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Water Quality Implications of Culvert Repair Options: Cementitious and Polyurea Spray-on Liners

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BRIDGET M. DONALDSON
Senior Research Scientist
Virginia Center for Transportation Innovation and Research

ANDREW J. WHELTON, Ph.D.
Assistant Professor
Department of Civil Engineering
University of South Alabama

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530 Edgemont Road, Charlottesville, VA 22903-2454
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Many commonly used culvert rehabilitation technologies entail the use of a resin or coating that cures to form a rigid liner within the damaged culvert. However, the potential environmental impacts of leaching or release of contaminants during normal installation practices have not been well studied. Evaluations of previous culvert repair operations by the Virginia Department of Transportation (VDOT) were conducted for conventional (styrene-based) cured-in-place pipe and fold and form repair technologies. The study reported herein included an evaluation of two additional technologies available for use by VDOT: a polymer-enhanced cement mortar (or cementitious) spray-on liner and a polyurea spray-on liner.

To evaluate the potential for these lining technologies to impact water quality, installations were monitored up to 49 days. Three water quality tests were conducted for each installation, and water samples were analyzed for water quality indicators and constituents listed in material safety data sheets. Tests included a water flow simulation with low dilution potential; an immersion test to simulate a standing water scenario; and a laboratory leaching test. Results were then compared against established regulatory standards and published toxicity criteria for aquatic species.

For the cementitious spray-on liner evaluated, pH and alkalinity exceeded specified Virginia water standards in laboratory tests but pH and other evaluated compounds were within the acceptable range in water flow and immersion tests. For the polyurea spray-on liner evaluated, elevated water quality indicators (i.e., biochemical oxygen demand, chemical oxygen demand, total organic carbon, and total nitrogen) in laboratory tests suggested that contaminants were released from the polyurea liner, particularly during its initial contact with water, but water quality impacts were not detected in the other tests. Water flow, dilution, and volatilization appear to play an important role in reducing water quality impacts from contaminant leaching.

The study recommends that VDOT specifications include protective controls for spray-on liners to prevent exceeding water quality standards or toxicity thresholds for aquatic species in receiving waters with low flows and little dilution potential.

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Bridget M. Donaldson
Senior Research Scientist
Virginia Center for Transportation Innovation and Research

Andrew J. Whelton, Ph.D.
Assistant Professor
Department of Civil Engineering
University of South Alabama

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ABSTRACT

Many commonly used culvert rehabilitation technologies entail the use of a resin or coating that cures to form a rigid liner within the damaged culvert. However, the potential environmental impacts of leaching or release of contaminants during normal installation practices have not been well studied. Evaluations of previous culvert repair operations by the Virginia Department of Transportation (VDOT) were conducted for conventional (styrene-based) cured-in-place pipe and fold and form repair technologies. The study reported herein included an evaluation of two additional technologies available for use by VDOT: a polymer-enhanced cement mortar (or cementitious) spray-on liner and a polyurea spray-on liner.

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For the cementitious spray-on liner evaluated, pH and alkalinity exceeded specified Virginia water standards in laboratory tests but pH and other evaluated compounds were within the acceptable range in water flow and immersion tests. For the polyurea spray-on liner evaluated, elevated water quality indicators (i.e., biochemical oxygen demand, chemical oxygen demand, total organic carbon, and total nitrogen) in laboratory tests suggested that contaminants were released from the polyurea liner, particularly during its initial contact with water, but water quality impacts were not detected in the other tests. Water flow, dilution, and volatilization appear to play an important role in reducing water quality impacts from contaminant leaching.

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University of South Alabama

INTRODUCTION

Background

As many pipes have reached the end of their service life, their repair or replacement is a large maintenance concern. The U.S. pipe renewal market is approximately $330 billion (Najafi, 2004). Trenchless pipe repair technologies, whereby existing pipes are repaired in place rather than by the use of the conventional method of unearthing and replacing damaged sections, have gained considerable market share in pipe installation and renewal for utility services. Because of the deteriorating state of many culverts maintained by transportation agencies, trenchless rehabilitation companies have expanded their focus on drinking water and sewer pipes to include road culverts. However, few studies have been conducted that quantify the impact of these technologies on the environment, despite numerous anecdotal reports of damage to aquatic habitat and treatment processes at wastewater treatment facilities from certain repair technologies (Whelton et al., 2012).

Many commonly used trenchless rehabilitation technologies entail use of a resin or coating that cures to form a rigid liner within the damaged culvert. Separate studies conducted by Donaldson and Baker (2008) for the Virginia Transportation Research Council (now the Virginia Center for Transportation Innovation and Research [VCTIR]) (the research arm of the Virginia Department of Transportation [VDOT]) and the New York State Department of Transportation, 2010) documented that one of these methods, cured-in-place pipe (CIPP) rehabilitation, has the potential to release a toxic chemical into the conveyed water in the absence of protective controls. Following subsequent changes to VDOT's specifications for CIPP installations (VDOT, 2008), VDOT requested that VCTIR review other culvert rehabilitation products and processes used by VDOT. Spray-on lining technologies, another widely used method of culvert repair in the United States (Najafi, 2004), are the focus of this report.

