Field evaluation of the service life of foul-release coatings in Columbia River

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Field evaluation of the service life of foul-release coatings in Columbia River (TI project #233)

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Abstract

A field experiment was conducted to assess effective service life of foul-release coatings to mitigate the impacts of invasive zebra and quagga mussels (*Dreissena*). Coated concrete and steel panels were deployed in the Columbia River (Oregon and Washington, USA) to compare to effectiveness of Sher-Release (Fuji/ Sherwin Williams), Intersleek900 (International), and HempasilX3 (Hempel) to the current protective coatings used on submerged concrete (CrystalSeal), and steel (Corps V-766e vinyl). Effective service life was evaluated by the resistance of coatings to physical damage after different service periods in the Columbia River as well as the resistance to fouling by zebra mussels and soft organisms. Approximately 1,000 panels were deployed in the Columbia River at the onset of the experiment in April 2012. A subset of panels was removed from the Columbia River every six months, and inspected for physical damage (e.g., substrate adhesion), and then deployed in a zebra mussel-infested water body to evaluate the resistance to zebra mussel biofouling (e.g., adhesion strength).

The foul-release coatings were susceptible to physical damage from gouging and exhibited poor coating adhesive strength to the substrate relative to the Corps vinyl in knife adhesion tests. Conversely, the foul-release coatings on steel panels were more resistant to an abrasive sanding disc than the Corps vinyl coating. All coatings were resistant to scribe attack and coating adhesion at the edges of the scribe remained intact. The three foul-release systems had acceptable resistance to physical damage caused by deployment in the main stem Columbia River for immersion periods up to 39-months. The HempasilX3 (steel) and Sher-Release (concrete) foul-release systems developed blisters after several months of service in the Columbia River, and by the end of the experiment, blistering was present on all of the HempasilX3 (steel) panels and most of the Sher-Release (concrete) panels. Despite the early and frequent blistering, the HempasilX3 (steel) system was the most resistant against both zebra mussel and soft fouling, as well as being the most resistant coating to weight loss by abrasive sanding disc.

The foul-release coatings were effective against zebra mussels when deployed in a zebra mussel-infested reservoir. The control coatings were heavily fouled by zebra mussels. There was a significant effect of coating type on zebra mussel adhesion strength, $F(7,201) = 1{,}166.2$, $p<0.001$, and post hoc Tukey tests found significant differences ($p<0.005$) in mussel adhesion strength between the foul-release coatings and the protective coatings. Some zebra mussels were able to attach to foul-release coatings but they were easily removed.

Overall, the Intersleek900 coating was the best foul-release system evaluated in this study. The Intersleek900 system worked on both concrete and steel and did not exhibit significant physical damage caused by service periods up to 39-months in the main stem Columbia River, e.g., blistering. The Sher-Release (steel) coating also performed well against fouling and did not

exhibit significant physical damage during the deployment, however, the Intersleek900 coating was more resistant than the Sher-Release coating to zebra mussel fouling and weight loss by abrasive sanding disc.

A pilot study using Intersleek900 should be conducted on a limited number of auxiliary water supply diffuser gratings to determine how long the coatings will last under normal facility operations, including the wear induced by the operations done during the in-water work period when the fishways are dewatered and work crews are walking on and working on the gratings for several weeks.

Introduction

Context

Zebra mussels (*Dreissena polymorpha*) and quagga mussels (*D. rostriformis bugensis*) are invasive freshwater mussels that cause extensive economic and ecological impacts in areas outside their native range (Dermott and Kerec 1997; Mann, Radtke, Huppert, Hamilton, Hanna, Duffield and Netusil 2010; Ricciardi, Neves and Rasmussen 1998). Zebra and quagga mussels, hereafter referred to as *Dreissena*, attach to hard submerged surfaces such as concrete, steel and rock using byssal threads and this biofouling can create operational problems for hydroelectric and irrigation facilities, e.g., clogging screens and pipes (Boelman, Neilson, Dardeau and Cross 1997; Claudi and Mackie 1994; Jenner, Whitehouse, Taylor and Khalanski 1998; Neitzel, Johnson, Page, Young and Daling 1984). *Dreissena* can form large dense populations and through their collective filter feeding and deposition of feces and pseudofeces, they change the physical and chemical characteristics of submerged substrates, and this increases corrosion, siltation, material loadings and frictional resistance (Venkatesan and Murphy 2009). *Dreissena* mussels have led to millions of dollars in additional maintenance costs for municipal water districts in Nevada, Arizona and California as well as instigating several lake closures (DeLeon 2012; Willett 2012), and if they become established in the Columbia River Basin (CRB), management costs at hydropower facilities are expected to exceed $24 million/ year (Phillips et al. 2005).

The risk of *Dreissena* mussel infestation in the CRB is increasing. In 2007, *Dreissena* mussels were found to have established populations west of the Rocky Mountains, and have since continued to spread in western waterways. *Dreissena* mussels are now established in the Colorado River and associated waterways including Lake Powell (Arizona and Utah), Lake Mead (Arizona and Nevada), Lake Mohave (Arizona and Nevada), and Lake Havasu (California and Arizona). In November 2016, Montana reported detecting *Dreissena* mussel larvae in Tiber Reservoir, MT; Tiber Reservoir is located near the headwaters of the CRB. Trailered watercraft with attached *Dreissena* mussels are regularly intercepted by watercraft inspection stations operated by the States of Idaho, Montana, Washington and Oregon (Begley 2013; Boatner 2013; Knight 2013; Pleus 2013). The risk posed to the Pacific Northwest by the proximity of these new infestations is significant and increases the likelihood of the successful transport and introduction of these species into the CRB.

Federal Columbia River Power System (FCRPS) hydropower facilities in the CRB are particularly vulnerable to macrofouling impacts by *Dreissena* due to the requirements for fish passage of threatened and endangered species and the dependence on once-through river water for raw-water cooled heat exchangers that are fed by concrete-embedded piping. In facilities located in infested waterways, *Dreissena* macrofouling impacts are most problematic on fixed screens and grates, grates used to regulate flow, smaller diameter intake conduits operated at capacity and small diameter piping with flow velocities less than 1.8 m/s (Claudi and Mackie 1994).

Planning is critical to minimizing and mitigating the costs of an invasion of the CRB by *Dreissena*, and Bonneville Power Administration (BPA), Pacific States Marine Fisheries Commission, US Army Corps of Engineers (USACE), US Bureau of Reclamation (USBR) and other stakeholders have recognized the need to develop long-term management measures. Combating the impacts of these fouling mussels will require an integrated management plan that may include specialized coatings to reduce mussel settlement and growth on vulnerable FCRPS facility components. There are reactive and preventative methods available for controlling *Dreissena* macrofouling including treating water with chemicals and heat, manual cleaning, replacing equipment, modifying open-loop cooling systems to closed-loop, mechanical filtration, etc. (Boelman, et al. 1997; Daling and Johnson 1984; Jenner, et al. 1998; Miller, Payne, Nelson and McMahon 1992). This document, however, pertains to anti-fouling coatings and specifically, to the foul-release type coatings that lack biocides and provide fouling protection by minimizing the initial attachment and strength of attachment through the properties of the coating surface.

This type of foul-release coating, hereafter referenced as foul-release, can develop fouling but the strength of the bond is weak and can be broken by the force of flowing water or by light cleaning (Chambers et al. 2006). Most commercially available foul-release coatings employ three basic layers: an epoxy primer, a tie coat and a room temperature vulcanized silicone or fluorinated topcoat that may contain proprietary free oil. The topcoats typically have properties like low surface energy, non-polarity and elasticity and they are slippery and rubbery. An example application of a foul-release coating involves using an immersion grade epoxy primer on the bare substrate. The second coat is another immersion grade epoxy primer that has a tethering agent added to promote adhesion. The third coat is the tie coat, and the silicone or fluorinated topcoat is the fourth and final coat (Hampton 2011). Naphtha is generally used to thin the topcoat and clean equipment (Music 2011).

Foul-release coatings are environmentally friendly and effective against macrofouling, but these coatings are mechanically weak and are expensive. The efficacy of foul-release coatings against macrofouling varies by product (Wells and Sytsma 2009), but several coating systems have shown excellent performance in panel and trial applications against fouling mussels (Drooks 2009; EPRI 1992; Matsui, Nagaya, Funahashi, Goto, Yuasa, Yamamoto, Ohkawa and Magara 2002; Poulton 2009; USBR 2012). The resistance of foul-release coatings to abrasion and gouging by flotsam and facility operations, as well as the resistance to adhesion failure (e.g., peeling and blistering), however, are major concerns (Drooks 2009; USBR 2012). Additionally, foul-release coatings are expensive, and were estimated in 1999 to range between \$108/m^2 (\$10.03/ft^2) and \$127/m^2 (\$11.80/ft^2) including installation, materials and labor (Gross 1997;

Jones-Meehan, et al. 1999). EPRI (1992) estimated the application costs, including material and labor, to be \$44/m^2 (\$4.09/ft^2) for concrete and \$55/m^2 (\$5.11/ft^2), and that the cost for recoating was half the initial application cost.

An effective *Dreissena* treatment and control program in the CRB will include proven technologies, maintain operational flexibility, can be rapidly implemented, and is cost effective and dependable. BPA funded this effort to evaluate the service life of foul-release coatings under Columbia River conditions, and to develop a detailed cost estimate for applying a foul-release type coating to selected component(s) at a FCRPS facility.

History of macrofouling in study area

Dreissena are not currently found in the CRB. The established *Dreissena* population closest to the CRB is in San Justo Reservoir, CA, although veligers were detected in Tiber Reservoir, MT in 2016, which is close to the CRB headwaters (Benson 2016). *Limnoperna fortunei* (Golden lake mussel), is another prolific freshwater mussel capable of attaching to hard submerged surfaces via byssal threads and developing encrusting colonies, but *L. fortunei* has not been detected in North America (Fusaro et al. 2015; Magara et al. 2001; Sylvester, Dorado, Boltovskoy et al. 2005). Foul-release coatings have also demonstrated effectiveness against *Limnoperna fortunei* macrofouling (Matsui et al. 2002).

Corbicula fluminea (Asian clam) is a freshwater bivalve that was introduced to the CRB in the 1930s (Burch 1944), and is causing macrofouling problems in FCRPS facilities on the main stem Columbia River, e.g., *Corbicula* are removed from cooling condenser tubes during main unit overhauls every five years (Athearn and Darland 2007; Kovalchuk 2007). *Corbicula* adults do not attach to hard surfaces using byssal threads, but these clams do accumulate in collection channels, fishways, under diffuser gratings, behind and lodged in valves, screens and on separator bars (Kovalchuk 2007). In addition to the macrofouling problems associated with blockage, *Corbicula* can cause physical injury to fish (Kovalchuk 2007).

Target macrofouling population

Foul-release coatings are being considered for application to FCRPS facility components to mitigate the potential macrofouling impacts of invasive epifaunal freshwater mussels that attach to hard submerged surfaces using byssal threads. Most adult freshwater mussels do not attach to hard surfaces but instead bury into the sediment using their foot (e.g., *Corbicula fluminea* and *Anodonta* sp.) (McMahon 1991). There are three species of freshwater mussels, however, that attach to and live on the surface of submerged rock, concrete, steel, etc. using byssal threads (i.e. *Dreissena polymorpha*, *D. rostriformis bugensis* and *Limnoperna fortunei).* This document deals specifically with *Dreissena* due to their proximity to the CRB, and because *L. fortunei* is not known to be established in North America (Benson 2016; Fusaro et al. 2015; Magara et al. 2001;

Sylvester et al. 2005); however, the efficacy of foul-release coatings against *L. fortunei* and hence the applicability of this document, is expected to be comparable for *Dreissena* and *L. fortunei (*Matsui et al. 2002).

Dreissena produce planktonic larvae (veligers) that disperse throughout hydrologic connected waterways and facility components. Similar to many marine and brackish water bivalves, *Dreissena* mass spawn gametes into the water column, and larvae feed and develop in the water column (Raven 1958). The extended duration the larvae are in the water column allows for greater potential long distance larval dispersal. Larval development for other freshwater bivalves is either direct (i.e. larvae develop within egg capsules or brood-pouch of adults) or indirect, involving a parasitic glochidium that attaches to a host such as fish (Raven 1958). The peak of *Dreissena* spawning in North America typically occurs between July and August (Adrian, Ferro and Keppner 1994; Garton and Haag 1993; Keppner, Adrian and Ferro 1996; Kraft et al. 1996) when water temperatures are between 16 and 19^{o}C (McMahon 1996). Spawning can begin at water temperatures as low as 9^{o}C, and veligers are present in the water column in North America for 8 to 10 months (McMahon and Bogan 2001).

Larval settlement out of the water column is an active process that involves initial settlement, metamorphosis and translocation to a preferred location. Larval settlement typically parallels temporal spawning patterns, and *Dreissena* juveniles are generally found in the Midwest of North America between August and September (Thorp et al. 1994). *Dreissena* do not appear to discriminate bewtween surfaces on which they initially settle (Sprung 1993). Once metamorphosis is complete, however, *Dreissena* move to a preferred location such as the backside of a screen where flow is baffled and there is constant influx of food and oxygen (Ackerman et al. 1994; Sprung 1993).

Dreissena attach to solid substrates using byssal threads. The byssal apparatus is a bundle of proteinaceous threads attached to the retractor muscle of the foot, and threads attach to the substrate using adhesive plaques (Figure 1) (Eckroat et al. 1993; Rzepecki and Waite 1993). *Dreissena* recruitment is reduced in oxygen concentrations less than 2.0 mg/ L (DeLeon 2009), water velocities greater than 1.8 m/s (5.9 ft./s) (Claudi and Mackie 1994), and in areas of unsuitable substrates and large amounts of sediment (Sprung 1993). *Dreissena* juveniles and adults translocate year-round (Claudi and Mackie 1994), and adults tolerate wide fluctuations in flow patterns, ranging between 0.05 cm/s to 1.8 m/s (0.002 ft./s to 5.9 ft./s) (Claudi and Mackie 1994; Jenner et al. 1998).

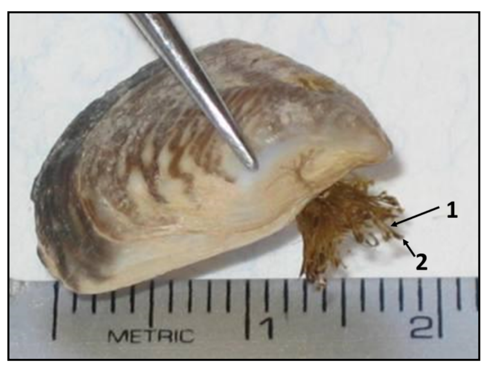


Figure 1: *Dreissena* byssal threads (1) and plaques (2).

Dreissena are small, short-lived mussels that are highly fecund and quickly reach sexual maturity. Adult *Dreissena* are typically 10 to 30-mm (0.4 to 1.2-in.) in shell length (Mills et al. 1993; Karatayev et al. 2007). *Dreissena* in the Great Lakes live 1.5 to 7 years with most living two years (Mackie 1993; Mackie and Schloesser 1996; McMahon 1991), and have an annual growth rate of 15 to 21 mm, and the mean growth rate was 0.12 and 0.13 mm/day for small *Dreissena* and 0.4 to 0.5 mm/day for 15-mm mussels (MacIsaac 1994; Mackie 1993; Wells 2013). *Dreissena* reach sexual maturity when shell lengths are 5 to 10 mm (Mackie 1993; Mackie and Schloesser 1996; Nichols 1996). *Dreissena* females release 275,000 to 1.5 million eggs/ year (Karatayev et al. 2007; Nichols 1996), and the density of newly settled *Dreissena* can be as high as 700,000 individuals/m^2 in one growing season; adult bed densities can be greater than 200,000 individuals/m^2 (Jenner et al. 1998).

Previous studies

This project builds upon prior and ongoing research being conducted by USBR (USBR 2012; USBR 2014), Metropolitan Water District (MWD), Portland State University (PSU) (Wells and Sytsma 2009), and others. USBR initiated steel panel and grate testing of anti-fouling and foul-release coatings in response to quagga mussels establishing in the lower Colorado River in 2007 and biofouling external structures such as trash racks and screens, e.g., untreated track racks at Parker Dam were almost completely occluded by *Dreissena* mussels after seven months immersion (USBR 2012; Willett 2012). The USBR coating research is currently focused on durable foul-release coatings because of the concern over drinking water, endangered species, and the durability of foul-release coatings. MWD was also involved with steel panel and grate experiments in the lower Colorado River using the Intersleek900 and Sher-Release systems (Drooks 2009; De Leon 2009). At the onset of this experiment, the Sher-Release and Intersleek900 foul-release coatings were effective on steel substrates in the lower Colorado River for a period over 36-months (USBR 2012).

In 2009, BPA funded PSMFC and PSU to explore the feasibility of using foul-release type coatings to mitigate *Dreissena* impacts at FCRPS facilities. In 2010, BPA funded PSMFC and PSU to evaluate the effective service life of the three most promising foul-release coatings coming out of the MWD and USBR research under Columbia River field conditions on both steel and concrete substrate and to compare these coatings to protective coatings used by USACE to protect submerged steel and concrete as well as bare concrete. The PSU test panels were deployed in the Columbia River from the breakwater dock at the Port of Camas-Washougal as well as from a moored buoy structure in San Justo Reservoir, CA, which is infested with zebra mussels. As part of this project, PSU developed a detailed cost estimate for applying a foul-release coating to a USACE facility component, which was reported previously (Wells and Sytsma 2013).

This project also builds upon older coating technology research and the experiences of other North American facilities. Foul-release coatings were evaluated in panel and trial applications by USACE (Beitelman 2009; Kelly 1998; Miller and Freitag 1992; Race 1992a; Race 1992b; Race and Miller 1992; Race and Kelly 1994; Race and Miller 1994), Ontario Hydro (Leitch and Puzzuoli 1992; Poulton 2009), Pacific Gas and Electric (Innis 2009), The Electric Power Research Institute (EPRI 1989; EPRI 1992), The Long Island Lighting Company (Gross 1997), and Consolidated Edison Company (Kovalak et al 1993). These findings have historical relevance, but it is important to note that coating manufacturers have changed coating formulations, and to the authors' knowledge, foul-release coatings have never been evaluated in the Columbia River.

