to toxic airborne materials, toxic waste containment, and toxic waste disposal. For example, the use of water jetting now diverts the focus from airborne lead contamination to large volumes of waterborne lead contamination.

Some of these limitations have been accommodated by the use of "sponge-type" materials for blast media. These materials envelop the ejected lead-containing paint particle with a non-toxic envelope, which has a twofold effect: (1) reducing the tendency for airborne particles by an increase in mass, and (2) reducing the immediate worker exposure to lead-containing particles. Although the worker may be protected from the immediate effects of lead, more stringent regulations in some states (e.g., California) have focused attention on total lead contained within the waste material as opposed to leachable lead, thus constraining this new enveloping media in the same way as do older technologies.

Another new paint removal technique used in the aerospace industry is the Flashjet system under development by The Boeing Company.[14] This method augments the dry ice blast media concept through the simultaneous application of pulsed light energy. The method is touted as being very efficient (4 ft^2/min). However, it is associated with issues regarding waste containment (to minimize worker exposure to toxic materials, now in the gaseous state) and toxic waste disposal.

The aerospace industry is faced with a problem very similar to that of DOTs in that conversion layers and primer paints for aircraft contain hexavalent chromium, an extremely toxic heavy metal. One alternate strategy that is being explored to minimize the costs associated with paint maintenance of these structures is the use of appliqués.[15] Appliqués are typically thought about in the context of their routine application as decals on aircraft, trucks, and signs. However, an ongoing collaboration between a major producer of appliqués (3M) and aerospace manufacturers (Boeing) is examining the efficacy of using this tape-based technology for the complete coating of aircraft to obviate costs associated with painting and paint removal of a heavy metal bearing paint. This approach offers potential savings in preparation costs, containment, and disposal and provides significant advantages in terms of worker exposure and environmental emissions.

PROBLEM STATEMENT

The worker and environmental hazards associated with the maintenance of lead-based paints on bridges has resulted in an increase in the refurbishment costs associated with these structures. These costs have come down in the last few years but will vary with the economic climate. Alternative maintenance strategies have been designed to minimize the worker and environment to lead exposure; however, they are encumbered by either a very low production rate or the creation of toxic waste of another form (e.g., large volumes of lead-containing waste water, alkaline waste, gaseous waste). Much of the extra costs associated with lead paint removal are due to waste disposal. This has led to alternate strategies, which to date include procrastination, spot repair, or overcoating. The "do-nothing" strategy not only leads to poor aesthetics, it also places the bridge owner in a position for future litigation since the generator of toxic waste is responsible from cradle-to-grave. Spot repair also has the major disadvantage of poor aesthetics. The overcoat strategy has been implemented through the use of various traditional coating materials. This method suffers from the disadvantage of limited coating viability since the substrate is not fully prepared in a traditional manner (i.e., abraded to white metal finish) and typically contains chemical contaminants from the environment (e.g., sulfates and chlorides). There is clearly a need for an alternate strategy.

Despite the regulation enacted 30 years ago on the use of lead-based paints, a significant number of lead-based painted bridge structures remains. The National Bridge Inventory indicates that 80 to 90 percent of the 200,000 steel bridges listed are painted with lead-based paint.[2] Approximately 50 percent of the 7,000 bridges having steel superstructures in Virginia are presently coated with lead-based paints.[6] Many of these aging bridges are in need of paint maintenance. However, the toxic and hazardous classification by OSHA and the U.S. Environmental Protection Agency of lead-containing materials has led to cost increases for the maintenance of these structures. These increases are associated with the containment of the removed paint, the minimization of worker exposure to the removed paint, and the removal and disposal of a toxic waste material. Although new methods of paint removal are under development, each has limitations and does not eliminate many of the cost factors mentioned.

Heavy metal inhibitors, such as lead-based pigments in paint, are some of the best corrosion suppressants available. These materials are both effective and harmless when they are in place and become toxic and hazardous only when they are ejected into the environment through a conventional paint maintenance procedure.

PURPOSE AND SCOPE

The purpose of this research was to examine a new approach for the maintenance of lead-based painted bridges through the use of appliqué technology. Since the coatings on existing bridges in Virginia span a large range of existing conditions, i.e., from those in which the paint is falling off of the structure to those in which the paint is essentially in pristine condition, multiple approaches for the use of an appliqué will eventually need to be examined.