Spray-on Liners

Spray-on liners are gaining wider acceptance as means to repair stormwater culverts in the United States (Tullis et al., 2009). These liners are fabricated by spraying material to the culvert interior via a hand-held nozzle or a robotic head. Two or more passes of spray are typically applied to achieve the desired thickness. As with other culvert repair technologies, studies of the potential effects on water quality from newly sprayed liners are lacking (Ellison et al., 2010). Only one study has been conducted to characterize a polyurea spray-on liner; this study found that for the one material examined, certain drinking water quality indicators (total organic carbon and pH) were adversely affected (Johnson, 2008). Because of other environmental and worker safety concerns (which have not been published), the California Department of Transportation has effectively banned the use of spray-on liners that contain isocyanate materials, including polyurea sprays (DeCou, 2012).

The use of spray-on lining technologies represents a potentially significant opportunity for cost-effective culvert rehabilitation for VDOT and other transportation agencies, but the potential environmental impacts of leaching or release of contaminants during normal installation practices have not been evaluated.

PURPOSE AND SCOPE

The purpose of this study was to evaluate two spray-on lining technologies for their potential impacts on water quality. These technologies included a polymer-enhanced cement mortar (or cementitious) spray-on liner and a polyurea spray-on liner. The objectives were to provide VDOT with information on each of these technologies to assist with specification development.

Culvert repair evaluations included monitoring installations and conducting water quality tests up to 49 days after the installations. The study was primarily designed to evaluate field scenarios. Laboratory analyses were also conducted to supplement field results. Field and laboratory evaluations were not comprehensive but can serve as a starting point for understanding water quality risks from the use of these repair technologies. A report describing the water quality analyses of unconventional CIPP (i.e., ultraviolet and vinyl ester based) has been published separately (Donaldson, 2012).

METHODS

Three primary tasks were carried out for each of the two spray-on technologies (i.e., cementitious and polyurea) to achieve the study objectives.

1. Conduct a literature review of information regarding the material and installation procedures and relevant standards and water quality studies.

2. Observe installations with other VDOT staff, and note comments made by VDOT staff regarding prior spray-on liner installations.

3. Conduct water quality tests, and compare the results with toxicity thresholds for aquatic species and/or water quality indicators.

Literature Review

A search of relevant literature and product information was conducted to determine (1) the methods and materials used for each spray-on lining technology; (2) relevant standards (including those of the American Society for Testing and Materials [ASTM] and federal and state water quality standards); and (3) water quality studies relevant to the product constituents. Product literature was obtained from the culvert repair vendors to determine the engineering material properties and installation procedures for their product, but specific vendor names and references to product literature are not disclosed in this report for confidentiality purposes. Information was also obtained from the websites of ASTM, the U.S. Environmental Protection Agency (U.S. EPA), the Virginia Department of Environmental Quality (DEQ), and online databases such as Biological Sciences, Environmental Sciences and Pollution Management, and WorldCat. Findings documented from the literature review on installation procedures and relevant water quality studies were intended to provide overviews rather than comprehensive descriptions.

Installation Observations

Installations using the spray-on technologies were conducted for the purposes of observing the lining procedures and conducting water quality tests on the newly installed liners. Each of the spray-on technologies was installed in an above-ground out-of-service corrugated metal culvert using the same materials and procedures as those used for liners installed in operating culverts.

The culvert lined with the cementitious spray had a diameter of 72 in and a length of 20 ft. The culvert lined with the polyurea spray had a cross section of 110 by 79 in and a length of 20 ft. Installation observers included the authors and VDOT staff with an interest in and/or prior experience with using the particular spray-on liner. Comments made by VDOT staff regarding prior installations issues were noted. Observations of methods or incidents during installations that might pertain to water quality were also documented.

Water Quality Tests

Water quality tests were conducted on the newly installed liners. Table 1 lists the tests conducted for each installation: a flowing water test, an immersion test, and laboratory leaching test, and Figure 1 illustrates the tests conducted. For the flowing water test and the immersion test (designed to simulate flowing water and standing water conditions, respectively), the

Table 1. Tests Conducted, Constituent or Parameter Tested, and Sampling Frequency for Water Samples Collected After Liner Installation

Tests Conducted	Water Sample Analyses and Sampling Frequency	
	Polyurea	**Cementitious**
Flowing water test	Analyses: methylene diphenyl diisocyanate (MDI), methylenedianiline (MDA), volatile organic compounds, total nitrogen, chemical oxygen demand, total organic carbon, pH Sampling frequency: Days 2,[a] 10	Analyses: metals, semivolatile organic compounds, volatile organic compounds, total organic carbon, pH Sampling frequency: Days 2,[a] 10
Immersion test	Analyses: same constituents and water quality indicators as above Sampling frequency: Day 3	Analyses: same constituents and water quality indicators as above Sampling frequency: Day 3
Leaching test	Analyses: alkalinity, biochemical oxygen demand, chemical oxygen demand, total nitrogen, total organic carbon, pH Sampling frequency: Days 3,[b] 6, 9, 12, 15	Analyses: alkalinity, biochemical oxygen demand, chemical oxygen demand, total nitrogen, total organic carbon, pH Sampling frequency: Days 3,[b] 6, 9, 12, 15

[a]Water sampling for spray-on installations was deferred 24 hr after installation in keeping with the company-recommended waiting period before water flow is reinstated.
[b]Laboratory leaching tests were conducted beginning 10 days after spray-on liner installations. Day 3 indicates the first day samples were analyzed after a 3-day exposure period to water.