Objectives

The goal of this project was to assist BPA, USACE and other stakeholders to develop accurate cost/benefit analyses to determine the cost effectiveness and feasibility of using foul-release coatings as part of an integrated management plan to mitigate the impacts of invasive species such as *Dreissena* macrofouling and the replacement of aging hydro power assets. If *Dreissena* mussels become established in the CRB and cause macrofouling problems, an integrated management plan will be required to mitigate impacts to FCRPS facilities. Control options at Columbia River facilities are especially limited due to multiple threatened and endangered species and critical habitat, which necessitates limited in-water work periods for manual cleaning. Foul-release coatings are environmentally friendly and effective against macrofouling (Matsui et al. 2002; Skaja 2011), and foul-release coatings may be used on particular components to reduce mussel settlement and growth. These coatings are soft, however, and the effective lifespan is unknown. The resistance to abrasion and gouging caused by suspended solids, flotsam and facility operations, as well as the resistance to adhesion failure (i.e. peeling, blistering) are major concerns with foul-release coatings. Marine vessel hulls and offshore equipment (steel) have been traditional markets for foul-release coatings, but many vulnerable facility components are concrete. Most of the current foul-release coating research has been focused on mitigating impacts in freshwater hydro facilities in the lower Colorado River with the quagga mussel (*Dreissena rostriformis bugensis*) (USBR and MWD). This project complimented these other efforts by evaluating both concrete and steel substrates in the Columbia River and with zebra mussels (*Dreissena polymorpha*), and comparing results to the protective coatings currently used by the USACE in the FCRPS.

The specific project objectives are:

- Determine effective service life of the Sher-Release (Fuji/ Sherwin Williams), Intersleek900 (International), and HempasilX3 (Hempel) foul-release coatings on concrete and steel substrates under Columbia River field conditions relative to the current coatings used to protect submerged concrete (CrystalSeal), and steel (Corps V-766e vinyl), as well as to bare, uncoated concrete. Effective service life was evaluated by the resistance of coatings to damage caused by field deployment and the resistance to zebra mussel attachment.

- Provide technology transfer activities through presentations, documents and meetings.
- Prepare final report summarizing coating evaluations including recommendations.

Methods

Schedule

The experiment was initiated in Fiscal Year 2011 under the BPA TI program. Approximately 1,000 coated concrete and steel panels were deployed in the Columbia River in late March and early April 2012 at the Port of Camas-Washougal (Table 1). In order to evaluate coating durability and resistance to fouling after different service periods, panel subsets (48 large and 48 small panels) were removed from the Columbia River after 3-months immersion (July 2012), 9-mo. (January 2013), 15-mo. (July 2013), 21-mo. (January 2014), 27-mo. (July 2014), 33-mo. (January 2015), and 39-mo. immersion (July 2015) (Table 1). After retrieval from the Columbia River, the panels were photographed, cleaned, and evaluated for physical damage caused by field deployment (e.g., blistering, scribe undercutting corrosion, surface roughness) as well as the coatings' resistance to damage induced during laboratory testing (e.g., abrasion and knife adhesion) (Table 1).

In order to evaluate the coatings resistance to *Dreissena* fouling after different service periods, the panels were transported to and deployed in a water body infested with zebra mussels, San Justo Reservoir, CA. The panels were deployed for five months during the time larvae are settling out of the water column, and juvenile mussel colonization and growth is most active (late summer-fall) (Table 1). The large panels were used for zebra mussel testing after the non-destructive laboratory evaluations were competed. The 0-, 3-, and 9-month immersion panels (from Columbia River) were deployed in San Justo Reservoir in April 2013 and retrieved in September 2013. The 15- and 21-mo. immersion panels were deployed in and retrieved from San Justo Reservoir in April and September of 2014, respectively. The 27- and 33-mo. immersion panels were deployed in and retrieved from San Justo Reservoir in April and September of 2015, respectively. The panels representing the longest immersion period in the Columbia River, 39-months, were deployed in and retrieved from San Justo Reservoir in April and September of 2016, respectively.

Throughout the project period, PSU communicated with numerous stakeholders throughout the CRB and beyond by attending and presenting at meetings, e.g., Columbia River Basin Team, university seminars, and engaging media representatives in order to disseminate information about the potential problems with *Dreissena* mussels in the CRB, provide project updates, and share what BPA and others are doing to address the threat. Monthly and quarterly reporting was done throughout the project period.

Table 1: Schedule of major project activities.

Task	FY 2012												FY 2013												FY 2014												FY 2015												FY 2016												FY 2017											
				CY 2012												CY 2013												CY 2014												CY 2015												CY 2016												CY 2017									
	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S
Coating application				■	■	■																																																																		
Panel deploy in Columbia Rv						■	■																																																																	
Panel retrieval from Columbia Rv										■						■						■						■						■						■						■																										
Physical damage evalations											■	■	■			■	■	■				■	■	■				■	■	■				■	■	■				■	■	■				■	■	■		■	■	■	■	■	■	■	■	■	■													
Panel deploy in San Justo Res.																			■												■												■												■																	
Panel retreival from San Justo Res.																								■												■												■												■												
Biofouling evaluations										■	■	■				■	■	■				■	■	■	■	■		■	■	■				■	■	■	■	■		■	■	■	■			■	■	■	■											■												
Cost estimate for application																■	■	■			■	■	■	■	■																																															
Presentation and meetings									■				■							■					■							■					■							■					■							■							■									
Reporting						■			■			■			■			■			■			■			■			■			■			■			■			■			■			■			■			■			■			■	■	■	■									

Coating systems

Three types of foul-release coatings were evaluated in this experiment and included Sher-Release (Sherwin Williams/ Fujifilm Smart Surfaces), HempasilX3 (Hempel), and Intersleek900 (International). The three controls in this experiment included Corps of Engineers V766e vinyl (Simco), CrystalSeal (Hydro-Loc), and bare concrete.

The coating were applied to concrete and/or steel panels to create the following coating systems evaluated in this experiment:

- Sher-Release (concrete)
- Sher-Release (steel)
- HempasilX3 (steel)
- Intersleek900 (concrete)
- Intersleek900 (steel)
- Corps 766e vinyl (steel)
- CrystalSeal (concrete)
- Bare (concrete)

Panel preparation

Steel panels were purchased from Southwestern Paint Panels. A trial batch of steel panels was inspected and approved by the applicator. Steel panels were prepared in two sizes (31-x15-x2.5-cm and 13-x10-x2.5-cm) by cutting to dimension, drilling holes in each corner, removing grease and oil, and wheel grinding to 3 to 4-MILS. Post preparation, the steel panels were handled with nylon gloves, cooled, wiped, and packaged in sealable plastic pails with desiccant packs to prevent flash rusting, and freight shipped to the coating applicator.

Concrete panels were fabricated and moisture cured by a concrete subcontractor (Flatwork Construction Inc.) according to ASTM D1734 (2003). Due to concerns of concrete panels breaking under field conditions, the thickness of concrete panels was 2.5 cm., and 1-cm gravel, reinforcing fiber, and rebar were added to increase panel strength. Concrete panels were stored indoors for approximately six months prior to use.

PSU prepared concrete panels for paint application. Small holes were drilled in the sides of each concrete panel at opposing corners and small eyehooks were secured with metal/concrete epoxy. Cured concrete panels were cleaned with a stiff bristle brush, abrasive blast cleaned with 60/30 Black Beauty media (very fine grit), cleaned with compressed air, and packaged in clean plastic according to ASTM D4258 (2005). Quality control measures included visually inspecting every panel for evidence of oil, salt and other contaminants, and measuring the surface profile on a subset of panels according to ASTM D4417 (1993) using an Elcometer 224 digital profile gauge.

Each panel face was characterized by averaging the profile values from five locations, with each location consisting of ten measurements in an 11-cm^2 area. A subset of prepared concrete panels was mailed to applicator to determine if patching or additional surface preparations were recommended. Upon applicator approval, the prepared concrete panels were packaged in boxes and freight shipped to applicator located in Maryland. PSU staff traveled to Maryland and unpacked all concrete panels and inspected for damage. Damaged panels were discarded.

Paint application

The coatings were applied to panels in the period between January and March of 2012 by Fujifilm Smart Surfaces LLC (Maryland, USA) according to project specifications that were developed using manufacturer recommendations and the product labels. Table 2 provides the application specifications for the Sher-Release (concrete) system, and Table 3 provides the specification for the Sher-Release (steel) system. The HempasilX3 (steel) details are provided in Table 4. Intersleek900 (concrete) and Intersleek900 (steel) application details are provided in Tables 5 and 6, respectively. The Corps vinyl (steel) system was applied according to Table 7, and CrystalSeal (concrete) was applied according to Table 8.

Table 2: Application details for Sher-Release (concrete).

Coating System:	Sher-Release	
Substrate:	concrete (Portland cement, gravel, fiber, rebar)	
Items to be coated:	all surfaces of panels, 31-x15-x2.5-cm and 13-x10x2.5-cm	
Surface preparation:	SSPC-SP #13	
Total surface area (m^2) to coat:	9.3	
Coating	**DFT (µm)**	**Product**
Epoxy prime coat	152	Corobond 100
Epoxy patching material	flush fill	Steel Seam FT 910
Epoxy second coat	152	Seaguard 6100
Silicone tie coat	152	Seaguard Sher-Release Tie Coat
Silicone Surface Coat	152	Seaguard Sher-Release Surface Coat
Total DFT of Coating System:	608	

Table 3: Application details for Sher-Release (steel).

Coating System:	Sher-Release	
Substrate:	steel (A36)	
Items to be coated:	all surfaces of panels, 31-x15-x0.32-cm and 13-x10-x0.318-cm	
Surface preparation:	Wheel-grind 3-4 MIL, cool, and nylon sweep	
Total surface area (m^2) to coat:	7.4	
Coating	**DFT (µm)**	**Product**
epoxy prime coat	152	Seaguard 6100
epoxy patching material	flush fill	Steel Seam FT 910
epoxy second coat	152	Seaguard 6100
silicone tie coat	152	Seaguard Sher-Release Tie Coat
silicone surface coat	152	Seaguard Sher-Release Surface Coat
Total DFT of Coating System:	608	

Table 4: Application details for HempasilX3 on steel panels.

Coating System:	HempasilX3	
Substrate:	steel (A36)	
Items to be coated:	all surfaces of panels, 31-x15-x0.32-cm and 13-x10-x0.32-cm	
Surface preparation:	Wheel-grind 3-4 MIL, cool, and nylon sweep	
Total Surface Area (m^2) to coat:	7.4	
Coating	**DFT (µm)**	**Product**
epoxy primer	152	HEMPADUR QUATTRO 17633
epoxy primer	152	HEMPADUR QUATTRO 17633
silicone tie coat	127	NEXUS 27302
silicone topcoat and crosslinker	152	HempasilX3 87500 and Crosslinker 98950
Total DFT of Coating System:	583	

Table 5: Application details for Intersleek900 (concrete).

Coating System:	Intersleek900	
Substrate:	concrete (Portland cement, gravel, fiber, rebar)	
Items to be coated:	all surfaces of panels, 31-x15-x2.5-cm and 13-x10-x2.5-cm	
Surface preparation:	SSPC-SP #13	
Total Surface Area (m^2) to coat:	9.3	
Coating	**DFT (µm)**	**Product**
epoxy sealer	51 - 76	Intergard 264 (thinned 20-30%)
anticorrosive primer	127	Intergard 264
anticorrosive primer	127	Intergard 264
silicone elastomer tie coat	102	Intersleek900 731
fluoropolymer topcoat	152	Intersleek970
Total DFT of Coating System:	584	

Table 6: Application details for Intersleek900 (steel).

Coating System:	Intersleek900	
Substrate:	steel (A36)	
Items to be coated:	all surfaces of panels, 31-x15-x0.32-cm and 13-x10-x0.32-cm	
Surface preparation:	Wheel-grind 3-4 MIL, cool, and nylon sweep	
Total Surface Area (mt^2) to coat:	7.4	
Coating	**DFT (µm)**	**Product**
anticorrosive primer	127	Intergard 264
anticorrosive primer	127	Intergard 264
silicone elastomer tie coat	102	Intersleek900 731
fluoropolymer topcoat	152	Intersleek970
Total DFT of Coating System:	508	

Table 7: Application details for Corps vinyl (steel).

Coating System:	Corps of Engineers V-766e vinyl grey/ white	
Substrate:	steel (A36)	
Items to be coated:	all surfaces of panels, 31-x15-x0.32-cm and 13-x10x0.32-cm	
Surface preparation:	Wheel grind 3-4 MIL, cool, and nylon sweep	
Total Surface Area (m^2) to coat:	7.4	
Coating	**DFT (µm)**	
Primer	25 - 38	V2108D
grey vinyl paint	25 - 38	V766e
white vinyl paint	25 - 38	V766e
grey vinyl paint	25 - 38	V766e
white vinyl paint	25 - 38	V766e
grey vinyl paint	25 - 38	V766e
white vinyl paint	25 - 38	V766e
Total DFT of Coating System:	175 - 266	

Table 8: Application details for CrystalSeal (concrete).

Coating System:	CrystalSeal	
Substrate:	concrete (Portland cement, fiber, rebar)	
Items to be coated:	all surfaces of panels, 31-x15-x0.32-cm and 13-x10-x0.32-cm	
Surface preparation:	SSPC-SP #13	
Total Surface Area (m^2) to coat:	9.3	
Coating	**DFT**	
Sealer	6.14 m^2/ L	Crystal Seal *NOTE: do NOT spray. Apply with roller
Sealer	6.14 m^2/ L	Crystal Seal
Total DFT of Coating System:		

The applicator, Fujifilm Smart Surfaces, LLC, was the parent company of the Sher-Release coating product, and certain procedures were implemented to address conflicts of interest. PSU staff traveled to the paint applicator facilities for the application of the coatings to provide paint supplies, assist with panel preparation, and to implement quality assurance and quality control measures. PSU stored paint supplies in an offsite storage facility in Maryland until time of application. All coating materials were furnished to the applicator by PSU in unopened, clearly identifiable containers. Mixing of different manufacturer's coatings was not permitted. Containers remained unopened until required for use. No coating was used that had expired its shelf life. PSU staff videotaped the application to ensure that each coating under evaluation in this study was applied with similar methods (e.g. number of passes, equipment, etc.), and according to individual application protocols (e.g. mixing ratios, film thickness, etc.). Ambient conditions (e.g. relative humidity, surface temperature, dew point) and product batch numbers were recorded by PSU during paint application.

The appropriate sealers, primers, tie coat and topcoat were applied using a traditional spray gun with touch-up by brush in an indoor paint booth according to the paint manufacturer's recommendations and project specifications. CrystalSeal (concrete) was the only exception, and was brushed on all surfaces using brushes specified by the manufacturer. Panels were suspended on two welded steel racks using wire hooks for paint application so that the entire panel surface could be coated at one time, i.e., continuous application. Surface temperature was at least 3^{o}C above the dew point with no visible moisture on the panel surface before application proceeded, and painting was suspended if the ambient temperatures were below 10^{o}C. Sprayed paint was applied using parallel passes. Coating was worked into all crevices and corners, and all runs or sags were brushed out in order to insure no air pockets, solvent bubbles, voids, or areas of excessive buildup. The manufacturer's recommendations for drying and curing times were followed, and all coatings were allowed to dry thoroughly, but not less than manufacturer's specified time prior to application of a succeeding coat. Maximum re-coat windows were adhered to at all times. The manufacturer's recommended pot life was not exceeded, and if reached, the spray equipment was emptied, the material destroyed, and new material was mixed.

The coating film thickness was specified by PSU, and was spot-checked during application using a wet mil gauge that was pressed into the paint film immediately after application to ensure coat was appropriate thickness and that coverage was uniform (ASTM D1212 2007). Painted surfaces were visually inspected after painting and drying to inspect for fish-eyes (indicating potential adhesion problems due to silicone contamination of epoxy layer), and orange peel indicating improper application (e.g., viscosity, insufficient air pressure, wrong nozzle size, fluid flow, spray gun distance, etc.) (Music 2011). Damage to intermediate coats, prior to application of the next coat, was repaired by applicator so that the finished work did not contain sags, runs, wrinkles, spots, blisters, or other visible application flaws that cause premature coating failure. Panels were cured for several days, removed from the rack and packaged in closed-cell foam for freight shipment to PSU.

Field deployment

A total of 960 panels (360 coated concrete, 120 uncoated concrete, and 480 coated mild steel panels) were submerged in the Columbia River, Oregon and Washington, USA at the onset of the experiment in late March and early April 2012. A randomly selected, 96-panel subset was removed from the Columbia River at approximate six-month intervals for different immersion periods (0-, 3-, 9-, 15-, 21-, 27-, 33-, and 39-mo.) (Table 9), and the coating effective service life was evaluated for the panels using the coating's resistance to physical damage and the resistance to fouling. Panels were evaluated in the PSU Laboratory for physical damage and resistance to soft fouling. Following the laboratory analyses, the panels were then deployed in a zebra mussel-infested waterbody for five-months to evaluate the coatings' resistance to zebra mussels. Panels were wrapped in polyethylene foam and transported in plastic containers covered with Columbia River water. Filtered Columbia River water was used to refresh containers as needed, e.g., after cleaning panels with water stream. After laboratory analyses, panels were stored and transported in distilled water.

Table 9: The number of panels used in this experiment. Treatments included immersion time (months) (8 levels), and the coating system (8 levels). The coating system included the coating and the panel material (concrete or steel). Each treatment was done in two panel sizes (large and small). Six replicates were removed for each treatment.

Coating system	Panel size	IMMERSION TIME TREATMENTS (MONTHS)									TOTAL
		0	3	9	15	*21*	*27*	33	39	extra	
Sher-Release (concrete)	large	6	6	6	6	***6***	***6***	6	6	12	60
Sher-Release (concrete)	small	6	6	6	6	***6***	***6***	6	6	12	60
Sher-Release (steel)	large	6	6	6	6	***6***	***6***	6	6	12	60
Sher-Release (steel)	small	6	6	6	6	***6***	***6***	6	6	12	60
Intersleek900 (concrete)	large	6	6	6	6	***6***	***6***	6	6	12	60
Intersleek900 (concrete)	small	6	6	6	6	***6***	***6***	6	6	12	60
Intersleek900 (steel)	large	6	6	6	6	***6***	***6***	6	6	12	60
Intersleek900 (steel)	small	6	6	6	6	***6***	***6***	6	6	12	60
HempasilX3 (steel)	large	6	6	6	6	***6***	***6***	6	6	12	60
HempasilX3 (steel)	small	6	6	6	6	***6***	***6***	6	6	12	60
CrystalSeal (concrete)	large	6	6	6	6	***6***	***6***	6	6	12	60
CrystalSeal (concrete)	small	6	6	6	6	***6***	***6***	6	6	12	60
Bare (concrete)	large	6	6	6	6	***6***	***6***	6	6	12	60
Bare (concrete)	small	6	6	6	6	***6***	***6***	6	6	12	60
Corps vinyl (steel)	large	6	6	6	6	***6***	***6***	6	6	12	60
Corps vinyl (steel)	small	6	6	6	6	***6***	***6***	6	6	12	60
Total		96	96	96	96	***96***	***96***	96	96	192	960

The Columbia River study location was the Port of Camas-Washougal, Washington on the Columbia River (N 45.57697 W 122.38012) (Figure 2a, 2b). The study location on the Columbia River was located along the south side of the breakwater dock and was oriented parallel to the main stem Columbia River (Figure 2c, 2d).