The objective of this research was to examine the efficacy of using the appliqué technique for the maintenance of lead-based painted bridges. The motivation for using an appliqué is several-fold. First, an excellent corrosion inhibitor (i.e., lead-based pigments within the paint) that is matched only by other heavy metal compounds (e.g., chromates) would be retained at the needed site. Second, the worker would not be exposed to unnecessary health risks. Third, costs associated with removal, containment, recovery, and disposal of toxic material would be reduced and possibly eliminated. Fourth, the savings in time would be tremendous.

Since the barrier properties of the appliqué tested were far superior (over 1000X) to those of conventional maintenance coating systems, this study focused on examining the qualities of the adhesion of the appliqué to the substrate. The adhesion quality of the appliqué to both bare steel and painted substrates was assessed.

METHODS

Overview

The steel used in this study was similar in composition to the steel used in bridges in Virginia. The composition of the paint used was similar to that of the lead-based paints used on the steel structures with the exception of the lead content. The adhesion strength of the appliqué was determined via an 180^{o} peel test, in which the peel strength was measured as the tape was pulled back on itself at a specific peel rate. With the added test variables of time, exposure condition, and surface preparation, many test conditions were generated. The complete test matrix could not be addressed because of the time limitations imposed by budget constraints. The baseline data acquired to date are reported.

Materials

Substrate

Steel manufactured in accordance with AISI 1025 was used as the substrate material. This is a mild carbon steel with 0.25 weight percent carbon. The material was acquired in the form of a 1/16-inch-thick sheet that was cut into 4- by 6-inch test panels. The steel substrate material was obtained from BMG Metals, Richmond, Virginia.

Appliqué

The appliqué used in this study was Paint Replacement Tape 5004 manufactured by 3M, Engineered Adhesive Division, Minneapolis, Minnesota. The tape consists of a fluoropolymer film coated with a pressure-sensitive adhesive and is packaged in roll form with a removable liner on the adhesive side of the tape.

The 3M Paint Replacement Tape system is designed to replace topcoat paint on a variety of aircraft, marine, and other surfaces. It is formulated to withstand the harsh service environments associated with these applications and will conform and adhere to standard surface features such as rivet heads, overlapping doublers, and weld seams. The appliqué can be applied easily by hand with common plastic squeegees and can be removed without the use of strippers or other caustic chemicals. It is suitable for normal landfill disposal and does not require the use of hazardous materials during application or removal. The appliqué would be a hazardous waste if lead-based paint adhered to it when it is removed. Approximately 40 ft^2 of the appliqué was received from 3M. Some of the physical properties of this material are provided in Table 2.

The appliqué has the added safety and regulatory advantages of being 100 percent solids with no hazardous air pollutants, volatile organic compounds, or other materials restricted by regulation or law. Respiratory protection is not required under normal use conditions. The paint replacement tape also has a hazardous rating of zero for health, fire, and reactivity and a flammability class rating of zero. This appliqué material meets federal and California regulations for landfill materials and is potentially recyclable.

As can be seen from the information in Tables 2 and 3, the appliqué has numerous physical qualities that make it a desirable option to conventional paint as an overcoat. The permeability of this film to water and oxygen is significantly less than with a conventional maintenance coating and thus will provide excellent barrier protection.

Table 2. Physical Properties and Performance Characteristics of 3M Appliqué 5004 (From 3M Technical Data Sheet)

Property	Test Method	Value
Applied thickness		0.0055 in (0.14 mm)
Polymer film thickness		0.0035 in (0.09 mm)
Tape weight/area		0.045 lb/ft^2 (0.22 kg/m^2)
Tensile strength at break	ASTM D882	2900 psi (20 MPa)
Elongation (% at break)	ASTM D882	580%
Dielectric strength	ASTM D149	1430 V/mil (50 kV/mm)
Surface resistivity	ASTM D257	2×10^{10} $ohms/mm^2$
Dielectric constant at 1 kHz	ASTM D150	5.7
Dissipation factor at 1 kHz	ASTM D150	0.025
O_2 transmission rate	ASTM D3895	1210 $cm^3/m^2/day$; 6.2×10^{-7} $mol/m^2/s$
Water vapor transmission rate	ASTM D1249	0.46 g/100 in^2/day; 7.2 $g/m^2/day$
Peel adhesion at 70° F to Stainless steel Primer Mil-P-23377E	ASTM D3330 Method A	 81 oz/in (89 N/100 mm) 76 oz/in (84 N/100 mm)
Impact at 100 in-lb measured at –60, 0, 75, 180, 275°F	ASTM D2794	No tearing, cracking, or lifting
Low-temperature flexibility: ¼ in (6.3 mm) mandril bend	ASTM D522	Pass (no cracking)