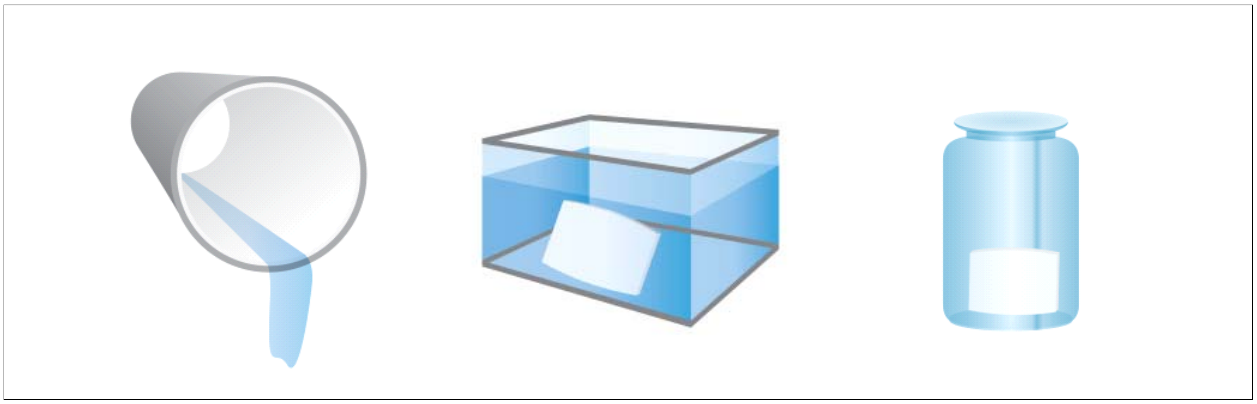

Figure 1. Illustrations of Water Quality Tests Conducted on Newly Installed Liners. Flowing water test (in the field; *left*); standing water test (open vessel; *middle*); and laboratory leaching test (closed vessel; *right*).

material safety data sheet (MSDS) for the particular spray-on product was used to determine the constituents to be analyzed in water samples. Samples collected from these tests were also analyzed for constituents potentially released from the product (e.g., constituents potentially found within or chemically related to those listed in the MSDS) and for typical water quality indicators. Samples from the laboratory test were analyzed only for typical water quality indicators.

Samples from the flowing water and immersion tests were collected until the chemical concentrations or water quality indicators were below the toxicity thresholds for aquatic species, were below the laboratory reporting limit, and/or complied with state water quality standards. This required only one sampling event for the flowing water test and one for the immersion test.

An additional sampling event was conducted for the flowing water test to confirm that concentrations remained below or within these limits or standards, respectively (Table 1). Water samples were packed on ice and sent to a laboratory via an overnight courier service. Test results were then compared with toxicity thresholds and/or water quality indicators identified in the literature review.

Flowing Water Test

The flowing water test was the only test conducted in the field (i.e., in the newly lined culvert). Unlike tests for potable water pipes, there are no standard methods for testing water quality implications of stormwater repair products. In the absence of any standard testing methods, the flowing water test (and the immersion test, described in the following section) was designed to simulate field conditions. For each newly lined culvert (each with a length of 20 ft), a rain event was simulated each sampling period by the slow pouring of 2.5 gal of tap water from the nearest source into the culvert inlet such that a single stream (approximately 2 in wide) contacted the bottom of the culvert liner. Water flow through all culverts was fairly slow, given the slope of approximately 1% to 2%. Water began flowing out of the outlet 25 sec after it was poured into the inlet. Water was captured in 40-ml sampling vials as it flowed out of the outlet. Control samples were taken each sampling event from the same water source used to flush the culvert for the purpose of water sampling.

This test was designed to simulate conditions with low flow and little dilution potential. Low dilution corresponds with a high liner surface area to water volume ratio and represents a worst case field scenario in terms of detectable water quality impacts from contaminant leaching. The surface area to volume ratio uses an estimate of the surface area of the liner (in square inches) contacted by the water, and the volume of that water (in gallons) contacting the liner at the time of sampling. The surface area was calculated by multiplying the width of the stream contacting the liner (2 in) by the length of the stream (which is the culvert length). The surface area to volume ratio was 192:1 for the flowing water test. The ratio provides a relative comparison of dilution levels among the tests conducted in this study; a higher ratio indicates less dilution of any existing contaminants.

Immersion Test

Because relatively high styrene concentrations have been detected in pools of standing water at culvert outlets after CIPP installations (Donaldson, 2009), an immersion test was conducted to simulate a standing water scenario as a comparison with the flowing water test. For each tested liner, an open 5-gal glass tank was filled with tap water. For both spray-on liners, vendors recommended waiting 24 hr before reinstating flow.

Sections of the cementitious and polyurea liners were removed from the installations and immersed in the tank 24 hr after each liner installation. For the test of the cementitious liner, a liner section 5 by 6 by 0.25 in was immersed in 1.3 gal of water in order to achieve the same surface area to volume ratio (70:1). For the immersion test of the polyurea liner, a section of liner 12 by 0.125 in was immersed in 2.2 gal of water within the open tank. This resulted in a surface area to volume ratio of 70:1. A control sample was collected from the tank into a 40-ml vial prior to immersion of each liner section. Water samples were collected from the tank in 40-ml vials on Day 3 (Table 1). Additional samples were unnecessary because of low or nondetectable levels of chemicals or water quality indicators.

Laboratory Leaching Test

Laboratory tests were conducted at the Department of Civil Engineering at the University of South Alabama to quantify water quality impacts of sections of cementitious and polyurea liners. In the absence of approved or standard methods for testing stormwater culvert repair products, the procedure applied was adapted from current practices for detecting water quality alterations from potable water pipes (NSF/ANSI Standard 61) (National Sanitation Foundation International, 2007). Similar to laboratory tests for potable water pipes, samples were collected and analyzed every 3 days (Table 1).