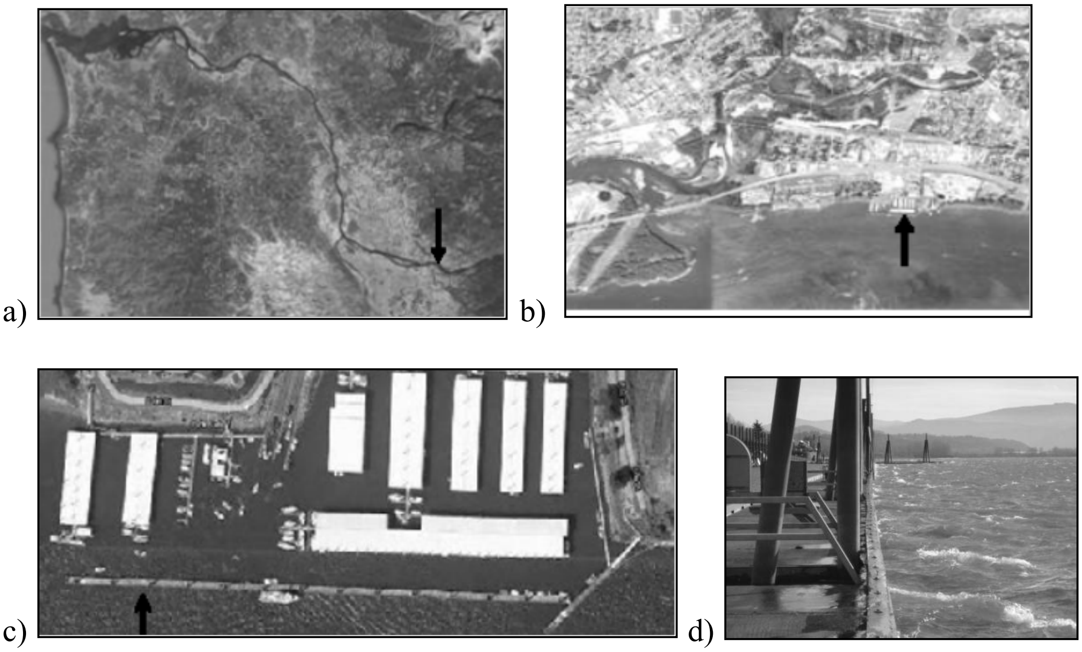


Figure 2: Columbia River main stem study location in relation to the a) Columbia River, b) the City of Camas and Washougal, c) the breakwater dock in the Port of Camas-Washougal, and d) on the breakwater dock looking upstream.

Coated panels were secured to steel support frames for deployment in the Columbia River (Figure 3). The support frame design was modeled from Stone and Webster Engineering Corporation as presented in EPRI (1989), and prototypes were constructed and evaluated in 2011 to make necessary modifications prior to full-scale deployment. Each support frame was approximately 1.8-m x 1.4-m (length x height) in size. In order to account for potential effects of water depth, ten different frame models were identified with the various configurations of three rows large panels and two rows small panels, and each of the 27 frames was assigned to a random frame model. The panel locations (row and panel position) were randomly assigned to the 18 large and 18 small panels deployed in each frame. The entire support frame, including 36 panels, weighed approximately 145 kg. Each support frame was secured to the breakwater dock using lag screws and by sandwiching the bullrail with angle iron bolted together. The frames were spaced approximately 1.0 m apart.

Proper planning provided for the safe collection of the field data. The support frames, buoy structure, and panels were designed to minimize direct contact with each other, and to withstand a service life of five years in the Columbia River and/or San Justo Reservoir. Polyethylene foam (2-mm thickness) was placed between the panels and the steel frame to reduce coating damage caused by the deployment mechanism. Each frame was attached to breakwater dock at five separate points of attachment, including four mounting plates with lag screws as well as angle iron secured to the dock bull rail with half inch diameter bolts. Similarly, the panels were designed and fabricated to maintain panel integrity. Mild steel panels were 3.2-mm thick. An extra 20% of panels were deployed at the onset to provide back-up for loss and other unforeseen events.

The water velocity was measured using a water velocity probe (Swoffer 2100) along the entire portion of the breakwater dock used for the Columbia River deployment. Velocity was measured at 26 locations on July 12, 2012. At each location, velocity was measured upstream and downstream of each frame at a water depth of approximately 1.0 m. Velocity was also measured in a depth profile down the front of each frame at 0.6-, 1.0-, and 1.5-m water depths. A multi-probe unit (e.g., Hydrolab Quanta) was deployed at both field sites to measure water temperature, dissolved oxygen, and pH along a depth profile at 1-m intervals when possible.

a)

b)

Figure 3: Steel frames used to deploy coated steel and concrete panels in the Columbia River, including a) frame and panels hoisted above the breakwater dock using davit crane, and b) several frames deployed against breakwater dock parallel to the Columbia River.

The study location for the zebra mussel attachment tests was San Justo Reservoir, located near Hollister, California (N 36.818183 W 121.446397) (Figure 4a). The study location within San Justo Reservoir was a moored buoy structure deployed near the dam (Figure 4b).

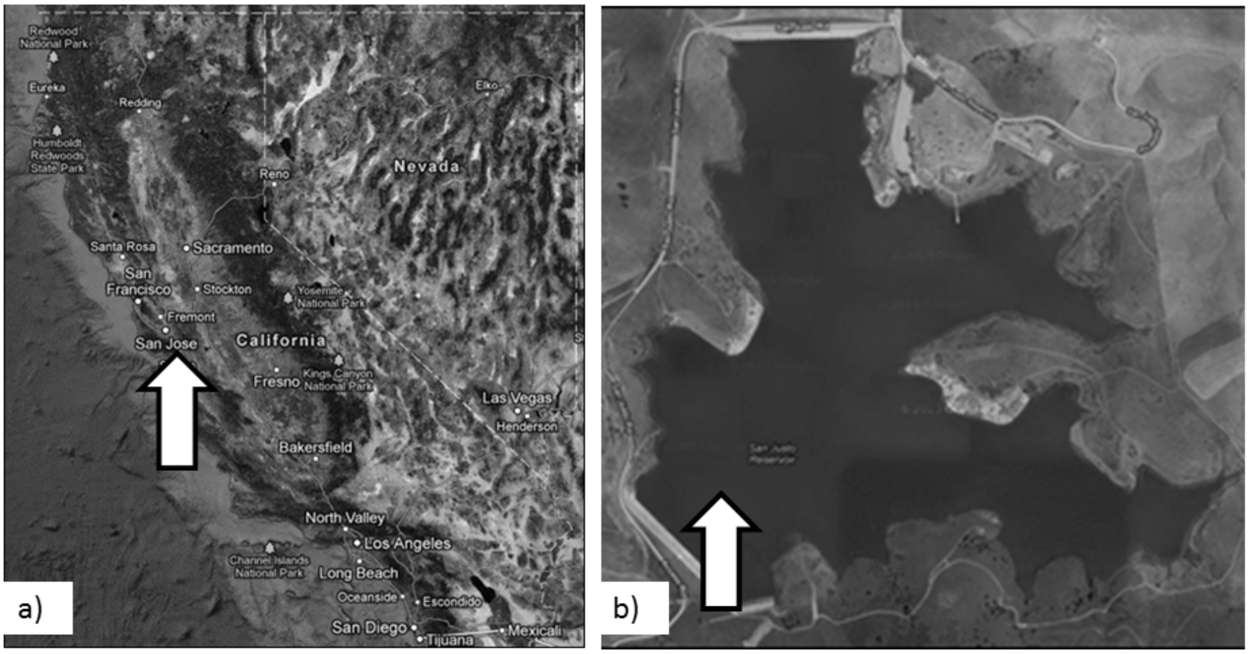


Figure 4: The location of the zebra mussel-infested water body, San Justo Reservoir, used for zebra mussel attachment tests within a) California, and b) within the reservoir.

The *in-situ* experiment provided for zebra mussel colonization on test panels under natural conditions. Panels were deployed during the period when zebra mussel larvae were settling out of the water column and juvenile mussel colonization and growth were active (April to September). A composited plankton sample (1,000-L water filtered) was collected during panel deployment (April) and retrieval (September) to determine if zebra mussel veligers were present in the water column. Plankton samples were collected using a 64-µm mesh simple conical plankton net, preserved in ethanol, and analyzed under cross-polarized light microscopy for presence/non-detect data.

Panels were transported to San Justo Reservoir, CA in order to evaluate the coatings' resistance to *in-situ* zebra mussel attachment following different service periods in the Columbia River (0-, 3-, 9-, 15-, 21-, 27-, 33-, and 39-months). The 0-, 3-, and 9-month immersion treatments were deployed in and retrieved from San Justo Reservoir in April and September of 2013, respectively. The 15- and 21-month immersion treatments were similarly deployed in 2014, as were the 27- and 33-month immersion treatments in 2015. The 39-month immersion treatment was deployed with no other immersion periods in 2016.

The panels were deployed at a water depth of 9 m for a period of 5 months. Panels representing the 39-month immersion treatment were deployed at 4-m depth instead of 9-m due to low water conditions at the time of deployment. The panels were deployed horizontally in San Justo Reservoir using pvc ladders (Figure 5a) that were attached to a series of moored-buoys 122-m in total length (Figure 5b). Approximately six panels were deployed in each pvc ladder. The panel face used for zebra mussel measurements (e.g., side of panel facing main stem Columbia River) was deployed facing down in the pvc ladder (Figure 5a). Buoys were made from 15-cm diameter pvc pipe filled with empty plastic sealable bottles and capped. Two 3-m length pipes were banded together using nylon-coated wire to make one buoy. Buoys were connected to sections of submerged chain, and the sections of chain were shackled together to form a series of buoys. A total of 74 buoys were deployed throughout the experiment. The deployment location in San Justo was the deepest area of the reservoir as indicated by existing topographic and bathymetric maps and depth soundings collected in the field. The reservoir is operated by San Benito Water District and is closed to the general public because the reservoir is infested with zebra mussels.

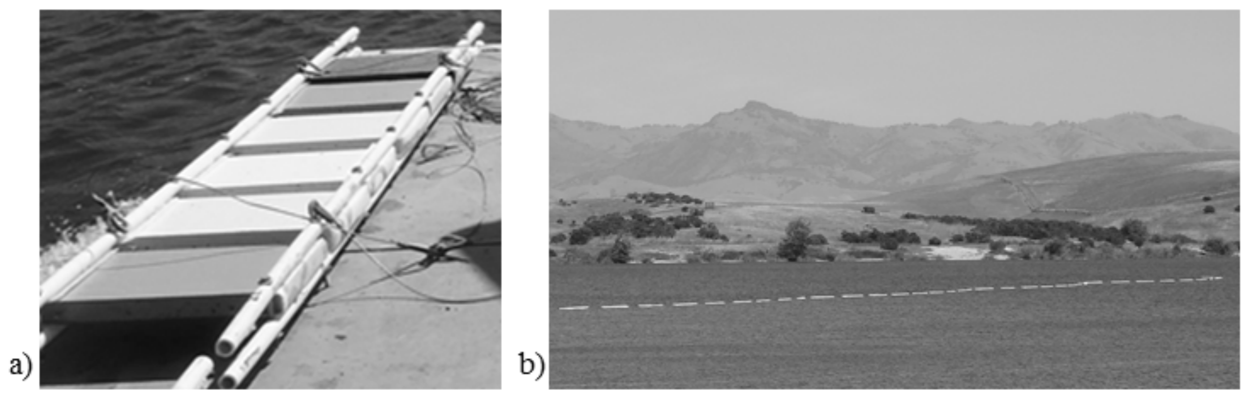


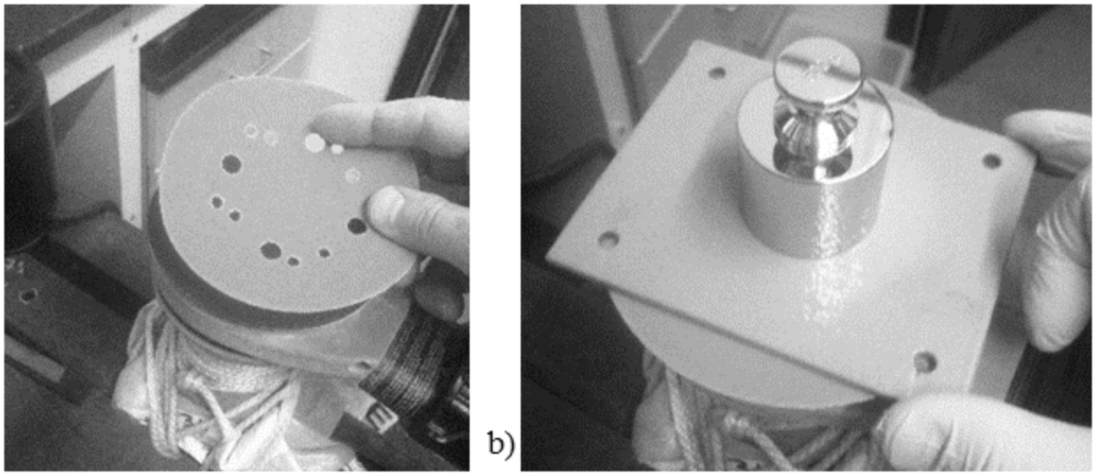
Figure 5: Photographs of the a) pvc ladders used to deploy the large panels in San Justo Reservoir from b) the moored-buoy structure.

Physical damage

The panels were visually inspected for physical damage after retrieval from the Columbia River. After the panels were retrieved from the Columbia River and photographed, the panels were packaged in polyethylene foam and transported to the PSU Laboratory submersed in Columbia River water. In the laboratory, the panels were cleaned using a water stream (water velocity 4.48 m/s ± 0.246 m/s, $\bar{X} \pm 1$ SD), visually inspected, and photographed again. The extent and degree of physical damage (peeling, flaking, blistering, cracking, and checking) visible to both the naked eye and under 12.5X total magnification were rated according to ASTM D6690 (2005), ASTM D714 (2009), ASTM D660 (1993), ASTM D661 (1993), ASTM D772 (1986). The small panels were used for microscopic analyses and for evaluating the resistance to sanding disc abrasion, surface profile, resistance to scribe attack, and knife adhesion strength to the substrate. The panel edges (13-mm from edge) were discounted from analyses. A Leica M165C stereo-microscope was used to evaluate and document the coating physical damage visible under total magnifications of 12.5X in four locations per panel. Physical damage visible under the stereo-microscope was described using the methods used for damage visible to the naked eye.

There were eight levels of immersion period (0-, 3-, 9-, 15-, 21-, 27-, 33-, 39-mo.), and eight levels of coating system including: Bare (concrete), Corps vinyl (steel), CrystalSeal (concrete), Sher-Release (concrete), Sher-Release (steel), HempasilX3 (steel), Intersleek900 (concrete), and Intersleek900 (steel). In each test, five panels were analyzed for each immersion period and coating system, except for scribe undercutting corrosion (scribe used three panels per treatment). In most cases, a total of six panels were retrieved from the Columbia River for each treatment (Table 9), and these additional panels served as back-up in case panels were destroyed or damaged during handling, transport, storage, and/or laboratory analysis. SPSS and R statistical packages were used to test assumptions, plot descriptive statistics, and compare means. Analysis of variance was used to explore for differences in population means, and post hoc Tukey tests were performed with significant results. Levene's test for homogeneity of variances was often rejected, however, little effect was expected on the Type I error rates because the group sizes were over five, and the ratio of variances in the different groups was less than 4 to 1. The level of significance for all tests was $\alpha = 0.005$.

The coatings' resistance to abrasion was evaluated using coating weight loss by a random orbital sanding disc according to protocols modified from ASTM D4060 (2007). The coating loss from sanding disc abrasion was determined by weighing the panels prior to and after panels were exposed to a sanding disc using a laboratory scale with a range of 0.1 to 1,100 g (A&D Company GX-1000). A random orbital sander (DeWalt, 3-amp motor with max spin at 12,000-rpm) was leveled and secured horizontally so that the sanding disk was facing up. Ceramic blend sanding discs, 150-Grit (Very Fine sanding grade) with aluminum oxide abrasive particles were used in this experiment. Sanding discs were replaced every five panels to minimize the effects of abrasive particles becoming clogged with removed material (Figure 6). The panel was oriented parallel with the sanding disc, and a 500-g top load was placed on the top of the panel (Figure 6b), the machine was turned on, and then the panel and 500-g load were lowered onto the sanding disc for a period of 30 seconds. Panels were cleaned with compressed air prior to weighing to remove loose debris. Five panels for each treatment were analyzed using the sanding disc abrasion test.



a) b)

Figure 6: Sanding disc abrasion set-up.

A contact surface profilometer (Mitutoyo Surftest 310) was used to measure the surface roughness of the coatings according to ASTM 7127 (2005). The surface roughness of the CrystalSeal (concrete) and Bare (concrete) was not evaluated because the roughness values exceeded the profilometer capacity. Surface roughness was assessed using the average peak to valley height (R_z) using the ten-point height of irregularities (the mean of the two values, the mean height of five highest peaks and the mean depth of the five deepest valleys from the measured line in each panel section) using the differential inductance method. The mean surface roughness (R_z) for each panel was calculated from measurements taken at six locations per panel excluding panel edges. Five panels for each treatment were analyzed for surface roughness. R_z was used as the surface roughness parameter versus the more common R_a to more heavily weight big events in the coating surface texture such as gouging. The contact profilometer was calibrated prior to use using a 2.95-µm reference. Profilometer settings included using a Gaussian digital filter, PC-50%, λ/L= 0.8, P_c= 1, and n=5. The Gaussian digital filter passed a weighted average through the primary profile measured with the diamond stylus (5-µm radius). The deviations above and below this weighted average were used to measure the roughness profile. The profilometer measuring force was 4 mN. The sampling length of each line, or cut-off valve was 0.8 mm.

The coating adhesion to the underlying substrate was evaluated using the knife method according to ASTM D6677 (2007). Knife adhesion was rated based on the degree of difficulty to remove the coating from the substrate as well as the size of the coating fragment or chip removed (Table 10). The dry film thickness was measured using a ultrasonic probe for concrete panels (PosiTector 200 C) and a ferrous probe for steel panels (PosiTector 6000 F) according to ASTM D1186 (1993) and ASTM D 6132 (2013). A box cutter blade (replaceable razor blades) was used to cut an "X" through the coating to the substrate using a metal guide. Holding the razor blade approximately parallel to the panel face, the point of the box cutter blade was used to remove the coating starting at the vertex of the two cut lines and extending towards the cut legs. This destructive test was repeated in two other panel locations on the same panel face, totaling three locations on each test panel. The average rating value of the three locations was used to describe the knife adhesion for the panel. Five panels for each treatment were analyzed using the knife adhesion test.