Table 3. Environmental Durability of 3M Appliqué (From 3M Technical Data Sheet)

Property	Test Method	Value
Fire resistance	Aircraft interior fire protection: FAR 25.853 (a) App. F, Part I (a) (1) (ii)	Self extinguish time < 1 sec Burn length = 2.4 in No flaming drips
Flame spread index	ASTM 162	Flame spread index = 0.2 No ignition Film drips from panel without flaming
Toxic gas generated from combustion	BSS 7239	Carbon monoxide 122.5 ppm Sulphur dioxide – none detected HCl – none detected HCN – none detected NOx – 0.75 ppm HF – none detected
UV aging: ASTM G154	500 hours	No visible change in dimensions No loss of adhesion: ASTM D3330, Method A Color change: < 1 ΔE: ASTM D2244 Gloss change: < 1 ΔE: ASTM D523
Salt spray: ASTM B117	30 days	
De-icing fluid: SAE/AMS 1424B Type I	7 days @ 70°F	
Turbine wash: Mil-PRF-85704C	24 hours @ 70°F	
Tap water immersion	24 hours @ 70°F	
De-ionized water: ASTM D227 @ 100% RH	7 days @ 100°F	
JP-4 jet fuel	14 days @ 70°F	
JP-8 jet fuel	14 days @ 70°F	
Hydraulic fluid: Mil-H-5606G	30 days @ 70°F	
High temperature: 325°F	1 hour	

Preparation of Specimens

Steel Substrates

The steel panels were sandblasted to a SSPC-SP5 white metal using a Trinco dry-blasting cabinet at the Virginia Transportation Research Council. The blast medium was aluminum oxide, Trin Blast 60.

Edge effects from corrosion were minimized by applying electroplaters tape on the entire periphery of each panel. The tape covered approximately ¼ in from the edge.

Painted Substrates

Approximately one half of the sandblasted steel panels were painted with a primer coat of Virginia Number 1 primer (SSPC Paint 25) and one topcoat of Virginia Number 8. These paints were applied with a conventional roller and allowed to air dry. The primer coat dry film thickness was 1 to 1.5 mils, and the topcoat was 1 to 1.5 mils, for a total of 3 to 3.5 mils. This is an alkyd-based paint system that best represents the matrix chemistry used in existing lead-based paints. This system was chosen so that paint degradation as a result of subsequent exposure tests would closely simulate the weathering damage on existing bridges. The Virginia Department of Transportation (VDOT) has used this combination of paints, known as System A, as a maintenance paint system over existing lead-painted structures. During the maintenance activities, any areas that were cleaned down to bare metal were primed with the Number 1 primer; then, the Number 8 was used over these spot-primed areas or to overcoat the entire structure. The Number 8 paint contains micaceous iron oxide pigment. This pigment imparts good barrier properties to the coating. The micaceous iron oxide contributed a surface texture to the dried coating. This surface texture will have an impact on the contact area of a pressure-sensitive adhesive. In this study, this coating system was applied to blast-cleaned steel and hence its adhesion is going to be much better than what would be encountered in the field on old lead-based painted structures.

Pre-Exposure of Painted Panels

The quality of appliqué adhesion is very much a function of the condition of the substrate. This applies to both bare and painted substrates. This study was originally designed to look at a full matrix of substrate conditions in which bare and painted substrates were to be pre-exposed to a variety of conditions. Once the appliqué was applied to these substrates, another full matrix of post-exposures was to be applied. This report focuses on a small number of pre-exposure conditions for the painted panels because of the truncation of this program.