Ten days after installations, sections of the polyurea and cementitious liners were removed and immersed in sealed glass vessels (headspace free) that contained synthetic water (pH 7.1, 47 mg/L as $CaCO_3$). For the cementitious liner, this resulted in a liner surface area to water volume ratio of 610:1. For the polyurea liner, this resulted in a liner surface area to water volume ratio of 94:1. The ratio differences are a result of the size differences in the liner sections able to be retrieved from the installations. After five subsequent 3-day exposure periods, contact water was removed and analyzed for typical water quality indicators (Table 1). Three water samples were collected and analyzed from each vessel. Control samples were also collected each sampling period from vessels filled with only synthetic water. Synthetic water was replaced after each 3-day period.

The laboratory test results described herein include a summary of the findings from the leaching tests. In the interest of keeping the emphasis on field installations, it was determined to be unnecessary to include the full analyses that are typically reported in potable pipe water quality studies. The presented laboratory data are therefore condensed in order to provide a sufficient understanding of a repair product's leaching potential in field installations.

RESULTS

Cementitious Spray-on Liners

Literature Review

Materials and Installation Procedures

The product monitored in this study was a cementitious geopolymer spray used to restore concrete, brick, or corrugated metal storm and sewer culverts. Unlike some spray-on liners, this liner can provide full structural support. Following surface preparation of the culvert (i.e., typically hydroblasting to remove debris), bags of the dry geopolymer material are mixed with water onsite to create the desired consistency. The material evaluated in this study is a centrifugally cast spray, applied by a robotic head positioned on a sled that moves through the culvert. Culverts must have a minimum diameter of 36 in to accommodate a worker, who closely monitors the process during application and makes adjustments as necessary. Two or three passes of spray are applied, depending on the thickness needed to handle the particular structural load. The average thickness of the product monitored in this study is 1.5 in. Liner thickness varies depending on the structural design parameters. Water flow can be reinstated 24 hr after application.

Because of the cement or ceramic base ingredients of cementitious sprays, as well as the incorporation of waste products such as fly ash, some, including the product evaluated in this study, are marketed as environmentally friendly. As with other sprays or resins, however, these products contain synthetic ingredients that may require a full cure to prevent chemical leaching.

Standards and Relevant Water Quality Studies

There is currently no published ASTM standard for the cementitious spray-on liner evaluated in this study. According to the vendor, an applicable standard is pending approval for centrifugally cast concrete pipes.

Metals and other toxins also have been found to leach from cementitious coatings into water (Berend and Trouwborst, 1999). Cementitious materials have also been found to increase pH substantially (Deb et al., 2010; Fitch, 2003).

Of the constituents analyzed in water samples, only metals, total organic carbon (TOC) concentration, pH, and alkalinity are specified in Virginia water quality standards (Virginia Administrative Code, 2004, 2010). Virginia water quality standards specify a pH range of 6 through 9 (Virginia Administrative Code, 2010). Virginia groundwater standards specify the maximum allowable concentrations for numerous metals (Virginia Administrative Code, 2004). Virginia ground water criteria specify a maximum TOC concentration of 10 mg/L and a maximum alkalinity concentration as 200 mg/L and 500 mg/L, depending on the physiographic province (Virginia Administrative Code, 2004). Although Virginia groundwater standards are enforceable, groundwater criteria are intended to provide guidance in preventing groundwater pollution and are not mandatory (Virginia Administrative Code, 2004).

Installation Observations

An installation was carried out on a 20-ft section of a 72-in corrugated metal culvert (Figure 2). Large globules of overspray were visible within a few feet of the downwind end of the culvert and were captured on fabric placed outside the inlet and outlet. Small gusts of wind carried airborne particles downwind a minimum of 60 ft. Following application, the product had a soft clay-like texture for the first several hours and had hardened by the following day. Because VDOT had no prior experience using this liner, there were no observations by VDOT staff present at the installation regarding past installations or liner performance.

Figure 2. Installation of Cementitious Spray-on Liner

Water Sampling Results

Flowing Water Test and Immersion Test

Of the 26 metals evaluated, potassium was the only metal with elevated concentrations following contact with the liner (Table 2). Potassium is not specified in Virginia water standards (Virginia Administrative Code, 2004) but is a known component of minerals used to create cement. The maximum pH value recorded was 8.8, which approached but did not exceed the Virginia threshold of 9 (Virginia Administrative Code, 2010). Concentrations of semivolatile organic compounds (SVOCs), volatile organic compounds, (VOCs), and TOC were below the MRL in all samples.

Table 2. Contaminant Concentrations From Samples Collected From Flowing Water and Immersion Tests Before and After Cementitious Spray-on Installation

Contaminant or Parameter	Day 2[a] Flowing Water Test[b]		Day 3 Immersion Test[b]		Day 10 Flowing Water Test[b]	
	Control	Experimental	Control	Experimental	Control	Experimental
Potassium[c]	<MRL	<MRL	1.6 mg/L	36.8 mg/L	1.0 mg/L	8.2 mg/L
SVOCs[d]	<MRL	<MRL	<MRL	<MRL	<MRL	<MRL
VOCs[e]	<MRL	<MRL	<MRL	<MRL	<MRL	<MRL
TOC	<MRL	<MRL	<MRL	<MRL	<MRL	<MRL
pH	7.2	8.0	6.9	7.8	7.5	8.8

MRL = minimum reporting limit; SVOCs = semivolatile organic compounds; VOCs = volatile organic compounds; TOC = total organic carbon.
[a]24 hr after installation.
[b]Concentrations below the MRL of the laboratory are designated “<MRL.”
[c]Concentrations of all other 25 metals evaluated were below the MRL.
[d]Includes 68 SVOCs analyzed in water samples.
[e]Includes 63 VOCs analyzed in water samples.