Table 10: Performance evaluation scale used for knife adhesion test (10 is good adhesion and 0 is poor adhesion). Based on Table 1 in ASTM D 6677 (2007).

Rating	Description
10	Coating is extremely difficult to remove; chips no larger than approximately 0.8- x 0.8-mm
9	Coating is extremely difficult to remove; chips larger than 0.8- x 0.8-mm
8	Coating is difficult to remove; chips ranging from approximately 1.6-x 4.6-mm to 3.2- x 3.2-mm
7	Coating is difficult to remove; chips ranging from approximately 3.2- to 6.3-mm
6	Coating is somewhat difficult to remove; chips ranging from approximately 3.2- to 6.3-mm
5	Coating can be removed with slight difficulty; chips ranging from approximately 3.2- to 6.3-mm
4	Light pressure with knife to remove; chips range and can ≥6.3-mm
3	Coating easily removed; chips ranging from approximately 4- x 6-mm to 4- x 8-mm
2	Coating easily removed; chips ranging from approximately 6.3- x 6.3-mm or 3- x 12-mm
0	Coating can be easily peeled from substrate greater than 6.3-mm

Prior to initial deployment, a subset of the steel panels was scribed using a box cutter knife (disposable razor blades) and a steel straightedge. Scribes were cut through the entire coating system into the steel panel to form a V-shaped cut through the coating. A maximum of three cuts were allowed per scribe to reach bare substrate, and multiple cuts were made in one-direction. Each scribed panel had two intersecting scribes, each at least 60-mm long, formed into an “X”.

After immersion in the Columbia River, the scribe was evaluated for corrosion and measured according to Weaver and Beitelman (2001) and ASTM D1654 (2005). Soft fouling and other debris were removed from panels using a water stream. Panels were patted dry with disposable towels immediately prior to testing, and the scribe was cleaned using the Air Blow-Off Method described in Section 7.1 of ASTM D1654 (2005). Measurements were made at 5-mm intervals from both sides of the centerline of the scribes resulting in a total of 24 measurements for each scribe. A template was taped onto the panel to make measurement as objective as possible along 5-mm intervals. If a 5-mm hash mark fell on the vertex of the two scribes, this interval was skipped. The distance (mm) between the scribe centerline and the edge of the paint loss was measured using a 1-mm scale ruler. The creepage from the scribe on each panel was measured using two parameters, the mean value of the 24 creep measurements along each scribe as well as the single maximum value located anywhere on the scribe. The mean creepage value of three panels was used to rate the scribe undercutting for each coating type according to Table 1 in ASTM D1654 (2005).

Biofouling resistance

Biofouling resistance was evaluated using fouling on large panels by zebra mussels in San Justo Reservoir, and soft fouling (e.g., algae, and bryozoans) in the Columbia River according to ASTM D6990 (2005), ASTM D3623 (2004), and using image analysis. The percent surface area of the large panels fouled by zebra mussels, algae, and bryozoans was calculated using image analysis software (ImageJ) on color digital photographs.

Panels were photographed immediately after retrieval from the Columbia River for each immersion period as well as after deployment in San Justo Reservoir for a 5-month period (April to September). Panels removed from the Columbia River were also photographed after cleaning using a water stream (water velocity 4.48 ± 0.246 m/s, $\bar{X} \pm 1$ SD). Panels were photographed in a custom photography booth in order to provide more consistent images, e.g., distance from lens to panel and background light. The photography booth (41x41x31cm, length x height x depth) was constructed of black-colored plastic, and had one open side for access. A dark-colored towel was draped over the open side and used as a curtain. The digital camera was secured on the top of the photography booth over a 5-cm diameter hole, and images were taken the using the camera flash. The distance from the camera lens to the panel surface was approximately 38 cm for concrete panels and 40 cm for steel panels. The panel information (frame#, panel position on frame, coating system, and immersion period) was recorded on a dry-erase label that was placed next to the panel and captured in the photograph.

The image analysis was done using ImageJ software. Zebra mussel fouling was evaluated for the side of the panels facing the reservoir bottom because the panel underside was protected from the gravitational settlement of sediment and other particulates that confounded image analyses for attached mussels. After deployment in the Columbia River, the panel face that was facing the main stem Columbia River was evaluated for soft fouling such as algae and bryozoans. The ImageJ settings included the Default thresholding method, with a threshold color of red and a color space of RGB. A small portion of the target area (e.g., zebra mussels) was sampled on each image to provide the software with a reference, and then the software would highlight the calculated target areas in red (Figure 7). The red areas were then visually compared to the original image, and adjustments were made as needed. Particles were then analyzed to record the percent cover of the image. Five panels were measured for each coating system and immersion period. Each panel was described using the mean percent area fouled (bare outlines) from five separate areas corresponding to each corner and the center and excluding panel edges.

a)

b)

Figure 7: ImageJ showing a zebra mussel and the software-identified 'mussel area' in red.

The resistance to zebra mussel fouling was also evaluated using the mussel adhesion strength (MPa) to the coating as well as the maximum size of attached mussels. Mussel adhesion strength varies with season, and all the zebra mussel tests were done in September. A hand-held force gauge (Shimpo MF30, 30 lbs. x 0.2 lbs.) was used to measure the maximum shear force to detach the 25 largest mussels attached to the coating after five months immersion in San Justo Reservoir according to ASTM D5618 (2011). Force measurements were done on individual mussels. In some cases, neighboring mussels were removed using a razor blade to provide better access.

After the mussel was pushed off the coating, the surface area of the panel where the byssal threads were attached was measured using the average of three measurements across the byssal area based on Section 7.3 of ASTM D5618 (2011). The byssal area was measured for every mussel on the control coatings when possible. Byssal thread measurements, however, were not recorded for all the mussels measured for detachment force and shell length. The byssal area was not measured on foul-release coatings because the byssal threads stayed with the mussels and detached from the coating. The mean byssal area measured on the mussels on the control coating systems 4.7 mm^2, which was used in all the adhesion force calculations in this study. The shell length (beak to ventral shell margin, longest distance) was measured using a 1-mm scale ruler for each removed mussel.

Results

Physical damage

No significant physical damage (flaking, blistering, cracking, and checking observed under the naked eye and under 12.5X total magnification) was recorded on the Intersleek900 (concrete), Intersleek900 (steel), and the Sher-Release (steel) systems after deployment in the main stem Columbia River for a period up to 39-months. There were small gouges and pitted areas visible under 12.5X total magnification on all the foul-release coatings. Microscopic gouges and pitted areas were first observed on all the foul-release coatings after exposure to the Columbia River for a 9-month period. These damaged areas did not penetrate through the topcoat and ranged in size from 70 to 1,000 µm. A limited number of gouges visible to the naked eye (1 to 2 mm) were recorded on the foul-release coatings, however, none of these penetrated through the topcoat. Gouges and pitted areas were not observed on the protective control coatings. The Sher-Release (concrete) and Sher-Release (steel) had slight discoloration first noted after 9-months immersion in the Columbia River and observed for all subsequent immersion periods. The discoloration appeared as an asymmetrical darker white area within the lighter white panel. It appeared as if the darker area had received another coat of paint; however, the coating thickness was measured and there was no difference in thickness between the darker and lighter areas.

The Sher-Release (concrete) and HempasilX3 (steel) blistered after immersion in the Columbia River. The onset of blistering on Sher-Release (concrete) was recorded in the 9-month immersion period, and the onset of blistering on HempasilX3 (steel) was recorded in the 3-month immersion period (Figure 8). The percentage of HempasilX3 (steel) with blisters appeared to increase with increasing immersion time, and all of the HempasilX3 (steel) had blisters for the last three immersion periods (27-, 33-, and 39-months, Figure 8). There was always a proportion of the Sher-Release (concrete) that lacked blisters (Figures 8).

Immersion time had no significant effect on blister size for the Sher-Release (concrete) and HempasilX3 (steel) systems. Coating type had a significant effect on blister size, $F(7,256) = 47.550$, $p<0.001$, but post hoc Tukey tests found significant differences ($p<0.005$) between the blistered group (Sher-Release (concrete) and HempasilX3 (steel); $\bar{X} = 8.08$, SD = 2.454; $\bar{X} = 7.31$, SD = 2.444, respectively) and the non-blistered group (Corps vinyl (steel), CrystalSeal (concrete), Sher-Release (steel), Intersleek900 (concrete), and Intersleek900 (steel); $\bar{X} = 10.00$, SD = 0.0000 for each). There was a lot variation in blister size within each immersion period for Sher-Release (concrete), and this variability was relatively stable over the different immersion periods (Figure 9a). The frequency of blistering on Sher-Release (concrete) increased with immersion period, ranging from Few to Medium in the earlier immersion periods, and then from Few to Medium Dense in the last four immersion periods (Figure 9b). The HempasilX3 (steel) blister size became more stable (less variation both within and between immersion periods) with increasing immersion time as the central tendency neared a blister size No. 6 (Figure 9a). The frequency of blistering on the HempasilX3 (steel) system was relatively stable over the experiment ranging from Few to Medium Dense (Figure 9b).

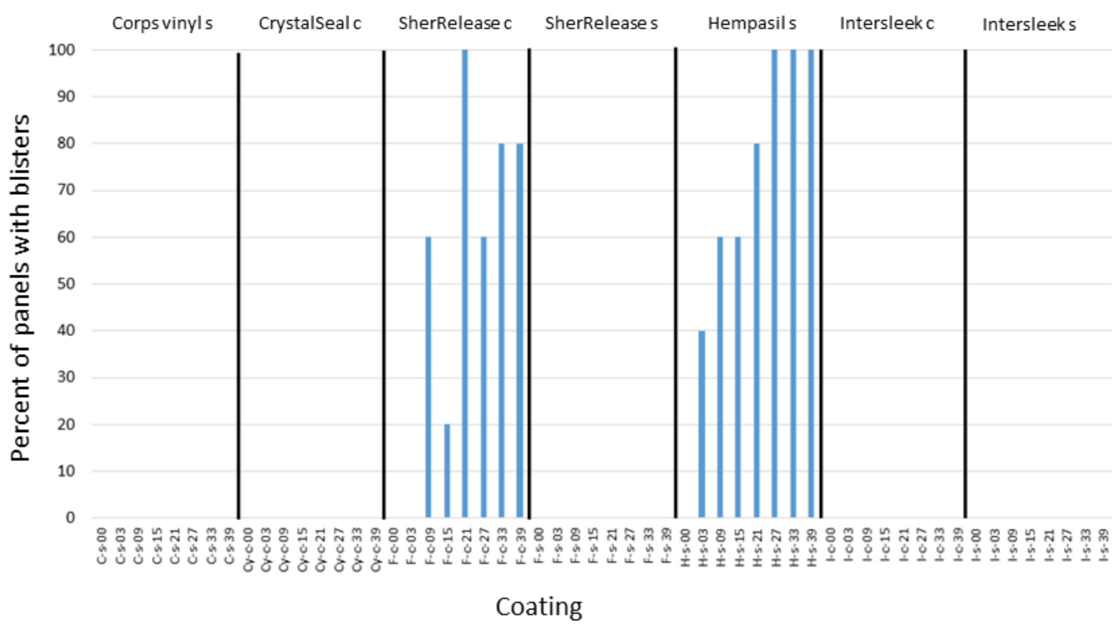
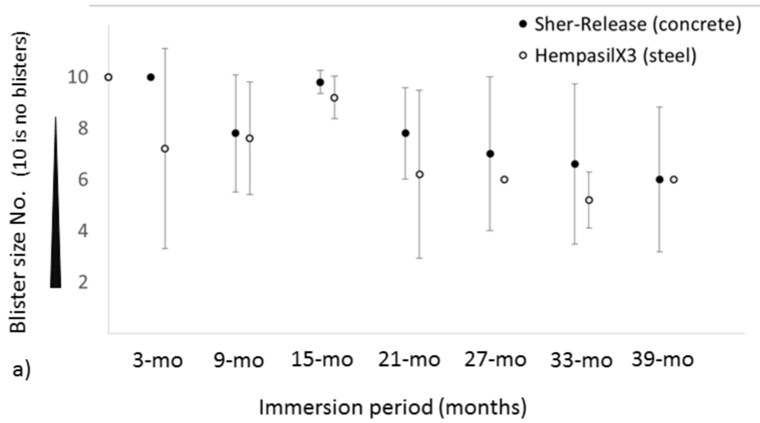


Figure 8. The percentage of the panels that contained blisters after Columbia River immersion period. Each immersion period is indicated in months (0-, 3-, 9-, 15-, 21-, 27-, 33-, and 39-months). The coating systems are labeled above the figure. Bare concrete was not evaluated for blistering.



b)

	Sher-Release (concrete)		HempasilX3 (steel)	
Immersion	Min	Max	Min	Max
0	na	na	na	na
3	na	na	Few	Medium
9	Few	Medium	Few	Medium Dense
15	Few	Few	Few	Few
21	Few	Medium Dense	Few	Medium
27	Few	Medium Dense	Few	Few
33	Few	Medium Dense	Few	Medium
39	Few	Medium Dense	Few	Medium

Figure 9: The a) blister size number on Sher-Release (concrete) and HempasilX3 (steel) ($\bar{X}$ ± 1 SD, n = 5); blister No. 2 is large, No. 8 is small, and No. 10 is no blisters; and the b) minimum and maximum blister frequency rating for the two blistering systems according to ASTM D714 (2009).

The foul-release coatings were more resistance to the sanding disc abrasion test than all the controls including the Corps vinyl (steel), CrystalSeal (concrete), and Bare (concrete). There was a significant effect of coating type on coating weight loss, F (7,251) = 110.7, p<0.001, and post hoc Tukey tests found the following groups to be significantly different (p<0.005): concrete control group (CrystalSeal (concrete) and Bare (concrete); $\bar{X}$ = 0.7039 g, SD = 0.4923 g and $\bar{X}$ = 0.7374 g, SD = 0.4728 g, respectively), foul-release on steel group (HempasilX3 (steel), Intersleek900 (steel), and Sher-Release (steel); $\bar{X}$ = 0.0606 g, SD = 0.0473 g, $\bar{X}$ = 0.0839g, SD = 0.0301 g, $\bar{X}$ = 0.1130 g, SD = 0.0425 g, respectively), and Group 3 (Corps vinyl (steel), Intersleek900 (concrete), and Sher-Release (concrete); $\bar{X}$ = 0.3066 g, SD = 0.0308 g, $\bar{X}$ = 0.2066 g, SD = 0.1015 g and $\bar{X}$ = 0.2411 g, SD = 0.1812 g, respectively).

The abrasion test used a 500-g load for all panels, but because the concrete panels were heavier than the steel panels ($\bar{X}$ = 813.43 g, SD = 40.66 g; $\bar{X}$ = 347.19 g, SD = 10.42 g, concrete and steel, respectively), the total loads acting upon the concrete coatings were greater than the loads on steel panels. Considering the effect of the panel weight on coating weight loss suggests that Group 3 can be further divided into two separate groups: steel control group and foul-release on concrete group. Weight loss comparisons were made between coatings on steel panels (Figure 10), and coatings on concrete panels (Figure 11).

The coating weight loss on the Corps vinyl (steel) was significantly greater than the coating weight loss on all the foul-release coatings on steel including Sher-Release (steel), HempasilX3 (steel), and Intersleek900 (steel) (Figure 10). HempasilX3 (steel) was the most resistant to coating loss under the abrasion test (Figure 10). Immersion period had no effect on coating weight loss for the steel panels.

The weight loss on the concrete control group was greater than the weight loss on foul-release coatings on concrete (Figure 11). The Intersleek900 (concrete) was the most resistant concrete system to weight loss under the abrasive sanding disc test (Figure 11). Immersion period had no effect on the resistance to weight loss for both Intersleek900 (concrete) and Sher-Release (concrete) systems (Figure 11). There was variation in weight loss within and between immersion periods on the concrete control panels, and although there were not significant differences, the weight loss on the Bare (concrete) and CrystalSeal (concrete) systems appeared to increase with immersion time, especially for the Bare (concrete) system (Figure 11).

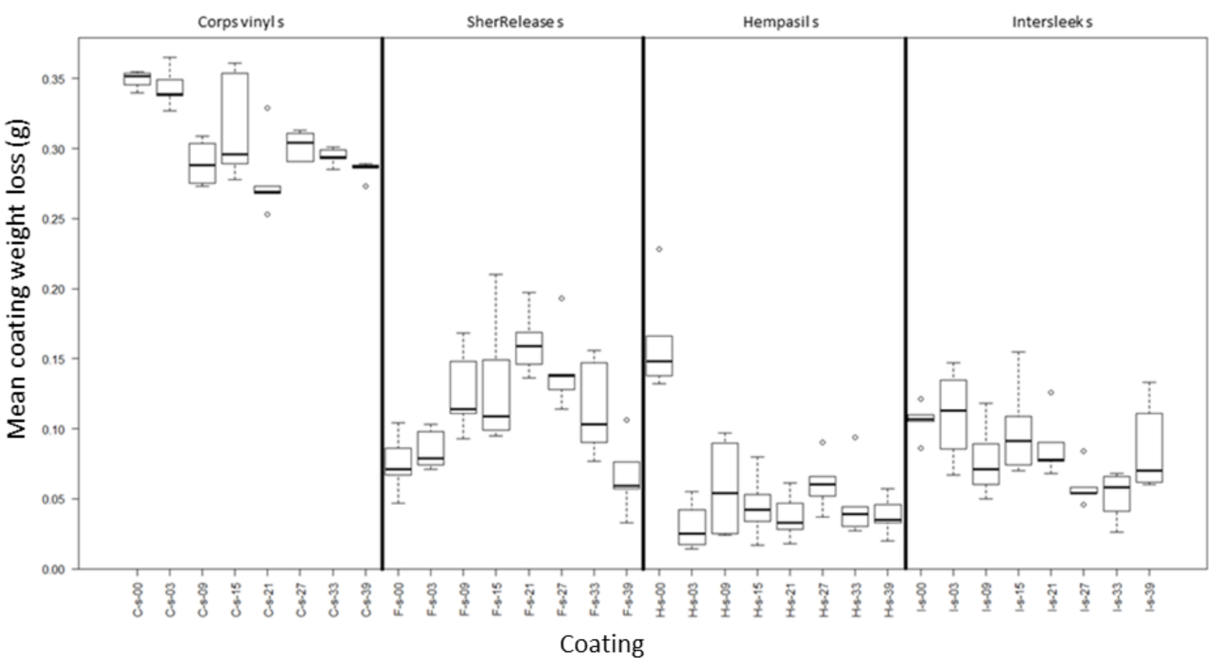


Figure 8: The coating weight loss (g) on the steel panels. Immersion periods are indicated by months, e.g., 03.