The outdoor weathered condition of painted bridges was simulated using a QUV chamber located at VDOT's Elko facility. This weathering chamber subjects panels to a combination of UV light and humidity that accelerates the natural outdoor exposure conditions. This was done in accordance with ASTM D4587-91, Procedure D, using UV bulbs at 1.55 $W/m^2/nm$, 8 hours UV exposure at 60ºC followed by 4 hours condensation at 45ºC. It is not possible to establish an exact ratio between time in the QUV chamber and time outdoors. Samples were withdrawn from the chamber at 837 hours, 1000 hours, and 1500 hours. Because the project was terminated early, adhesion tests were done only on samples that were in the chamber for 837 hours.

Adhesion Testing

Adhesion of the appliqué was assessed using the 180-degree peel test for pressure-sensitive tape specified in ASTM D3330, Standard Test Method for Peel Adhesion of Pressure-Sensitive Tape. Because of the dimensions and properties of the film, the test had to be modified slightly. The film has high stretch at low stress. A "pre-peel" delay was inserted into the test so that the film could stretch before adhesion data were recorded.

One-inch-wide strips were cut into the appliqué. An initial 1-inch-long tab of the appliqué was pulled from the sample and wrapped around the pull bar of the testing device. Adhesion data were recorded for at least 2 in after the first 1 in of adhered material to obtain a representative adhesion value. The testing device was a Thwing-Albert Model 225-1 friction peel tester. This instrument was equipped with a 10 kg load cell, as well as variable pre-test and test times, variable speeds, and computer-based statistical analysis and storage. A clip on the left holds down the sample while the film is attached to a clamp. A rod then begins to move to the right, de-adhering the film and measuring the force necessary to peel the film.

For any given test, adhesion data were recorded at 0.01-second intervals. Two or three strips per panel were assessed. Strips of appliqué near the edges of the panel were avoided and did not enter the data pool. A data set for a given condition consisted of approximately 15 strips taken from approximately six different panels.

Wet adhesion behavior was assessed by placing a bead of water at the contact line of the appliqué with the substrate. All other test conditions and analysis parameters remained the same as for dry tests.

RESULTS AND DISCUSSION

Dry Adhesion

Peel strength data for the appliqué applied to bare steel samples are shown in Table 4. As can be seen, the average peel strength for the appliqué to the sandblasted steel surface was 5.33 lb with a standard deviation of 0.26 lb. This is to be compared with the peel strength for painted panels summarized in Table 5.

Table 4. Summary of Appliqué Peel Strength Data for Bare (Sandblasted) Steel

Sample No.	Peel Strength Avg. (lb)	Peel Strength SD (lb)
1	5.15	0.13
2	5.58	0.11
3	5.62	0.18
4	5.55	0.06
5	4.93	0.12
6	5.11	0.12
7	5.35	0.15
8	5.76	0.13
9	5.79	0.11
10	5.36	0.10
11	5.57	0.10
12	5.00	0.08
13	5.14	0.14
14	5.58	0.09
15	4.92	0.18
16	5.28	0.06
17	5.29	0.09
18	5.08	0.08
19	5.23	0.13
20	5.21	0.15
21	5.50	0.08
AVG	**5.33**	0.11
SD	**0.26**	

Table 5. Summary of Peel Strength Data for Appliqué Applied to Painted Samples

Sample No.	Peel Strength Avg. (lb)	Peel Strength SD (lb)
1	4.46	0.07
2	3.84	0.09
3	3.84	0.03
4	3.95	0.03
5	4.30	0.07
6	3.66	0.05
7	3.79	0.07
8	4.66	0.08
9	4.68	0.09
10	4.60	0.10
11	4.48	0.05
12	3.98	0.06
13	4.15	0.11
14	4.38	0.10
15	4.18	0.13
16	4.20	0.05
17	4.28	0.14
18	4.29	0.14
19	3.60	0.08
20	3.89	0.13
AVG	**4.16**	0.08
SD	**0.33**	

As can be seen, there was an approximately 22 percent reduction in the peel strength when the appliqué was applied to the painted samples. This reduction in adhesion is not expected to affect the performance of this appliqué for the intended purpose of protecting the paint. Much of this reduced adhesion may be attributable to the surface roughness caused by the addition of micaceous iron oxide to the paint or to the slick binder component (alkyd resin). A smoother surface may or may not result in such a reduction. This roughness also produced more scatter in the data as seen by the larger standard deviation. This surface roughness is present on many lead-based painted bridges in Virginia.