Laboratory Leaching Test

The laboratory leaching test revealed that the cementitious liner altered water quality. Water pH increased from 7.2 to 11.8 following the first 3-day exposure period. Water pH decreased gradually, but remained above 10, over the remaining exposure periods (12 days). Alkalinity (measured as $CaCO_3$) was elevated (577.5 ± 74.4 mg/L) to a statistically significant degree for the first 3-day exposure period and was increased by roughly 18 to 50 mg/L as $CaCO_3$ for each subsequent exposure period.

The TOC concentration in the water was elevated for two contact periods. Chemical oxygen demand (COD), total nitrogen (TN), and biochemical oxygen demand (BOD_5) concentrations were not detected.

Polyurea Spray-on Liners

Literature Review

Materials and Installation Procedures

The polyurea spray monitored in this study can be applied to concrete and metal culverts. Although this liner enhances the strength of the damaged culvert to some degree (depending on thickness), it is not intended to provide full structural support.

Preparation for installation begins with measures to bypass any water conveyed by the host culvert. Surface preparation includes hydro- or grit-blasting the host culvert to remove dirt and debris. Cracks and holes in the host culvert are filled with concrete before the spray is applied. Although some companies use a robotic sprayer, installers for VDOT are now using hand-held nozzles in order to allow a better evaluation of the liner during application and make any necessary adjustments. Culverts must have a minimum diameter of 36 in to accommodate the worker. Typical installation includes two or three passes of spray on the interior surface, for a final thickness of approximately 0.5 to 0.75 in. The initial cure time for the spray is under 10 sec, although the company recommends waiting 24 hr before reinstating water flow.

Standards and Toxicity Studies

Polyurea sprays comply with the material specifications in ASTM A849 (ASTM International, 2012). ASTM F-1216 (ASTM International, 2007) is also used by polyurea installers to determine the project-specific liner thickness.

The primary constituent of the polyurea spray monitored in this study is an unspecific methylene diphenyl diisocyanate (MDI). MDI is used almost entirely for the production of polyurethane polymers, which are used to produce foam and as hardeners in epoxy resins (Allport et al., 2003). Studies on the toxicity of MDI show very low acute toxicity and low chronic toxicity to aquatic species. MDI is hydrophobic and forms a hard insoluble polymer on the outer shell when released in water as large droplets or globules and as such is presumably unavailable to aquatic organisms (Allport et al., 2003; Yakabe et al., 1999). Any toxicity observed is likely due to soluble reaction products of MDI, which largely comprise methylenedianiline (MDA) (Allport et al., 2003). MDA is a suspected human carcinogen (Agency for Toxic Substances and Disease Registry, 1999) and is toxic to some aquatic species

(Allport et al., 2003). MDA is not readily biodegradable and is not expected to bioconcentrate in aquatic organisms or biomagnify in terrestrial or aquatic food chains (Agency for Toxic Substances and Disease Registry, 1999; Allport et al., 2003; Heimbach et al., 1996). If released to the ground, MDA becomes strongly attached to soil and will not easily move into groundwater. Spills or accidental releases of MDA into the environment of 1 lb or more must be reported to the U.S. EPA (Agency for Toxic Substances and Disease Registry, 1999).

Risks to the aquatic environment arising from heavy loadings (400-10,000 mg/L) of MDI are expected to be low (Allport et al., 2003; Yakabe et al., 1999). However, at very low loadings (under approximately 10 mg/L), when the surface area to volume ratio of the MDI globule is very high (i.e., for a very small droplet), high conversions to MDA can be found (Yakabe et al., 1999). Toxicity effects from low loadings of MDI in water bodies, such as residual molecules desorbing from a culvert lining product, have not been documented.

Table 3 provides a summary of published values for acute MDI and MDA toxicity studies for several aquatic indicator species that are found in freshwater habitats.

Of the constituents analyzed in water samples, only TOC concentration, pH, and alkalinity are specified in Virginia water quality standards (Virginia Administrative Code, 2004, 2010). The only available publicly released laboratory investigation on polyurea coatings determined that there were water quality implications such as a reduction in pH (Johnson, 2008). In addition to isocyanates (such as MDI), polyurea sprays also contain hardeners that may contain VOCs, as well as amine-based hardener compounds. If these compounds are released into the water, water quality indicators such as COD, BOD, TOC, and pH may be affected.