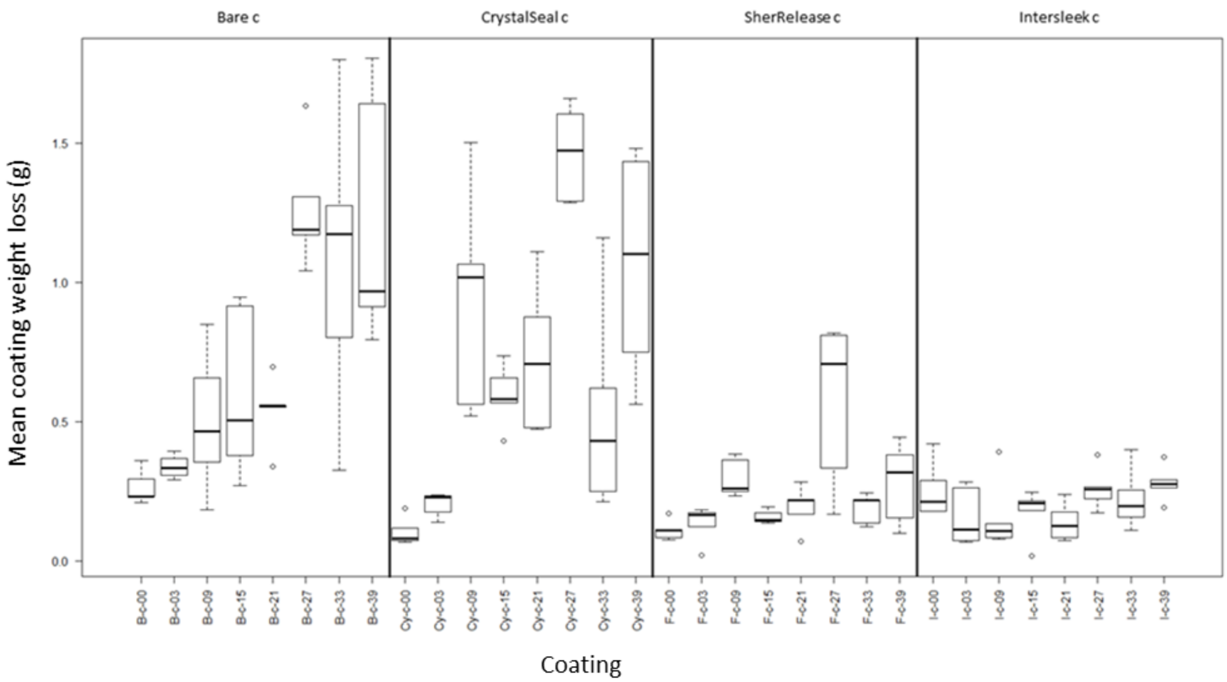


Figure 9: The coating weight loss (g) on concrete panels. Immersion periods are indicated by months, e.g., 03.

The surface profile of Bare (concrete) and CrystalSeal (concrete) panels exceeded the measurement range for the contact profilometer, and these two systems were excluded from the surface roughness evaluations. The instrument measuring ranges for the average peak to valley height and arithmetic mean deviation from the profile are 0.3 – 160 µm and 0.05 – 40 µm, respectively.

Immersion time had no effect on coating surface roughness for periods up to 39-months for any of the coatings evaluated (Figure 12). The texture of the foul-release topcoats on steel panels was significantly smoother than the Corps vinyl coating. There was a significant effect of coating type on coating surface roughness, $F(5,173) = 303.2$, $p<001$, and post hoc Tukey tests found significant differences ($p<0.005$) between the Corps vinyl (steel) ($\bar{X} = 7.172$ µm, SD = 1.778 µm) and the foul-release coatings (Figure 12). Post hoc Tukey tests also found differences between Group 1 (Sher-Release (steel) and Intersleek900 (steel); $\bar{X} = 0.8667$ µm, SD = 0.3463 µm, and $\bar{X} = 1.196$ µm, SD = 0.2156 µm, respectively) and Group 2 (HempasilX3 (steel), Sher-Release (concrete), and Intersleek900 (concrete); $\bar{X} = 1.555$ µm, SD = 0.3551 µm, $\bar{X} = 1.753$ µm, SD = 0.4554 µm, and $\bar{X} = 1.778$ µm, SD = 0.7240 µm, respectively). The Sher-Release (steel) and Intersleek900 (steel) had the smoothest texture (Figure 12).

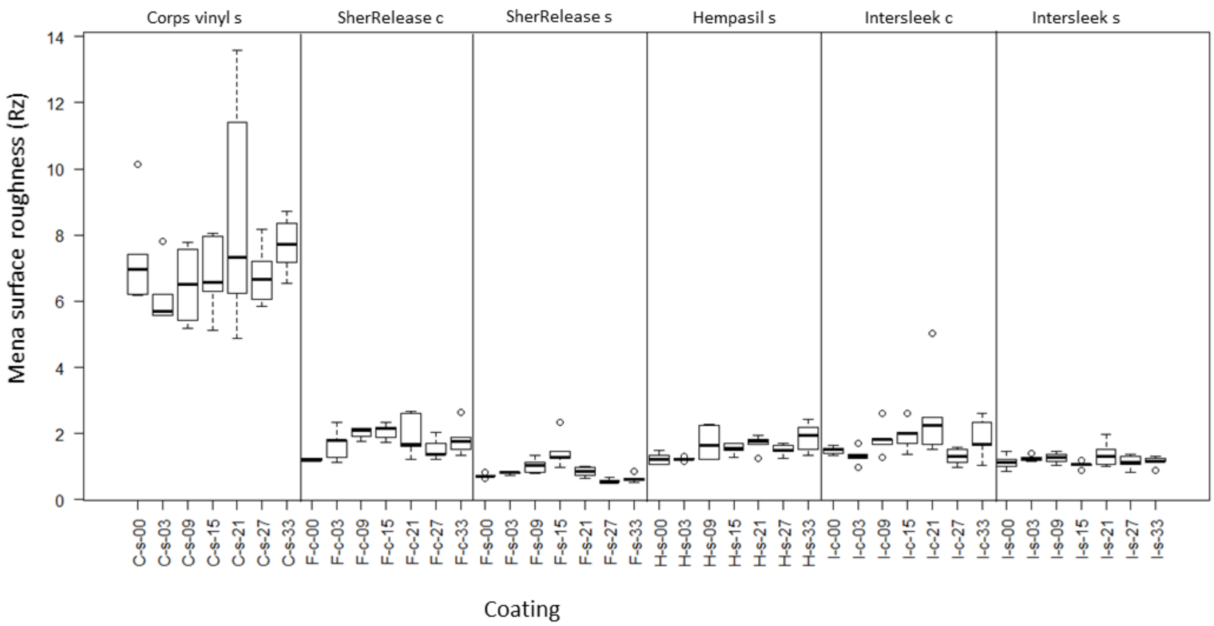


Figure 10: Mean surface roughness (R_z) for coatings on steel panels across immersion time (months).

All of the foul-release coatings were easily removed from the underlying coating layer or substrate in the knife adhesion test (Figure 13). The size of paint chips removed from the foul-release coatings during the knife adhesion test ranged from approximately 1.6 mm to greater than 6.3 mm. Long thin strips were cut out of the foul-release coatings extending from the vertex of the cuts to the end of the legs (Figure 14). The most common chip shape for the foul-release resembled long thin rectangles or ribbons. The first cut of the knife on the Sher-Release and Intersleek900 coatings typically resulted in a flap, with the knife blade slicing under the topcoat and traveling longitudinally through underlying layers before slicing through the topcoat again. The first cut of the knife on the HempasilX3 coating typically gouged out a thin strip of coating. The primary location of failure for the Sher-Release (concrete), Sher-Release (steel), Intersleek900 (concrete), and Intersleek900 (steel) was between the tie coat and second epoxy coat. In some cases, the failure on the Sher-Release and Intersleek900 coatings occurred between the foul-release topcoat and the tie coat, as well as between the base substrate and the epoxy primer. The primary location of failure for the HempasilX3 (steel) system was between the topcoat and the tie coat. The HempasilX3 tie coat (NEXUS 27302) was the most durable foul-release tie coat encountered in the knife adhesion testing, and it was difficult to remove using the knife blade.

The Corps vinyl (steel) was difficult to very difficult to remove from the underlying coating during the knife adhesion testing. The size of chips removed from the Corps vinyl (steel) during knife adhesion testing ranged from less than 0.8 mm to 5 mm, and chips were only removed near the vertex of the two cuts (Figure 14). The most common chip shape for the Corps vinyl coating was a small triangle (Figure 14). The primary location of failure for the Corps vinyl (steel) was the bare steel and the bottom epoxy coat.

There was a significant effect of coating type on knife adhesion rating (KAR), F (5,187) = 2,968.3, p<001, and post hoc Tukey tests found significant differences (p<0.005) between the Corps vinyl (steel) ($\bar{X}$ = 7.9 KAR, SD = 0.6775 KAR) and all the foul-release coatings (Sher-Release (concrete), Sher-Release (steel), HempasilX3 (steel), Intersleek900 (concrete), and Intersleek900 (steel); $\bar{X}$ = 2.4 KAR, SD = 0.4414 KAR, $\bar{X}$ = 2.1 KAR, SD = 0.2363 KAR, $\bar{X}$ = 2.3 KAR, SD = 0.4063 KAR, $\bar{X}$ = 2.3 KAR, SD = 0.2695 KAR, $\bar{X}$ = 2.1 KAR, SD = 0.2049 KAR, respectively). The Corps vinyl (steel) had good adhesion to the substrate, and all of the foul-release coatings had poor adhesion to the substrate (Figure 13).

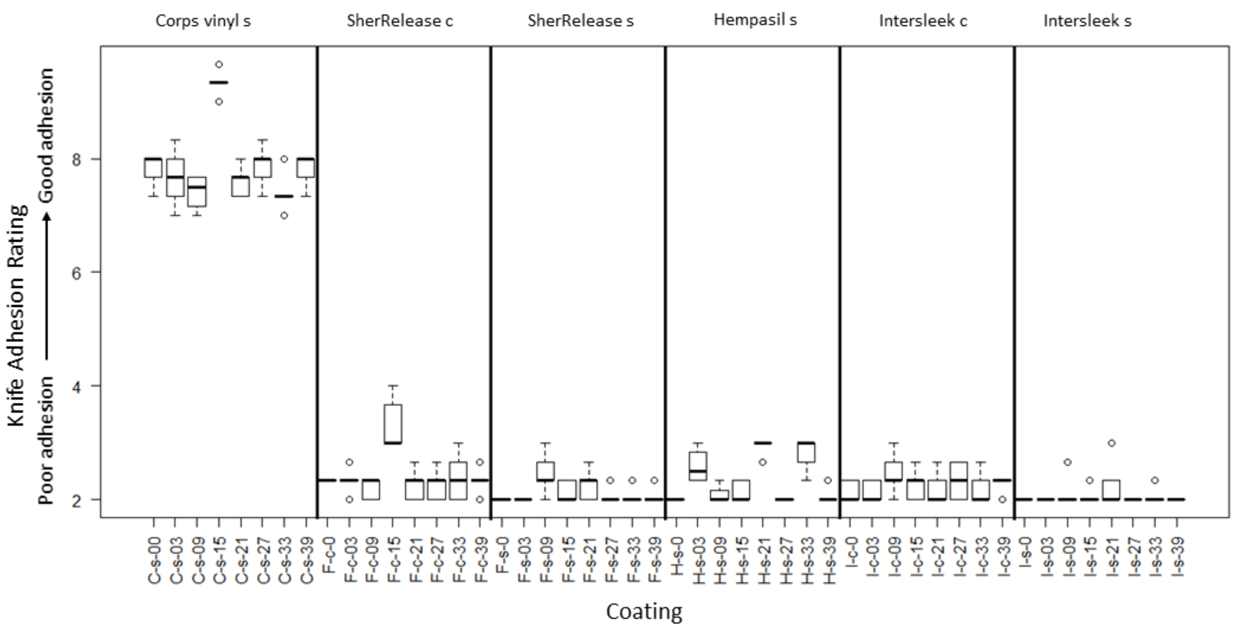


Figure 11: Knife adhesion ratings based on Performance Evaluation Scale in ASTM D 6677 (2007). A rating of 0 means the coating can be easily peeled from the substrate to a length greater than 6.3-mm. Conversely, a rating of 10 means the coating is extremely difficult to remove, and fragments are no larger than 0.8- x 0.8-mm in size. The rating is based on both the degree of difficulty to remove the coating from the substrate and the size of the removed fragments.

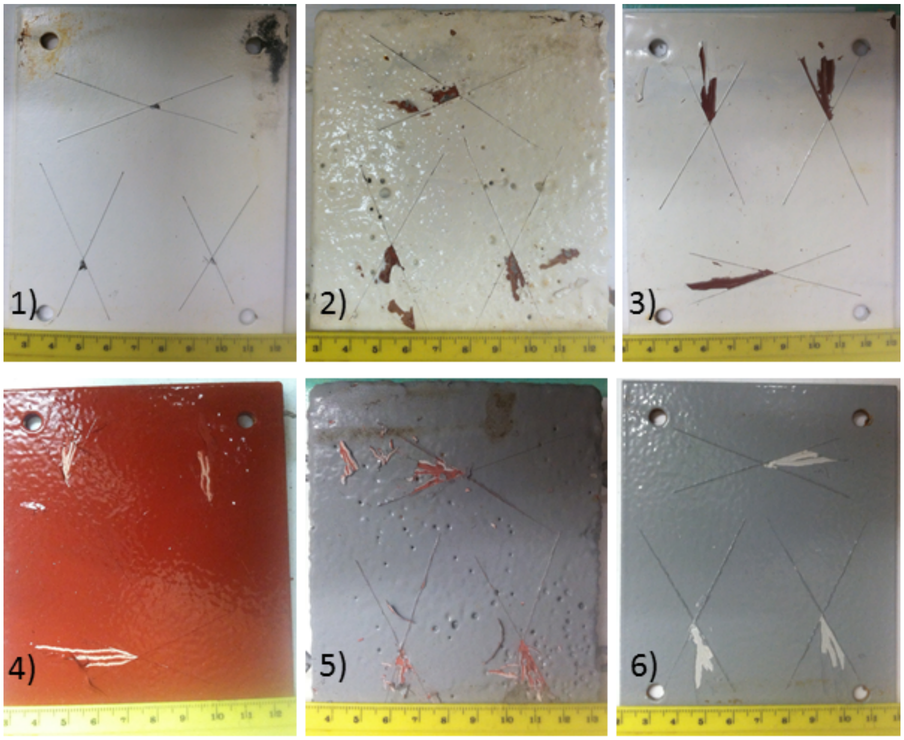


Figure 12: Photographs of knife adhesion results for 1) Corps vinyl (steel), 2) Sher-Release (concrete), 3) Sher-Release (steel), 4) HempasilX3 (steel), 5) Intersleek900 (concrete), and 6) Intersleek900 (steel).

There was no scribe activity for all coatings for Columbia River immersion periods up to 39-months. Slight corrosion developed along portions of the scribe on all the coatings, but the coatings around the scribe remained intact, and there was no undercutting. The coatings were rated according to ASTM D1654 (2005) using the maximum values for creepage, and all of the coatings performed well against scribe attack (Figures 15 and 16). All of the coatings were rated at 8 or above, and these ratings represent maximum creepage of less than 1-mm (Figure 17).

There were small areas of paint loss that extended from the scribe mark and these areas were counted as creepage from the scribe (Figures 16 and 17). There was no corrosion in these areas. These damaged areas around the scribe were typically less than 0.5 mm in length from the scribe, and were more common in the foul-release than in the Corps vinyl (steel). There was a significant effect of coating type on scribe failure, F (3,57) = 21.604, $p<0.01$, and post hoc Tukey tests found significant differences ($p<0.005$) in the mean creepage from scribe between two groups: the HempasilX3 coating ($\bar{X}$ = 0.0668 mm, SD = 0.0582 mm), and all other coatings (Corps vinyl (steel), Sher-Release (steel), and Intersleek900 (steel); $\bar{X}$ = 0.0020 mm, SD = 0.0066 mm, $\bar{X}$ = 0.0073 mm, SD = 0.0145 mm, $\bar{X}$ = 0.0100 mm, SD = 0.0245 mm, respectively). HempasilX3 (steel) had significantly more creepage from the scribe, and this pattern was maintained when using other values to characterize the creepage including the maximum value (Figure 17). Immersion time had no effect on scribe creepage (Figures 16 and 17).

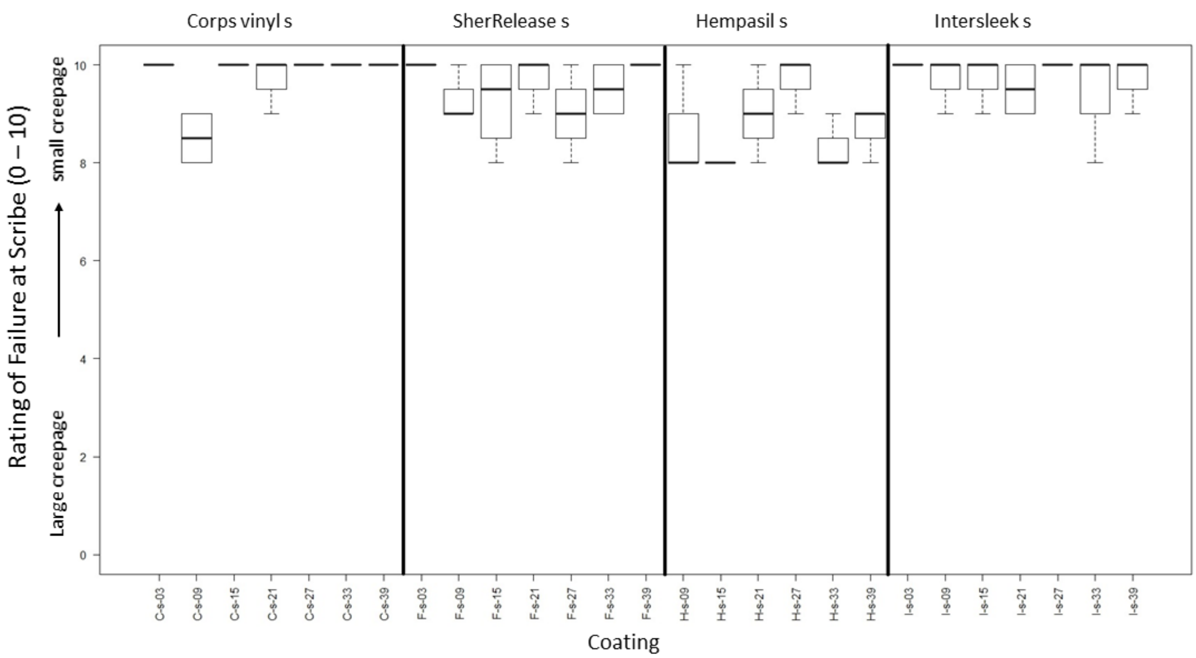


Figure 13: Rating of failure at scribe according to Table 1 in ASTM D1654 (2005). Failure rating used the maximum measurement along the scribe.