Wet Adhesion

One of the most limiting factors for the maintenance of adhesion is moisture. For this reason the wet-state adhesion of the appliqué was assessed in the direct presence of water. During the peel test, water was introduced at the crease of the interface where the appliqué meets the substrate. In the case of a coating on a metal, this water would cause an immediate drop in the adhesion strength. This was not observed in the case of the appliqués and was interpreted as a very positive indication of the performance of this material in the environment. Since the barrier properties were excellent, the maintenance of wet-state adhesion will be tantamount to long-term protection. Further testing in the outdoors with freeze/thaw cycling and scratch protection are required. The excellent barrier properties of the appliqué could be a negative attribute in that moisture could be trapped if condensation should form during a freeze/thaw cycle. This could be overcome by the introduction of micro-porosity into the appliqué, which would allow the escape of water molecules but not the ingress of bulk water. Peel data for a bare steel substrate in the presence of water are summarized in Table 6. Peel data for a painted substrate in the presence of water are summarized in Table 7. As can be seen in Table 8, water had no effect on the adhesive strength of the appliqué.

Table 6. Summary of Peel Strength Data for Wetted Bare Steel Substrate

Sample No.	Peel Strength Avg. (lb)	Peel Strength SD (lb)
1	5.50	0.13
2	6.11	0.13
3	5.96	0.20
4	6.32	0.17
AVG	5.97	0.16
SD	0.32	

Table 7. Summary of Peel Strength Data for Painted Substrate in Presence of Water

Sample No.	Peel Strength Avg. (lb)	Peel Strength SD (lb)
1	4.20	0.09
2	3.79	0.06
3	4.14	0.05
4	4.25	0.09
5	4.35	0.08
6	3.79	0.07
7	3.86	0.12
8	3.95	0.10
AVG	**4.04**	**0.08**
SD	**0.23**	

Table 8. Average Peel Strength Data for Bare and Painted Substrates Showing the Lack of Effect of Water

Bare Steel		Painted	
Dry Peel Strength (Avg. ± SD) (lb)	**Wet Peel Strength (Avg. ± SD) (lb)**	**Dry Peel Strength (Avg. ± SD) (lb)**	**Wet Peel Strength (Avg. ± SD) (lb)**
5.33 ± 0.26 (n = 21)	5.97 ± 0.32 (n = 4)	± 0.33 (n = 20)	4.04 ± 0.23 (n = 8)

Effect of Weathering

It was of interest to examine the qualities of the adhesion of the appliqué to weathered paint. To simulate the chemical and physical changes in the paint as a function of moisture and UV light, selected panels were subjected to a QUV chamber for varying times. Initial samples were exposed for 837 hours and subjected to similar dry- and wet-state adhesion testing as performed previously. Samples were tested in dry condition. The peel strength data for the 837-hour samples are shown in Table 9. The weathered samples were also tested in a wet condition. These data are shown in Table 10.

Table 9. Summary of Peel Strength Data Acquired for Weather (837 hr QUV) Painted Samples

Sample No.	Peel Strength Avg. (lb)	Peel Strength SD (lb)
1	4.85	0.40
2	4.35	0.37
3	5.01	0.32
4	5.68	0.26
5	4.82	0.22
6	4.88	0.32
7	4.85	0.41
8	4.35	0.37
9	4.55	0.29
10	4.88	0.27
11	4.48	0.29
AVG	**4.79**	0.32
SD	**0.31**	

Table 10. Summary of Peel Strength Behavior of Appliqué on Wetted Weathered (837 hr QUV) Paint

Sample No.	Peel Strength Avg. (lb)	Peel Strength SD (lb)
1	5.62	0.28
2	5.66	0.35
3	5.50	0.35
4	5.23	0.44
5	4.33	0.34
6	5.32	0.17
7	5.14	0.13
8	4.68	0.30
9	4.98	0.45
10	5.12	0.37
11	5.17	0.20
12	4.71	0.13
13	4.64	0.18
AVG	**5.09**	0.28
SD	**0.40**	

As can be seen in the summary table (Table 11), adhesion to the weathered samples was not only unchanged but its strength increased significantly compared to that of the freshly painted surfaces. It is unclear why an increase in adhesion strength occurred, but this may have been due to the altered chemistry (e.g., oxidation) of the resin caused by the QUV chamber. There may also be a slight roughening effect caused by the weathering, which increased the effective contact area of the appliqué. It is hoped that future testing at increased weathering times will corroborate this phenomenon, which is considered a promising attribute of the use of appliqués for the maintenance of lead-based painted bridges.