Table 3. MDI and MDA Toxicity Thresholds for Various Freshwater Indicator Species

Species	MDI LC_{50} or EC_{50}[a] (mg/L)	MDA LC_{50} or EC_{50}[a] (mg/L)[b]
Vertebrates		
Zebrafish (*Brachydanio rerio*)	24-hr LC_{50}: >1000[c]	96-hr LC_{50}: 42.0
Ide fish (*Leuciscus idus)*		96-hr LC_{50}: 53.0
Japanese killfish (*Oryzias latipes)*	24-hr LC_{50}: >1000 [d]	48-hr LC_{50}: 32.0
Rainbow trout (*Oncorhynchus mykiss*)		96-hr LC_{50}: 39.0
Invertebrates		
Pond snail (*Limnea stagnalis*)	24-hr EC_{50}: >500[d]	
Daphnia (*Daphia magna*)	24-hr LC_{50}: >1000[c]	
Daphnia (*Moina macrocopa)*		24-hr EC_{50}: 2.3
Microorganisms		
Photobacterium phosphoreum		30-min EC_{50}: 6.6

MDI = methylene diphenyl diisocyanate; MDA = methylenedianiline.
[a]Lethal concentration (LC_{50}) and effective concentration (EC_{50}), or the concentration required to kill (LC_{50}) or have a defined effect on (EC_{50}) 50% of the test population after a given number of hours of exposure in that concentration.
[b]Organization for Economic Cooperation and Development, undated.
[c]Results of vendor tests listed in their product literature (which were the only identified test results for these species). Product literature is not referenced in this report for confidentiality purposes.
[d]Allport et al., 2003.

Installation Observations

The polyurea spray-on installation was conducted on a 20-ft section of a corrugated metal arch culvert with a cross section of 110 by 79 in (Figure 3). Overspray was evident at both culvert openings, and airborne particles were visible a minimum of 90 ft downwind.

The monitored installation resulted in a smooth liner that was seemingly fully bonded to the host culvert. However, as noted by VDOT staff with prior experience using this liner, polyurea spray-on applications in damaged VDOT culverts have resulted in instances of unsuccessful final products (i.e., separation of the liner from the host culvert and several cracks in the liner) (S. Hite, personal communication; J. Milton, personal communication). Company representatives claim that problems with prior installations were likely a result of the use of the robotic head applicator (which has since been replaced with hand applicators) (T. Meyer, personal communication). However, difficulties with the bond between the liner and the host culvert are typically experienced when water infiltrates during the spraying process (Najafi, 2004). Not only does water infiltration during installation affect the liner performance, but surface water contacting the coating before it is fully cured may also impact water quality.

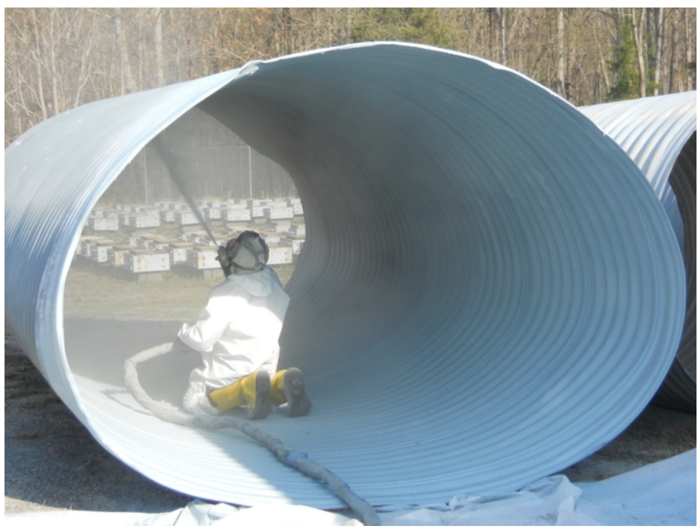

Figure 3. Installation of Spray-on Polyurea Liner

Water Sampling Results

Flowing Water Test and Immersion Tests

Concentrations of MDI and MDA were below the MRL for every sampling event, as were concentrations of VOCs and COD (Table 4). Although the TOC concentration was slightly elevated (5.7 mg/L) in water samples taken from the outlet the day after installation, this concentration was below the maximum threshold of 10 mg/L specified in the Virginia groundwater standards (Virginia Administrative Code, 2004). The pH of water samples in each sampling event was within the range (6 through 9) specified in the Virginia water quality standards (Virginia Administrative Code, 2010).

Table 4. Contaminant Concentrations in Samples Taken From Field Tests Before and Following Polyurea Spray-on Installation

Contaminant or Parameter	Day 2[a] Flowing Water Test (mg/L)		Day 3 Immersion Test (mg/L)		Day 10 Flowing Water Test (mg/L)	
	Control	Experimental	Control	Experimental	Control	Experimental
MDI	<MRL	<MRL	<MRL	<MRL	<MRL	<MRL
MDA	<MRL	<MRL	<MRL	<MRL	<MRL	<MRL
VOC[b]	<MRL	<MRL	<MRL	<MRL	<MRL	<MRL
TOC	<MRL	5.7	<MRL	<MRL	<MRL	<MRL
COD	<MRL	<MRL	<MRL	<MRL	<MRL	<MRL
TN	1.2	<MRL	1.8	1.4	0.8	<MRL
pH	7.5	7.8	6.3	7.1	8.2	8.3

MDI = methylene diphenyl diisocyanate; MRL = minimum reporting limit; MDA = methylenedianiline; VOC = volatile organic compound; TOC = total organic carbon; COD = chemical oxygen demand; TN = total nitrogen.
[a]24 hr after installation.
[b]Includes 63 VOCs analyzed in water samples.