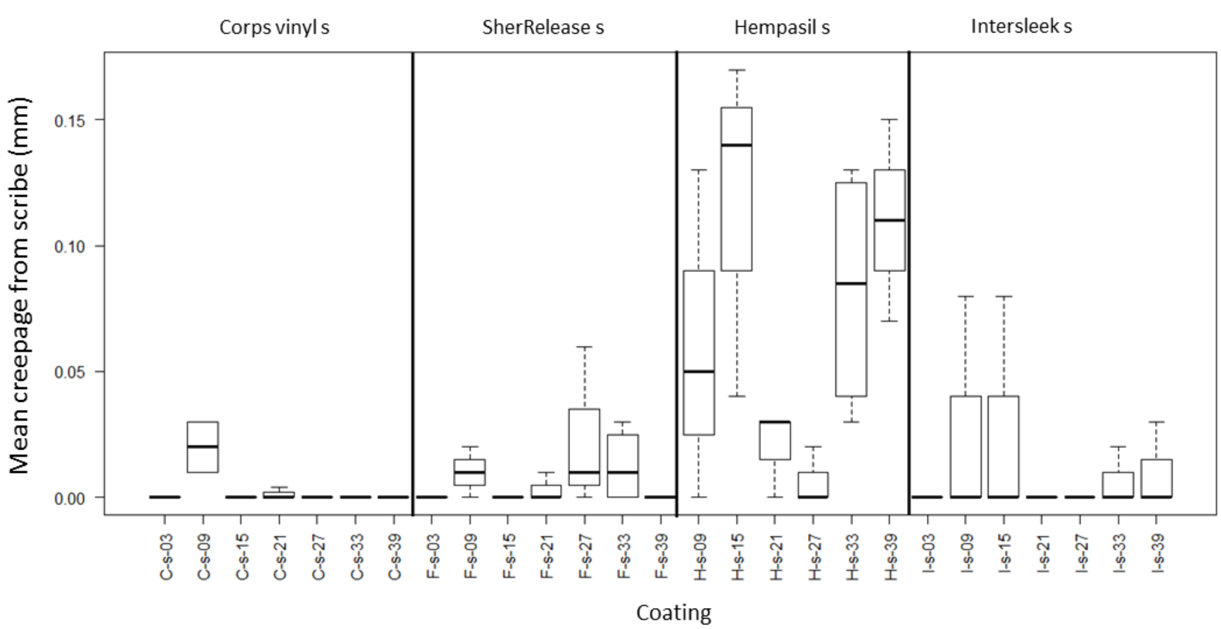


Figure 14: Mean creepage (mm) from scribe centerline on steel panels.

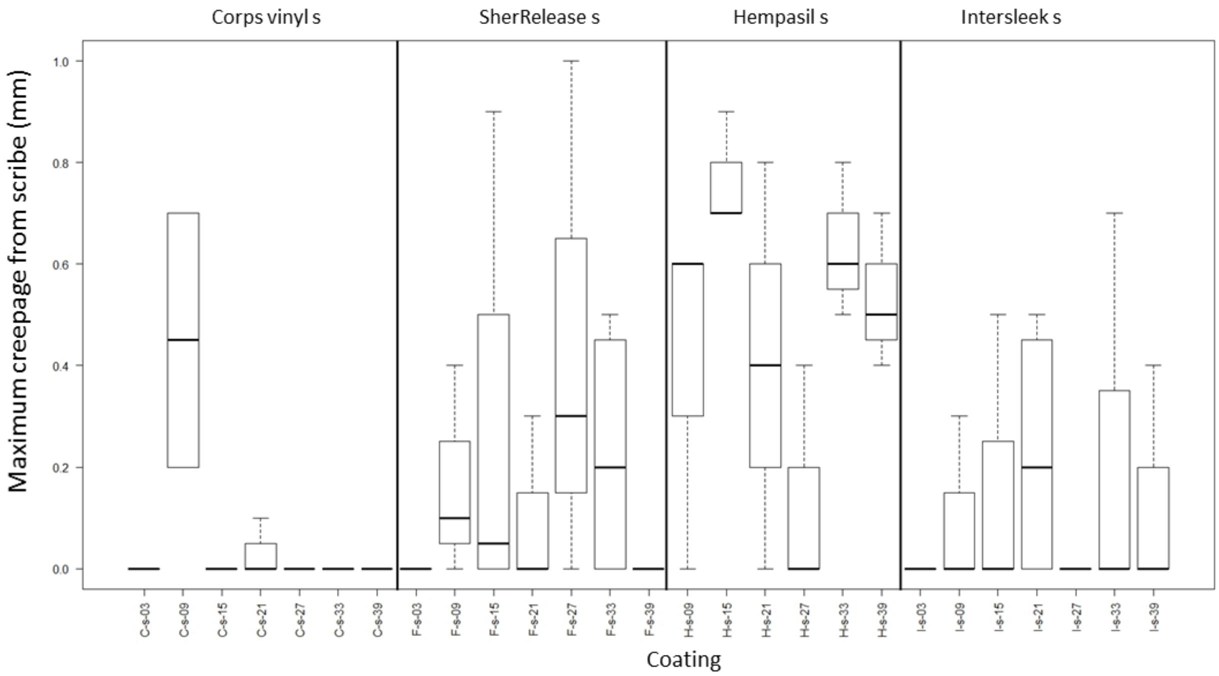


Figure 15: Maximum creepage from scribe (mm).

Biofouling resistance

There was a significant effect of coating type on surface area fouled by zebra mussels, F (3,57) = 21.604, p<001, and post hoc Tukey tests found significant differences (p<0.005) in the mean surface area fouled between two groups: the foul release coatings (Sher-Release (concrete), Sher-Release (steel), HempasilX3 (steel), Intersleek900 (concrete), and Intersleek900 (steel); $\bar{X}$ = 7.35%, SD = 12.23%, $\bar{X}$ = 6.10%, SD = 7.50%, $\bar{X}$ = 2.52%, SD = 4.11%, $\bar{X}$ = 4.40%, SD = 4.19%, $\bar{X}$ = 4.94%, SD = 5.00%, respectively), and the control group (Bare (concrete), Corps vinyl (steel), and CrystalSeal (concrete); $\bar{X}$ = 79.53%, SD = 24.27%, $\bar{X}$ = 81.76%, SD = 19.05%, $\bar{X}$ = 74.04%, SD = 26.37%, respectively). Zebra mussel colonization was significantly greater on the protective coatings versus the foul-release coatings, but zebra mussels did colonize the foul-release coatings (Figure 18).

Columbia River immersion time had a significant effect on surface area fouled by zebra mussels, F (7,246) = 61.186, p<0.001, and post hoc Tukey tests found significant differences (p<0.005) between two groups: the 2013 group (0-, 3-, and 9-months immersion treatments) and the 2014 to 2016 group (15-, 21-, 27-, 33-, and 39-months). The deployment schedule in San Justo Reservoir included four summers (2013 through 2016), and the first deployment in 2013 involved the 0-, 3-, and 9-month immersion treatments. The lower mussel colonization was observed across multiple coatings for all three of the immersion treatments exposed to San Justo

Reservoir in 2013, and the colonization was the same for these three immersion periods (Figures 18, 19, and 20). Thus it appears that the lower mussel colonization in the 0-, 3-, and 9-month immersion periods is more likely caused by inter-annual fluctuations in the zebra mussel population as compared to a reduction in coating performance over immersion period.

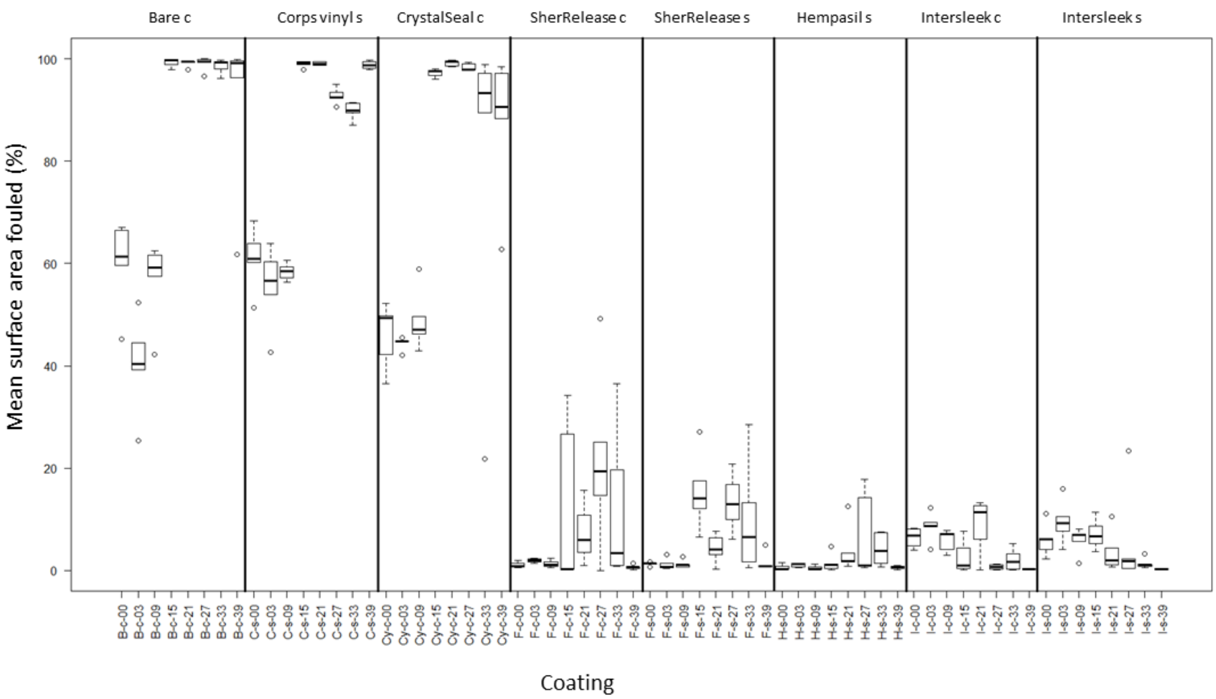


Figure 16: Surface area fouled by zebra mussels after five months exposure in San Justo Reservoir, CA. Coating system is identified on the top of the figure, and the test panel material is labeled with a (c) for concrete and (s) for steel, and the immersion period is listed by months, e.g., 03.

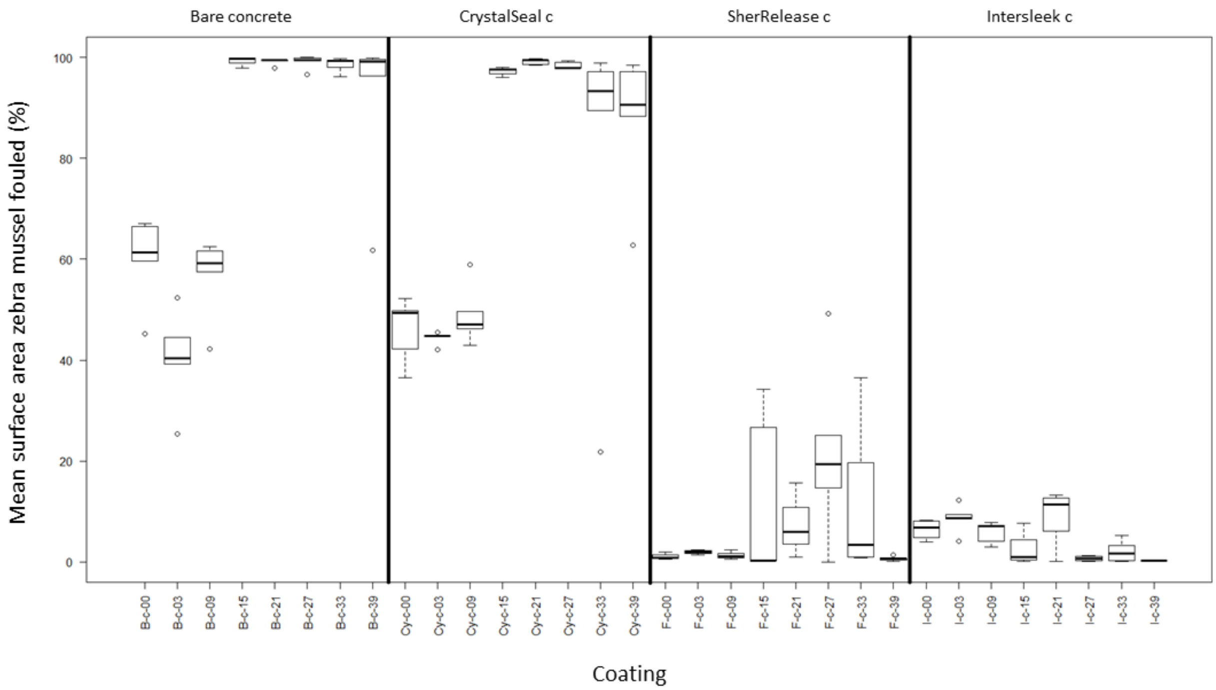


Figure 17: Surface area fouled by zebra mussels on coatings on concrete. Coating system is identified on the top of the figure, and the test panel material is labeled with a (c) for concrete and (s) for steel, and the immersion period is listed by months, e.g., 03.

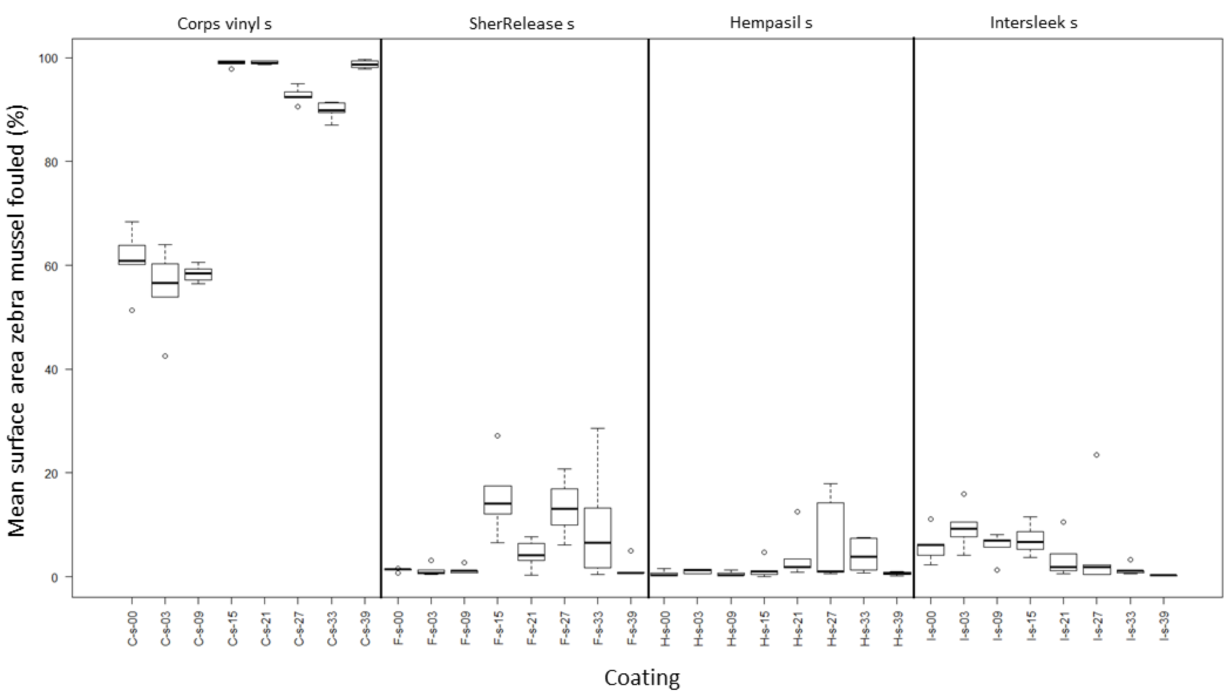


Figure 18: Surface area fouled by zebra mussels on coatings on steel. Coating system is identified on the top of the figure, and the test panel material is labeled with a (c) for concrete and (s) for steel, and the immersion period is listed by months, e.g., 03.

Zebra mussels were more difficult to remove from the control coatings than from the foul-release coatings. There was a significant effect of coating type on zebra mussel adhesion strength, $F(7,259) = 1{,}054.74$, $p<0.001$, and post hoc Tukey tests found significant differences ($p<0.005$) in the mean mussel adhesion strength (MPa) between foul-release coatings (Sher-Release (concrete), Sher-Release (steel), HempasilX3 (steel), Intersleek900 (concrete), and Intersleek900 (steel); $\bar{X}$ = 0.0005 MPa, SD = 0.0032 MPa, $\bar{X}$ = 0.0055 MPa, SD = 0.0334 MPa, $\bar{X}$ = 0.0055 MPa, SD = 0.1984 MPa, $\bar{X}$ = 0.0009 MPa, SD = 0.0057 MPa, and $\bar{X}$ = 0.0000 MPa, SD = 0.0, respectively) and the controls (Bare (concrete), Corps vinyl (steel), and CrysalSeal (concrete); $\bar{X}$ = 1.3889 MPa, SD = 0.3024 MPa, $\bar{X}$ = 1.0796 MPa, SD = 0.2800 MPa, and $\bar{X}$ = 1.3289 MPa, SD = 0.3046 MPa, respectively). In most cases, the shear force required to detach zebra mussels from the foul-release coatings was below the instrument detection level (0.1 lb) (Figure 21). Anecdotally, the zebra mussels on the foul-release coatings preferred to attach to areas of exposed tie coat or epoxy, or in bugholes on concrete panels.

There was a significant effect of immersion time on mean mussel adhesion strength (MPa), $F(7,259) = 20.086$, $p<0.001$, and post hoc Tukey tests found significant differences ($p<0.005$) in adhesion strength between two groups: the 39-month immersion ($\bar{X}$ = 0.6735 MPa) and all other immersion periods (0-, 3-, 9-, 15-, 21-, 27, and 33-months; $\bar{X}$ = 0.4753 MPa, $\bar{X}$ = 0.4752 MPa. $\bar{X}$ = 0.4903 MPa, $\bar{X}$ = 0.3882 MPa, $\bar{X}$ = 0.4076 MPa, $\bar{X}$ = 0.4231 MPa, and $\bar{X}$ = 0.3910 MPa). The increased zebra mussel adhesive strength in the 39-month immersion treatment was observed for each of the control systems including Bare (concrete), Corps vinyl (steel), and CrystalSeal (concrete) (Figure 21).