Table 11. Summary of Peel Strength Data Showing Effect of Weathering (837 hr QUV) on Adhesion to Painted Surfaces

New Paint		Weathered Paint	
Dry Peel Strength (Avg. ± SD) (lb)	**Wet Peel Strength (Avg. ± SD) (lb)**	**Dry Peel Strength (Avg. ± SD) (lb)**	**Wet Peel Strength (Avg. ± SD) (lb)**
4.16 ± 0.33 (n = 20)	4.04 ± 0.23 (n = 8)	4.79 ± 0.31 (n = 11)	5.09 ± 0.40 (n = 13)

SUMMARY OF RESULTS

- The 3M 5004 Paint Replacement System (appliqué) adheres well to bare steel with a sandblasted surface finish. The peel strength was 5.33 + 0.26 lb for a 1-inch strip. A non-blasted finish was not examined.

- The peel strength of the appliqué to bare steel is unaltered by the presence of water. In fact, it is seen to increase statistically above the dry state. The reasons for this increase are unknown and should be reconfirmed. This hydrostability is a positive finding with regard to the utility of this material in the refurbishment of lead-based painted structures.

- The peel strength of the appliqué to a painted structure (Virginia Number 1 primer and one topcoat of Virginia Number 8) was reduced to that of bare steel by 22 percent. This decrease was statistically significant and may be attributed, in part, to the surface texture of this paint system created by the presence of micaceous iron oxide or the slick painted surface. This material and texturing are present on many lead-based painted bridges, but this reduced peel strength may not affect performance. The paint system was selected based on the similarity of the matrix system (alkyd) to the matrix of pre-existing lead-based painted structures (also alkyd).

- The peel strength of the appliqué to painted structures is unaffected by the presence of water. This hydrostability of the bonding is a positive finding with regard to the utility of this material in the refurbishment of lead-based painted structures.

- The dry peel strength of the appliqué to painted structures is increased by 837 hours of outdoor aging using a QUV chamber (16% increase). This increase is statistically significant. The increase may be attributable to a chemistry change in the matrix (e.g., oxidation) or possibly a micro-roughening effect, which would increase the effective contact area of the appliqué. This attribute is considered a very positive finding with regard to the use of this appliqué material in the refurbishment of lead-based painted structures.

- The wet-state peel strength of the appliqué to weathered (837 hour QUV) paint was greater than to fresh paint (25% increase). This increase was statistically significant. Again, hydrostability of the adhesive bond and improved adhesion to the weathered system are demonstrated.

- The blast-cleaned metal panels that were painted and weathered prior to the application of the appliqué do not replicate exactly what occurs in the field, and the reader is cautioned that the values obtained are likely on the optimistic side. It is entirely possible that in the field, the appliqué could stick well to the paint, but if the underlying adhesion of the paint to the steel is poor, the entire system could fail. This has happened when lead paint was overcoated with another paint system. The stresses that may be generated by the appliqué are unknown.

CONCLUSIONS

- *The barrier properties, self-cleaning characteristics, chemical stability, and thermal stability of the 3M 5004 Paint Replacement System are superior to those of conventional industrial maintenance paints.*

- *The use of the paint system as a method to refurbish lead-based painted bridge structures precludes the introduction of lead into the environment or exposure to workers. However, pre-cleaning the surface to remove loose rust and paint would produce lead-containing material.*

- *The use of an appliqué system over an existing lead-based painted structure could entomb the leaded material,* which is a very capable corrosion inhibitor and cannot be replaced if removed.

- *The adhesion stability of the appliqué in the presence of moisture and as a function of weathering of paint in an artificial environment (QUV) is very promising and shows the possibility of improvement in the presence of these harsh conditions.*

- *The cost of the 3M 5004 appliqué system in pre-production is approximately $10.41 per square foot. A less expensive 4805 system, in pre-production, may perform as well (slightly thinner, but same adhesive), and the cost will be approximately $6.31 per square foot. When in production, these costs will be less than half of the quoted values.* This compares very favorably with the present costs incurred by VDOT for the re-furbishment of lead-based painted bridges with non-leaded paint.