Laboratory Leaching Test

The laboratory leaching test indicated that the polyurea coating altered water quality to a statistically significant degree. Following the first 3-day exposure of the liner to the water, COD in contact water had increased from 0 to 98.3 ± 7.6 mg/L, TOC had increased from 0 to 19.9 ± 0.3 mg/L, TN had increased from 0 to 2.8 ± 0.3 mg/L, and BOD_5 had increased from 0 to 9.2 ± 0.5 mg/L. In addition, water pH had decreased; the greatest reductions occurred during the first two periods in which water pH decreased from 7.1 to 5.9 and 7.5 to 6.5, respectively. Subsequent water contact periods resulted in gradual reductions in water quality impacts, but water quality indicators (COD and TOC) remained elevated throughout the testing period, indicating that organic contaminants were still imparted to some degree by the liner after 15 days of water contact. The polyurea coating did not affect alkalinity concentrations.

DISCUSSION

The flowing water test was designed to simulate field conditions with low flow and little dilution potential and therefore represented a worst case field scenario in terms of having the greatest potential for contaminants to impact water quality. For both spray-on technologies evaluated, the flowing water test results were consistent with those from the immersion test, neither of which demonstrated considerable water quality impacts from the liners. The laboratory leaching test was designed to identify water quality impacts attributable to the materials through a series of water stagnation periods, not typical flowing conditions for stormwater culverts. Laboratory tests detected water quality alterations caused by the liners. These alterations were particularly pronounced in the test of the polyurea liner.

Results obtained in the laboratory analyses would not be the same as those expected from field installations. However, an analysis of the water flow test (a field test) in conjunction with the laboratory data provides a more complete picture of whether water flow typical to field installations mitigates impacts to water quality that may be seen in the laboratory. Whereas field tests are meaningful in that they reflect a true scenario, it is difficult to capture the range of results that may be found given the variety of potential field scenarios and installation variables. For example, numerous field conditions may affect water quality results, including culvert design, water volume, slope (and associated flow rate), and water quality characteristics of the stream or stormwater. Although controlled laboratory tests are not necessarily reflective of field applications, they provide a true indication of contaminant leaching behavior from a liner in the absence of variable field conditions.

Overspray was observed during both liner installations. Measures to contain the overspray would likely prevent adverse impacts that uncured airborne spray particles might have on soil and water quality.

Cementitious Spray-on Liner

In the water flow and immersion tests of the cementitious liner, pH increased to a maximum of 8.8 but did not exceed the maximum regulatory value of 9 (Virginia Administrative Code, 2010). Other evaluated water quality indicators were only minimally affected by the liner. The laboratory leaching tests, however, demonstrated a much greater increase in pH (to a maximum of 11.8) than was found with the other tests, and the liner consistently elevated water pH throughout its five subsequent testing periods. The rise in pH following hydration of the liner was likely caused by elevated concentrations of hydroxyl ions (OH^-) entering the water that contacted the liner (Fitch, 2003). Alkalinity also increased to 577.5 mg/L (although only in the initial contact water), exceeding the Virginia groundwater criteria of 500 mg/L (Virginia Administrative Code, 2004). Alkalinity represents the buffering capacity of water (i.e., its ability to neutralize hydrogen ions and prevent a pH shift). Water with an elevated alkalinity concentration requires a greater amount of acid to decrease the pH. Water pH and alkalinity levels that exceed water standards can adversely affect aquatic species.

Water flow in the field test, however, mitigated the water quality effects from the hydroxyl ions leaving the liner. Because the response of pH to cementitious materials depends largely on stream flow (Fitch, 2003), the pH values found in the laboratory test were not as elevated in the field test with flowing water. Despite a lower surface area to volume ratio in the laboratory leaching test (94:1) and, therefore, more water available for contaminant dilution than in the flowing water test (192:1), the pH response was less in the flowing water test and remained within the range established in Virginia water standards.

Polyurea Spray-on Liner

In the water flow and immersion tests of the polyurea liner, MDI was below the MRL in all water samples, as was its reaction product MDA. Water contact with the liner slightly increased pH, but pH remained within the acceptable range established in Virginia water standards. Other evaluated water quality indicators (TOC, COD, and TN) were not affected in the water flow and immersion tests.

The laboratory leaching test conducted at the University of South Alabama, however, demonstrated that an initial flux of contaminants escapes from the liner during its first contact with water. This was reflected by the increased TOC, COD, TN, and BOD_5 levels. Of these, TOC is the only water quality indicator regulated in Virginia, with a maximum recommended concentration of 10 mg/L (Virginia Administrative Code, 2004). The initial TOC concentration in the contact water (19.9 ± 0.3 mg/L) after a 3-day exposure period to the liner exceeded this threshold. Concentrations of COD and TOC remained elevated throughout the entire 15-day testing period. Laboratory leaching testing also demonstrated an initial pH decrease (from 7.1 to 5.9); this level was slightly less than the acceptable minimum of 6 (Virginia Administrative Code, 2010). It is unclear why pH increased in the flowing water and immersion tests but decreased in the laboratory test.

The discrepancy between results from the immersion test and the laboratory test may in part be explained by contaminant volatilization. Unlike the laboratory leaching test in which the water containers were sealed, the immersion test container was open and exposed to air in order to replicate standing water scenarios at culvert outlets. Organic contaminants could have volatilized from the water in this open container, thereby reducing the aqueous concentration available for detection.