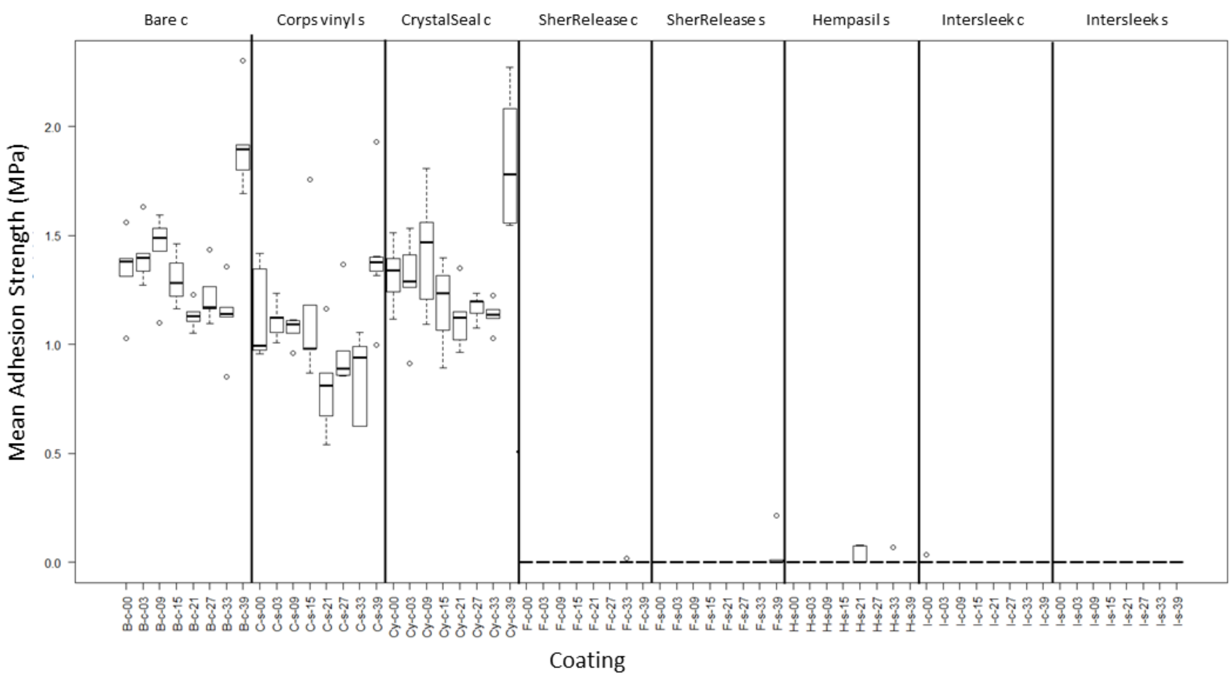


Figure 19: Mean adhesion strength (MPa) of zebra mussels on coatings. Coating system is identified on figure, and test panel material is labeled with a (c) for concrete and (s) for steel, and the immersion period is listed by months, e.g., 03.

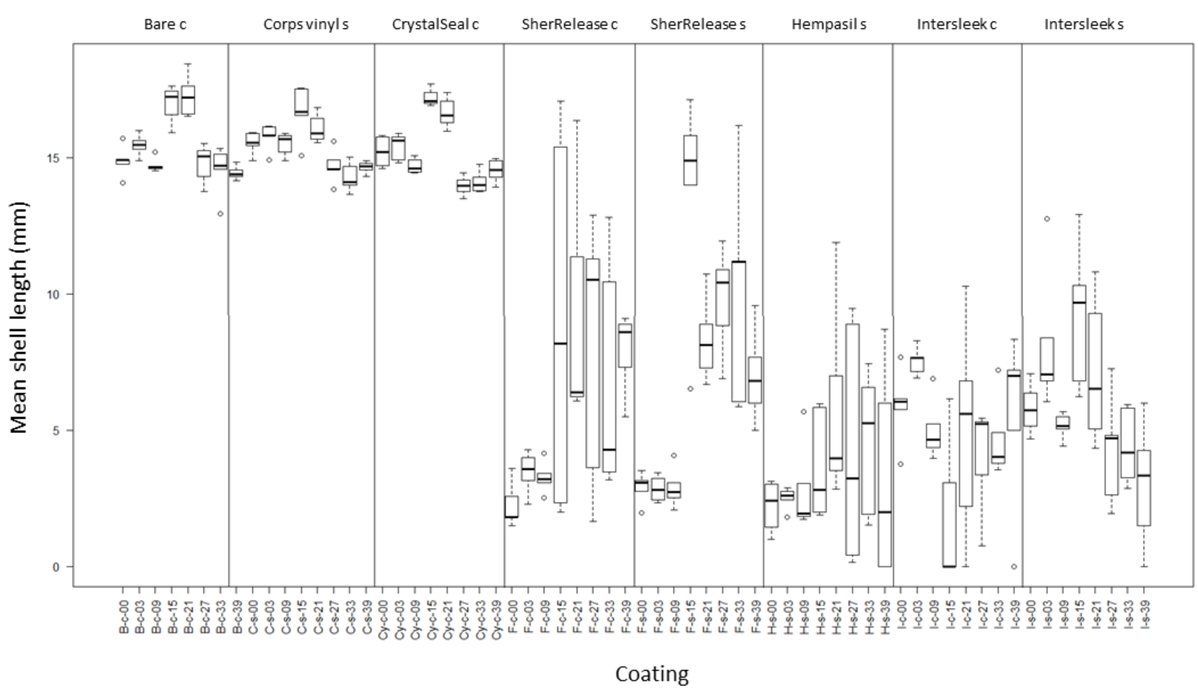


Figure 20: Mean shell length (mm) of zebra mussels attached to coatings. Coating system is identified on figure, and test panel material is labeled with a (c) for concrete and (s) for steel, and the immersion period is listed by months, e.g., 03.

The zebra mussels attached to the protective coatings were larger than the mussels attached to the foul-release coatings. There was less variation in size of the zebra mussels attached to the protective coatings, both within and between immersion periods, than on the foul-release coatings (Figure 22). There was a significant effect of coating type on the size of attached mussels, $F(7,257) = 213.93$, $p<0.001$, and post hoc Tukey tests found significant differences ($p<0.005$) between the foul-release coating group (Sher-Release (concrete), Sher-Release (steel), HempasilX3 (steel), Intersleek900 (concrete), and Intersleek900 (steel); $\bar{X} = 6.13$ mm, SD = 4.3032 mm; $\bar{X} = 7.29$ mm, SD = 4.3474 mm; $\bar{X} = 3.6711$ mm, SD = 2.8551 mm; $\bar{X} = 4.98$ mm, SD = 2.6472 mm; $\bar{X} = 5.76$ mm, SD = 2.8217 mm, respectively) and the protective coating group (Bare (concrete), CrystalSeal (concrete), and Corps vinyl (steel); $\bar{X} = 15.26$ mm, SD = 1.1541 mm; $\bar{X} = 15.11$ mm, SD = 1.1066 mm; and $\bar{X} = 15.36$ mm, SD = 0.9180 mm, respectively). The HempasilX3 (steel) had the smallest attached mussels followed by the Intersleek900 (concrete) and then the Intersleek900 (steel).

The F test indicated there was a significant effect of immersion time on the size of the attached mussels, $F(7, 257) = 9.042$, $p<0.001$, however, post hoc Tukey tests suggested that the different groups were a result of the deployment year. The largest mussels recorded on Bare (concrete), CrystalSeal (concrete), Corps vinyl (steel), Sher-Release (steel), HempasilX3 (steel), and Intersleek900 (steel) were for both the 15- and 21-mo. immersion periods; both of these immersion periods were deployed in 2014. The next largest mussels were in the 27- and 33-immersion periods, and these panels were deployed together in 2015. Thus it appears that the patterns in mussel size are likely the result of inter-annual variations in the zebra mussel population.

All of the coating systems were heavily fouled with algae and other soft organisms after deployment in the Columbia River. The control panels were the most heavily fouled and the level of fouling was relatively constant within each immersion period as well as between immersion periods (Figure 23). There was more variability in the percent cover on the foul-release coatings within and between immersion periods. The panels retrieved from the Columbia River in January (9-, 21-, and 33-month immersion treatments) were more heavily fouled with soft organisms than the panels retrieved from the Columbia River in July (3-, 15-, 27-, and 39-mo. treatments) (Figure 23). Within each of the following coating systems, the greatest soft fouling occurred for the three immersion periods that were retrieved in January: Bare (concrete), Corps vinyl (steel), CrystalSeal (concrete), Sher-Release (concrete), Sher-Release (steel), and HempasilX3 (steel). This pattern was partially valid for both the Intersleek900 (concrete) and Intersleek900 (steel) (Figure 23).

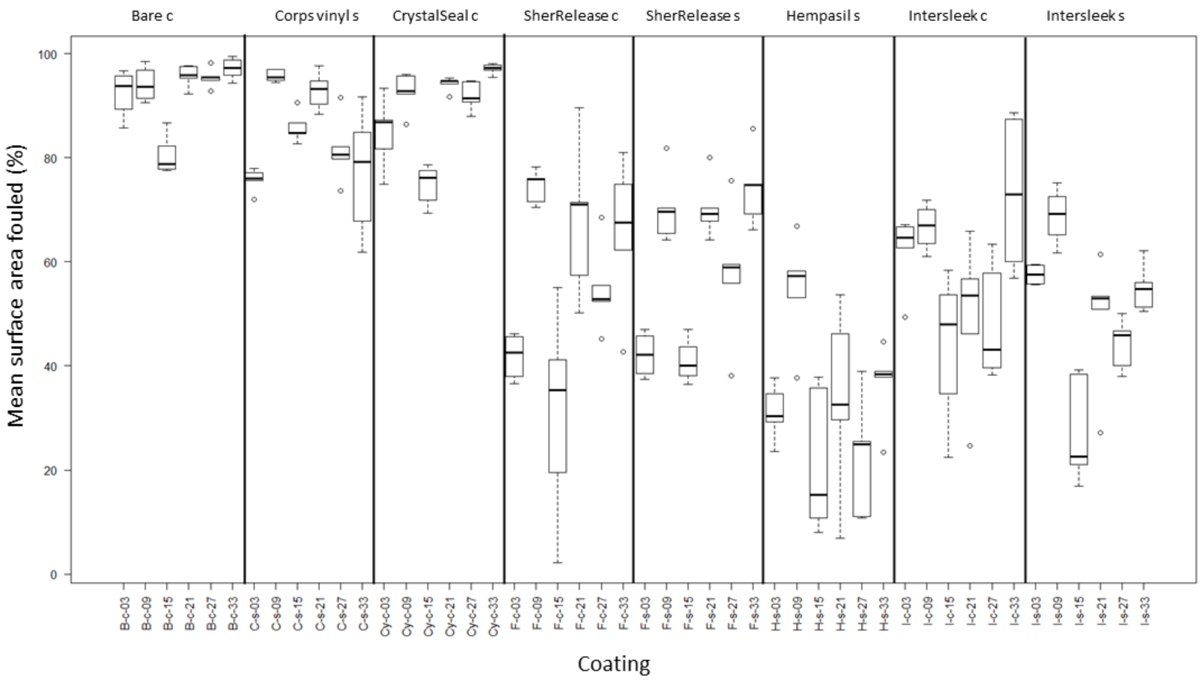


Figure 21: Surface area of panels fouled by algae, bryozoans, and other soft organisms immediately after retrieval from Columbia River. Coating system is identified on figure, and test panel material is labeled with a (c) for concrete and (s) for steel, and the immersion period is listed by months, e.g., 03.

It was easier to remove soft fouling from the foul-release coatings than the protective coatings. Most of the algae and other soft fouling were removed from all the foul-release coatings after cleaning the panels using a water stream from a common garden hose nozzle. Conversely, it was difficult to remove the soft fouling from the protective coatings using just the water stream (Figure 24). Interestingly, the percent cover remaining after cleaning for the 3-month immersion treatment was much higher than all other immersion periods for Intersleek900 (steel), Intersleek900 (concrete), Sher-Release (steel), Sher-Release (concrete), and Bare (concrete) (Figure 24). The 3-month immersion treatment was deployed with all the other panels at the onset of the Columbia River field test in March and April of 2012, meaning the 3-month period panels were exposed to fouling organisms for approximately half the amount of time as all other immersion periods.

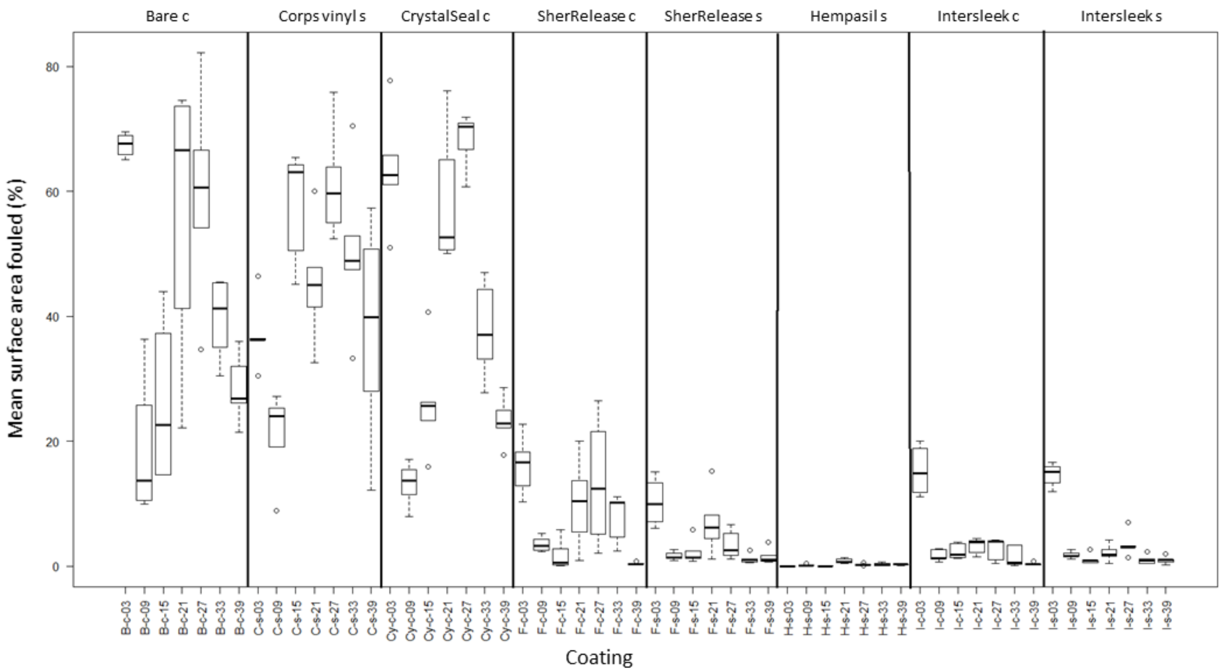


Figure 22: Surface area of panels fouled by algae, bryozoans and other soft organisms after panels were cleaned with a water stream. Coating system is identified on figure, and test panel material is labeled with a (c) for concrete and (s) for steel, and the immersion period is listed by months, e.g., 03.

Panel deployment conditions

The water velocity at the Columbia River field site was 2.64 ± 0.2080 m/s ($\bar{X}$ ± 1 SD; n = 130, min = 1.98 m/s, and max = 3.13 m/s). The water velocity near the frames increased with depth, with the highest velocities encountered near the bottom of the frame (4 in Figure 25, $\bar{X}$ = 2.75 m/s, SD = 0.1543 m/s) and the slowest velocities encountered near the top of the frame and water surface (2 in Figure 25, $\bar{X}$ = 2.55 m/s, SD = 0.2054 m/s). At the 1.0-m depth, the water velocity was slower upstream of the frame (1 in Figure 25, $\bar{X}$ = 2.56 m/s, SD = 0.1678 m/s) as compared to adjacent (3 in Figure 25, $\bar{X}$ = 2.70 m/s, SD = 0.2022 m/s), and behind the frame (5 in Figure 25, $\bar{X}$ = 2.64 m/s, SD = 0.2391 m/s).

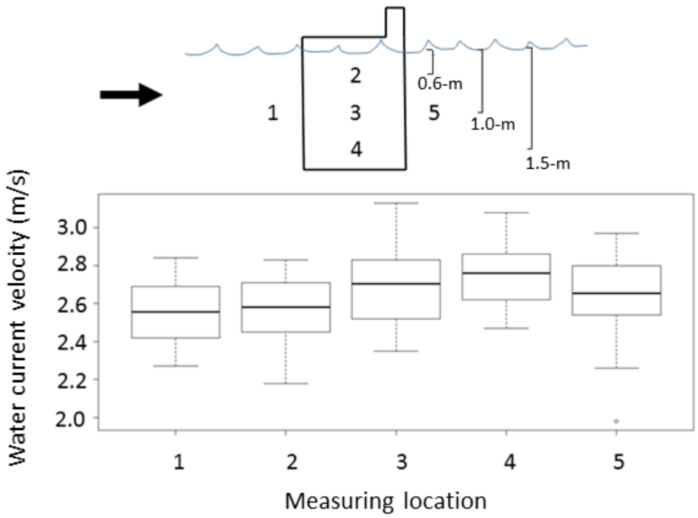


Figure 23: Water current velocity (m/s) along steel frames deployed in Columbia River. Water current direction is indicated with the arrow.

The water quality measured at the Columbia River field site was adequate for fouling throughout the panel exposure periods. The water column was mixed and isothermal throughout the field test (Figure 26). Water temperature ranged from 8 to 21.5^{o}C, dissolved oxygen was generally above 10.0 mg/L, and pH ranged from 7.17 to 8.59 (Figure 26).