- *When labor for surface preparation and application of the appliqué is included, the total cost might be higher than what VDOT currently pays for the re-furbishment of lead-based painted bridges.* The increased performance of the appliqué might compensate for the installation costs. In addition, the appliqué would considerably reduce the introduction of lead into the environment or to the worker. Further testing and research are needed to determine all aspects of the cost analysis.

RECOMMENDATION

- *VDOT should not use the 3M 5004 Paint Replacement System at this time because of its high cost.*

SUGGESTED FUTURE RESEARCH

If the cost situation improves, further testing and analysis of appliqués for the refurbishment of lead-based painted bridges should include examination of the following:

- increased weathering periods of painted surfaces
- wet-state adhesion as a function of time
- adhesion in the presence of wet-dry cycling and freeze-thaw cycling
- edge retention and performance where the appliqué application is defective after small patches of the appliqué are placed on existing lead-based painted bridge structures
- appliqué as a splash shield for the oncoming traffic side of an overpass if the cost analysis is not supportive of its use over the entire bridge structure; a splash shield would have considerable protective and aesthetic value
- effects of applications to salt-contaminated, rusty bridges as compared to a relatively clean aluminum aircraft in a nice temperature-controlled shop
- appropriate surface preparation
- adhesion of the paint to the steel
- how to deal with bolts, etc.
- appliqué removal
- alternative (pre-production) 4805 material.

ACKNOWLEDGMENTS

Wendy D. Ealding, C. Wayne Fleming and Jeffrey L. Milton are acknowledged for the major contributions they made throughout the project by assisting with the cost analysis of the appliqué, identifying practical issues associated with using the appliqué, and providing technical comments and additions to the report. In addition, Michael W. Burton is acknowledged for preparing the test specimens, and C. Wayne Fleming is acknowledged for weathering the specimens.

REFERENCES

1. Smith, L.M., and Ticklenberg, G.L. *Lead-Containing Paint Removal, Containment, and Disposal.* FHWA-RD-94-100. Federal Highway Administration, McLean, Va., 1995.

2. Appelman, B.R. Removing Lead Paint from Bridges: Costs and Practices. *Journal of Protective Coatings and Linings*, 15(8):52-60, 1998.

3. Florini, K.L., and Silbergeld, E.K. *Getting the Lead Out: Issues in Science and Technology*, 9(4):33-40, 1993.

4. Chisolm, J.J., Jr. What Lead Does to Kids. *NEA Today*, 12(4):13, 1993.

5. Society for Protective Coverings. *Supervisor/Competent Person Training for Deleading of Industrial Structures.* SSPC-97 V4-T. Pittsburgh, Pa., 1997.

6. Virginia Department of Transportation. Highway Traffic Records Information System. Richmond, 1998.

7. Brock, J., Sprinkel, B. and Milton, J. Personnel communication, 2003.

8. Angeloff, C. Overcoating Bridges Containing Lead-Based Paints: An Economical Alternative. *Public Works,* 124(1):56-7, 1993.

9. Hower, H.E. The Dilemma of Removing Lead-Based Paint. *Journal of Protective Coatings and Linings*, January 1988, pp. 30-37.

10. Bates, N. Lead Paint Removal: A Comparison of Costs. *Journal of Protective Coatings and Linings*, January 1996, pp. 31-38.

11. Michelsen, R.L., and Haag, W.M. Removing Lead-Based Paint from Steel Structures with Chemical Stripping. *Journal of Protective Coatings and Linings*, July 1997, pp. 22-29.

12. Keller, R., Burleigh, T.D., and Hydock, D.M. *Electrolytically Assisted Paint Removal from a Metal Substrate*, U.S. Patent No. 5,507,926, 1996.

13. Waterjetting Removes Lead Paint on Communications Facility. *Journal of Protective Coatings and Linings*, May 1997, pp. 33-36.

14. FLASHJET Paint Removal Systems Completes Fiftieth Apache Fuselage. Accessed at http://www.aerotechnews.com/starc/062298/062398d.html.

15. Paintless Film Evaluated in C-130 Flight Test at Lockheed Martin. Accessed at http://www.aerotachnews.com/starc/062298/062398d.html.