Water flow and dilution also likely contributed to the discrepancy between the results of the laboratory test and the flowing water and immersion tests. With the availability of water flow in the flowing water test and only a small fraction of the surface area exposed to that water for a 25-sec period, any residual contaminants on the liner did not have an opportunity to accumulate in water flowing through the culvert. Despite the low flow and no flow conditions simulated in the flowing water and immersion tests, respectively, the surface area to volume ratios (192:1 and 70:1) were smaller in both tests and there was, therefore, more water available for contaminant dilution than in the laboratory leaching test (610:1). The elevated concentrations of numerous water quality indicators in the laboratory tests indicate that in minimal dilution, water quality in standing water is affected by contaminant(s) leaching from the liner. Although the flowing water test replicated low flow conditions, it cannot be determined from test results whether water quality effects would have been detected in field scenarios with even *less* water available for contaminant dilution or more liner surface area in contact with the water (i.e., a higher surface area to volume ratio). Ratios as high as those seen in the laboratory may be feasible in field scenarios with standing water (puddles) in the culvert, but they are probably uncommon in field scenarios with water flow.

CONCLUSIONS

- *The cementitious spray-on liner evaluated in this study is not expected to have an adverse impact on water quality if protective controls are followed in installation procedures.* Water pH and alkalinity exceeded state regulatory standards (i.e., 11.8 and 577.5 mg/L, respectively) in laboratory tests, but in flowing water and immersion tests of an installation in the field, concentrations in water samples evaluated for a suite of toxins and water quality indicators were below MRLs and state water standards.

- *For polyurea spray-on liners, concerns include liners exceeding water quality standards or exceeding toxicity thresholds for aquatic species in receiving waters having little dilution potential (i.e., receiving waters with very low flows).* Several water quality indicators in laboratory tests demonstrated that contaminants were released from the polyurea liner, particularly during its initial contact with water (i.e., COD increased from 0 to 98.3 mg/L; TOC increased from 0 to 19.9 mg/L; TN increased from 0 to 2.8 mg/L; BOD_5 was 9.2 mg/L; and pH decreased from 7.1 to 5.9). COD, TOC, and TN impacts on water quality were not detected in flowing water and immersion tests, and BOD_5 was not monitored. Stringent protective controls and water quality monitoring are expected to mitigate water quality impacts.

- *For the polyurea spray-on liner evaluated in this study, improper installation practices (e.g., potential water infiltration during installation) have resulted in defective liners in recently installed VDOT culverts.* The possible effect on environmental factors and liner performance may be one VDOT might choose to consider in future product approval decisions.

RECOMMENDATIONS

1. *VDOT's Materials Division in consultation with VDOT's Scheduling and Contract Division, Location and Design Division, and Environmental Division should consider the following specifications to prevent environmental contamination resulting from the installation or use of cementitious spray-on liners:*

   (1) The contractor should perform all installations in the dry (e.g., by diverting water flow).
   (2) The contractor should install a temporary curtain at the outlet and inlet to prevent overspray during installation.
   (3) The contractor should reinstate water flow no sooner than 24 hr after installation.
   (4) The contractor should either (A) capture and properly dispose of the rinse water prior to reinstating flow or (B) continuously monitor the pH of the rinse water and if the pH exceeds 9 should capture and properly dispose of the rinse water.

2. *Pending product approval decisions regarding polyurea spray-on liner, VDOT's Materials Division in consultation with VDOT's Scheduling and Contract Division, Location and Design Division, and Environmental Division should consider the following specifications to prevent environmental contamination resulting from the installation or use of polyurea spray-on liners*:

   (1) The contractor should perform all installations in the dry.
   (2) The contractor should install a temporary curtain at the outlet and inlet to prevent overspray during installation.
   (3) The contractor should reinstate water flow no sooner than 24 hr after installation.
   (4) The contractor should thoroughly rinse the cured liner with clean water and capture and properly dispose of the rinse water prior to reinstating flow.

(5) The contractor should employ the services of a qualified independent environmental services or environmental consultant to collect the following samples:

(a) pre-rehabilitation water and soil samples within 3 feet of the pipe ends (or otherwise as close as possible) upstream and downstream of the pipe location
(b) water and soil samples within 3 feet of the pipe ends (or otherwise as close as possible) upstream and downstream of the pipe location within one week after the liner has cured.

Samples with appropriate triplication should be collected in accordance with applicable ASTM standard procedures and analyzed for total methylene diphenyl diisocyanate (MDI), methlyenedianiline (MDA), and total cyanide. Water characterization for COD and TN concentrations should also be conducted.

Details to supplement this sampling specification (i.e., where results should be reported, etc.) should be considered for inclusion in the final specification.

BENEFITS AND IMPLEMENTATION PROSPECTS

Spray-on liners are expected to add 45 to 50 years of additional service life to the pipe (Cooney et al., 2011). The literature does not appear to provide cost information for spray-on lining installations.

Increased regulatory scrutiny of stormwater culverts has recently increased pressure on VDOT to find environmentally sound methods of culvert repair. A Public Notice issued in March 2010 by the U.S. Army Corps of Engineers regarding stormwater culvert permitting requirements resulted in a change in VDOT's culvert repair selection process. Prior to this Public Notice, applications of pneumatically applied concrete (also known as "shotcrete") over damaged culvert floors was an affordable and common method of culvert repair in some VDOT districts. Because these applications result in raised culvert bottom elevations, concerns of the U.S. Army Corps of Engineers regarding their effect on stream dynamics and passage by aquatic organisms resulted in a recent increase in the enforcement of VDOT's permitting requirements (U.S. Army Corps of Engineers, 2010). The consequent added labor, costs, and project delay to VDOT have decreased the number of culverts repaired with concrete. Because spray-on liners result in nominal increases in bottom elevation (0.25 to 1.5 in), their availability as options for culvert repair provides VDOT with greater flexibility and efficiency in repairing damaged culverts.

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