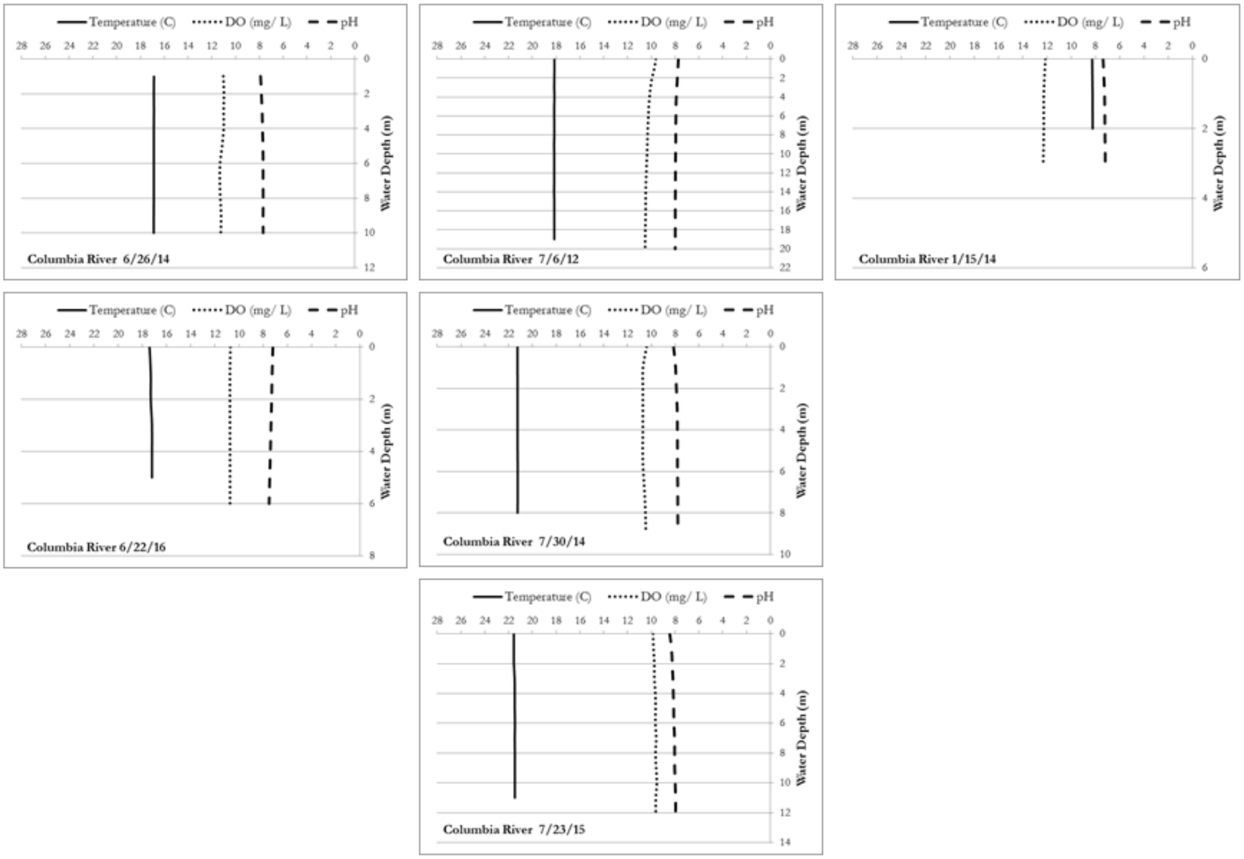


Figure 24: Water temperature, dissolved oxygen, and pH at the Columbia River field site.

The panels were deployed during the zebra mussel reproductive period in San Justo Reservoir. Zebra mussel veligers were detected in plankton samples collected in both April and September each year. Relatively large mussels (e.g., 23-mm in shell length) heavily colonized the pvc ladder and control panels at both the 9- and 4-m water depths by the panel retrieval in September. Wells, et al. (2015) reported that the zebra mussels in San Justo Reservoir initiated spawning in early April of 2015, veliger densities in the water column peaked in the June to July period, and the densities of the settlement-ready larvae (late umbonal/ pediveligers) peaked in late summer.

San Justo Reservoir stratified by early April during the project period as indicated by the water temperature and dissolved oxygen concentration profiles (Figure 27). In April, the bottom of the thermocline was near the 9-m water depth (14 ^{o}C and 1.76 mg/L dissolved oxygen (Figure 27). Based on the slope of the metalimnion in April, San Justo Reservoir was expected to strongly stratify during the summer period with the panels deployed near the bottom of the thermocline. San Justo Reservoir was relatively isothermal when the panels were retrieved although there were some gradients in dissolved oxygen (Figure 27). The water temperature and dissolved oxygen concentrations at both the 4- and 9-m water depths were not limiting to zebra mussel survival, colonization, and growth (Figure 27).

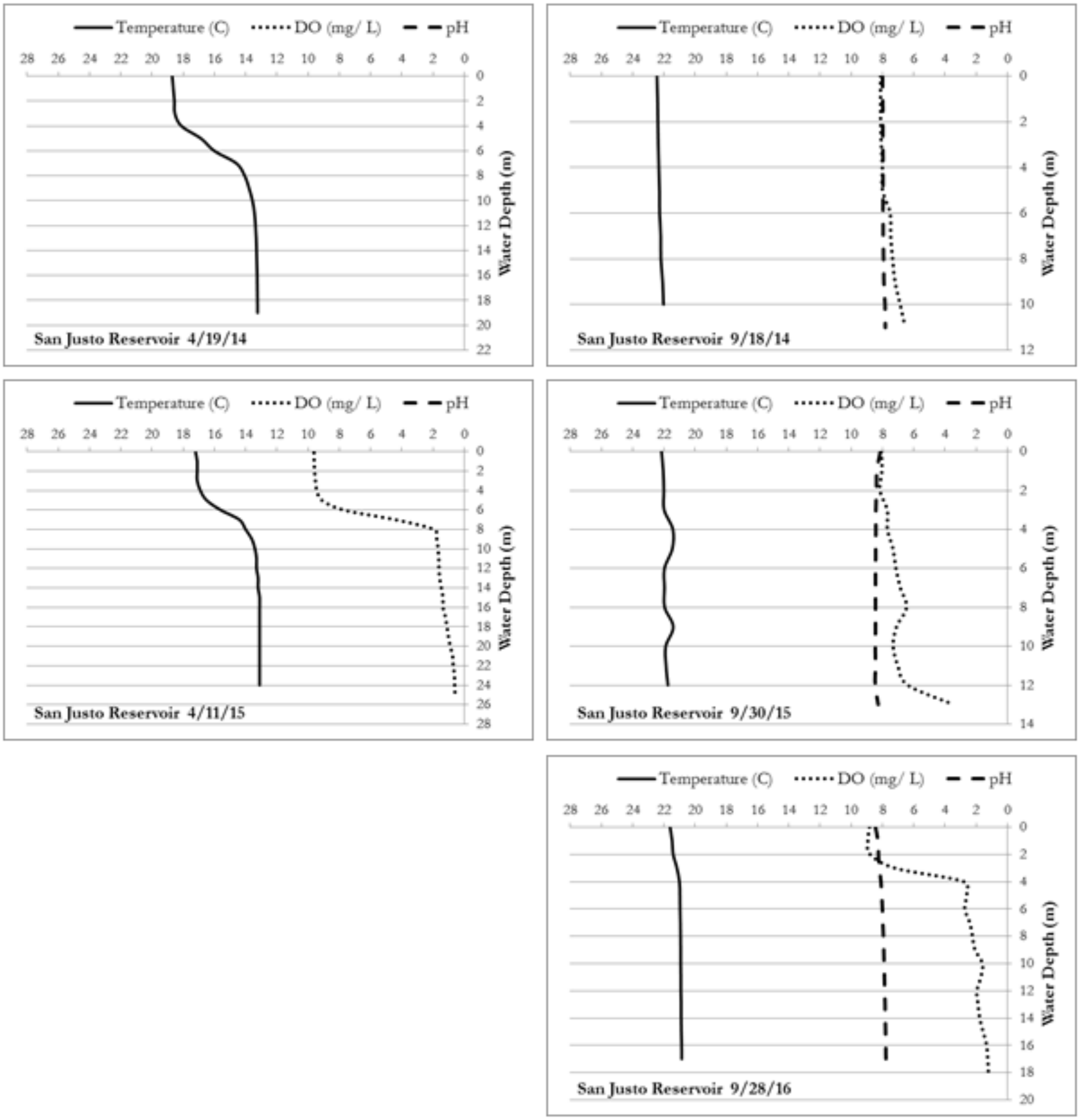


Figure 25: Water quality profiles at the moored buoy structure in San Justo Reservoir.

Discussion

Foul-release coatings are an effective *Dreissena* control option for specific service environments. The susceptibility of the evaluated foul-release coatings to gouging physical damage means that they would be best used in areas where raw water has been filtered through trash racks or screens to remove large debris. The foul-release coatings in this study performed as well as the protective coating, Corps vinyl (steel), against scribe attack, and Sher-Release (steel), HempasilX3 (steel), and Intersleek900 (steel) were more resistant to the sanding disc abrasion test than the Corps vinyl (steel). The foul-release coatings worked well against *Dreissena* mussels on both concrete and steel; the protective coatings were heavily fouled in comparison. Foul-release coatings may also be a good candidate for service environments exposed to high suspended loads or other types of wear in which a flexible coating confers greater advantages over more brittle coating. Coatings are a possible control option for facility components that can be dewatered, cleaned and completely dried for paint application.

All of the foul-release coatings evaluated in this study were susceptible to gouging and other similar types of mechanical damage. All of the foul-release coatings exhibited poor coating adhesive strength to the substrate relative to the Corps vinyl (steel) in the knife adhesion tests. It was difficult to remove small chips from the Corps vinyl (steel) whereas the knife easily cut the foul-release coatings and removed long strips or gouges. The location of failure for the HempasilX3 (steel) was between the tie coat and topcoat, whereas on the Sher-Release and Intersleek900 coatings, the location of failure was most common between the epoxy and tie coat. The knife adhesion test is a qualitative test that favors hard brittle coatings that easily fracture (smaller chip size) versus coatings with higher cohesive strength that tear in larger chips such as the foul-release coatings. Quantitative methods such as pull-off adhesion testers (e.g., ASTM D4541) were not used with foul-release coatings because the epoxy adhesive used to secure the pull-off dolly to the coating did not form an adequate bond with the foul-release topcoat.

Three of the foul-release systems had acceptable resistance to physical damage caused by deployment in the main stem Columbia River for immersion periods up to 39-months. Flaking, blistering, cracking and/or checking were not observed on the Sher-Release (steel), Intersleek900 (concrete), and the Intersleek900 (steel) foul-release coatings. Physical damage caused by field deployment was not observed on the Bare (concrete), Corps vinyl (steel), and CrystalSeal (concrete). The HempasilX3 (steel) and Sher-Release (concrete) developed blistering after 3- and 9-month immersion periods in the Columbia River. By the end of the experiment, blistering was present on all of the HempasilX3 (steel) panels and most of the Sher-Release (concrete) panels.

All of the coatings evaluated in this study resisted scribe attack for immersion periods up to 39-months in the Columbia River. There was slight corrosion at the scribe, but there was no undercutting, and the coating adhesion at the edges of the scribe remained intact. Immersion period had no effect on the creepage. The Corps vinyl (steel) represents an industry benchmark for corrosion resistance, and with the exception of HempasilX3 (steel), there was no difference between the foul-release coatings and the Corps vinyl (steel) for scribe undercutting corrosion for immersion periods up to 39-months. The small amount of creepage recorded represented areas of paint loss extending from a scribe mark, but there was no corrosion activity associated with the areas of paint loss. These small areas of paint loss around the scribe are possibly the result of mechanical damage caused when making the initial scribe using the box cutter knife.

All the foul-release coatings were effective against zebra mussels. In contrast, all the control systems were heavily fouled by zebra mussels and it required considerable force to remove the mussels. The mean adhesion strength of zebra mussels on the control systems (Bare (control), Corps vinyl (steel), and CrystalSeal (concrete)) was 1.3889 MPa ± 0.3024 MPa, 1.0796 MPa ± 0.2800 MPa, and 1.3289 MPa ±0.3046 MPa, respectively ($\bar{X}$ ± 1 SD). For comparison, this adhesion strength was less than the adhesion strength of marine barnacles (*Balanus eburneus*) on a static immersion grade epoxy, MIL-P-2444, ($\bar{X}$ = 2.060 MPa, SD = 0.527 MPa) (ASTM D5618-2005). Most of the force measurements to remove attached zebra mussels from the foul-release coatings were below the gauge detection limit, and the limited number of force measurements recorded on foul-release systems were mussels attached to the exposed tie and epoxy coats or lodged into a surface imperfection.

The shell valves of the zebra mussels were often crushed during the force tests on the control systems. Additionally many of the mussels attached to the control panels were separated from their entire byssus during the force tests, leaving the stem, root, threads and plaques still attached to the coating. It can be more difficult to remove the byssus remaining on the surface after the rest of the mussel has been removed.

The coatings' resistance to zebra mussel fouling was not affected by Columbia River immersion periods up to 39-months. The foul-release coatings were very effective against the zebra mussels (percent cover, adhesive strength, and attached mussel size) whereas the control systems were heavily fouled. The increased zebra mussel adhesive strength observed in the 39-month immersion treatment was for all the control systems, and was likely due to variations in zebra mussel byssal thread dynamics instead of degradation in coating performance. The 39-month immersion period was the only immersion period deployed in San Justo Reservoir at a water depth of 4 m, due to drawdown of the reservoir; whereas, all other immersion periods were deployed at a water depth of 9 m. *Dreissena* mussel thread formation including the number of threads and strength of attachment vary according to multiple factors including water temperature, food availability and quality, time of year, and age (Moeser and Carrington 2006). It seems likely that the habitat differences between the 4-m and 9-m deployment depths could account for the observed differences in byssal thread formation.

The size of mussels attaching to the foul-release coatings increased with immersion period, and there was a general positive relationship between immersion time and the variability of the mean shell length of zebra mussels attached to all the foul-release coatings and lower variability in mussel size on all the control systems within and between immersion periods. This pattern applied to the two foul-release systems that developed blisters as well as the three foul-release systems that lacked visible physical damage, and none of the experimental controls, which suggests that increased immersion period is associated with a few larger mussels attached to the foul-release coatings regardless of the presence of blisters.

The presence of intact blisters on the HempasilX3 (steel) coating system did not appear to affect the coatings' immediate foul-release performance. The HempasilX3 (steel) system blistered early and it was common for several of the HempasilX3 (steel) blisters to get sheared off during panel handling and analysis. The exposed tie or epoxy coat was subsequently regularly colonized by zebra mussels. Despite this, the HempasilX3 (steel) was the most resistant against both zebra mussel and soft fouling, as well as being the most resistant coating to weight loss by abrasive sanding disc. The presence of blistering on steel is a physical defect-related failure and indicates a loss of adhesion to the underlying substrate. A common cause for blistering on steel is surface contamination prior to coating application such as abrasive blast. Contamination is always a risk during paint application, especially in a facility that handles both epoxy and silicone components such as used for this experiment. The application procedures included procedures to limit contamination, and these same procedures were applied for all the foul-release systems used in the study. All the steel panels used in the experiment were from the same batch.

The panel deployment in the Columbia River provided adequate exposure of the test panels to the main stem Columbia River conditions for a period of 39-months. The water velocity along the frames ranged from 1.98 to 3.13 m/s, and the water quality conditions were typical of the main stem. The experiment location was on the river side of the breakwater dock, and this exposed the frames and panels to the water current and large woody debris; the purpose of the breakwater dock is to protect the Port of Camas Washougal from the main stem Columbia River. Large woody debris was often entangled with the frames and was removed during panel retrieval. During one of the retrieval events, a large waterlogged blow down tree was seen moving down the length of the breakwater dock.

Zebra mussels in San Justo Reservoir were fecund and grew quickly. In the five-month period the panels were in San Justo Reservoir in 2013, two separate Year-1 cohorts colonized the panels with the largest cohort measuring approximately 12 to 21 mm in shell length and the second cohort measuring approximately 5 mm in shell length. Although juvenile and adult mussels translocate year-round by drifting on mucus threads and other means, the vast majority of the mussels colonizing the panels were young-of-the-year mussels in the water column in the summer, likely pediveligers, that settled onto the panels, underwent metamorphosis, translocated to a preferred location, and grew into juvenile and adults mussels.

Accidents did occur but proper planning assured that none of them prevented the completion of project deliverables. One of the steel frames deployed in the Columbia River was lost with all the attached panels when the 5-mm diameter steel cable used to hoist the frame onto the deck surface snapped. Nobody was injured, and the needed panels were retrieved from extra frames that were deployed at the start of the experiment to account for loss. Similarly, one of the pvc ladders was lost with all the panels in San Justo Reservoir when the steel cables snapped. Additional panels had been deployed in other pvc ladders and this loss was mitigated. A highway roll-over accident occurred when transporting equipment and supplies to San Justo Reservoir to fabricate and deploy the moored buoy structure in San Justo Reservoir. The tow vehicle and one of the boats were totaled in the accident, but only one of the panels was damaged because each panel was individually wrapped in 2-mm thick polyethylene foam and stored in 8-L plastic containers with water.

PSU disseminated project information to stakeholders. PSU staff contacted and met with BPA public affairs personnel and media representatives during the project to augment public awareness and understanding regarding the project and its status, zebra and quagga mussels in general, and the various efforts being undertaken by BPA and others to prevent introduction and mitigate potential impacts of zebra and quagga mussels. PSU staff responded to media requests for project information, e.g., PSU coordinated media interviews with fieldwork on the Columbia River (Florip 2012). PSU regularly attended and presented project updates at the Columbia River Basin Team Meetings held in Boise, ID, Spokane, WA, and Portland, OR/ Vancouver, WA. An abstract for an oral presentation was recently submitted to the 20th International Conference on Aquatic Invasive Species to be held on October 22 to 26, 2017 in Fort Lauderdale, FL.

Recommendations/Next Steps

- Intersleek900 was the best foul-release system evaluated in this study. The Intersleek900 system worked on both concrete and steel and did not exhibit significant physical damage caused by service periods up to 39-months in the main stem Columbia River, e.g., blistering. The Sher-Release (steel) coating also performed well against fouling and did not exhibit significant physical damage during the deployment, however, the Intersleek900 coating was more resistant than the Sher-Release coating to zebra mussel fouling and weight loss by abrasive sanding disc.

- All the foul-release systems were susceptible to gouging. Foul-release coating should only be used in areas where raw water has been filtered through trash racks or screens to remove large debris to limit physical damage.

- The blistering on HempasilX3 (steel) and Sher-Release (concrete) should be explored further. Aside from the blistering, the performance of the foul-release systems was relatively similar. The loss of adhesion indicated by blistering is a serious type of failure. It is possible that the HempasilX3 blistering was caused by contamination during paint application, and is unrelated to the coating formulation. HempasilX3 out-performed the other foul-release coatings in percent cover of mussel and algae fouling and coating weight loss in sanding disc abrasion despite the blistering. The Sher-Release (concrete) system utilized two different epoxy layers, Corobond 100 and Seaguard 6100, whereas the Sher-Release (steel) system only used the Seaguard 6100 epoxy. Concrete is difficult to coat, and apparently this combination of epoxies was not able to block water from infiltrating into the concrete panel.

- A pilot study on a limited number of auxiliary water supply diffuser gratings should be conducted to determine how long the coatings will last under normal facility operations, including the wear induced by the operations done during the in-water work period when the fishways are dewatered and work crews are walking around and working on the gratings for several weeks.

- Monitor the USBR coating research that is exploring the trade-offs between durability and foul-release properties in search of effective, long-lived foul-release systems.

- Continue developing a regional *Dreissena* control strategy for USBR and USACE facilities in the Northwest Region as well as at facilities across North America. The aim of the strategy should be to identify best control options, predict rates of mussel colonization, increase coordination and efficacy, and reduce costs. Pilot projects could be used to better inform cost estimates and the efficacy of different control options. Experiences from USBR and USACE facilities in waters infested with *Dreissena* should be used to inform the control strategy.

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