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Managing Water in the West

Scoping Level Study – Test Method Development for Adhesion Strength of Protective Coatings under Real-life Hydraulic Conditions

Research and Development Office
Science and Technology Program
(Interim Report) ST-2018-1821-01

PAP-1172

U.S. Department of the Interior
Bureau of Reclamation
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Mission Statements

Protecting America's Great Outdoors and Powering Our Future

The Department of the Interior protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities.

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A literature review and discussions with Naval Research Laboratories identified the need for a new test method to determine adhesion strength of coating systems. A new test that uses hydraulic conditions similar to those encountered in the field will be used in the test to help provide a clearer correlation between test results and actual field performance. The development of a new test will help increase the service life of new coating systems that are exposed to high-velocity environments such as penstocks and outlet pipes.

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Scoping Level Study – Test Method Development for Adhesion Strength of Protective Coatings under Real-life Hydraulic Conditions

JOSHUA MORTENSEN Digitally signed by JOSHUA MORTENSEN
Date: 2018.09.27 12:12:01 -06'00'

Prepared by: Josh Mortensen, P.E.
Hydraulic Engineer, Hydraulic Investigations and Laboratory Services, 86-68560

ALLEN SKAJA Digitally signed by ALLEN SKAJA
Date: 2018.09.27 12:01:32 -06'00'

Reviewed by: Allen Skaja, PhD
Technical Specialist, Materials and Corrosion Laboratory, 86-68540

ROBERT EINHELLIG Digitally signed by ROBERT EINHELLIG
Date: 2018.09.27 12:47:58 -06'00'

Technical Approval: Bob Einhellig, P.E.
Manager, Hydraulic Investigations and Laboratory Services, 86-68560

Introduction

The main objective of this scoping-level study was to identify the specific research gap for correlating test results of new coating systems to their performance in the field. Findings from this study have been used to steer planning for developing a new test method that is more representative of field conditions to better predict coating longevity and performance. Findings from a literature review are included as well as preliminary plans for the new test method based on hydraulic conditions that can be created in a laboratory. This effort is being done in collaboration with engineers and scientists from the United States Naval Research Laboratories (NRL).

Background

Finding dependable coatings with good adhesion and durability characteristics for long service life is an ongoing challenge for Reclamation. In a recent Research Roadmap for Mechanical Components of Hydropower Plants (Mortensen, 2018) coatings issues were identified as the top priority. The specific research need for coatings states "Improve durability & extend service life for coatings materials in high velocity environments." Extending the service life of linings in penstocks and outlet pipes where high velocities are typical is an urgent Reclamation need since many coal tar enamel linings are near the end of their service life. Since coal tar enamel linings can no longer be re-applied due to environmental and safety reasons, other linings systems are taking their place and their performance so far has not been promising.

For example, a new lining system failed after only four years of service in a penstock at Flatiron Powerplant in 2015 before significant delamination occurred which caused major issues for the plant. A similar incident in the outlet pipe at Enders Dam where the coating began delaminating, but was caught in time to do repairs, before a large section delaminated. Upgrades to lining systems in penstocks and outlet pipes are expensive (2-5 million dollars) due to large surface areas to be prepared and lined, as well as extra safety precautions for working in confined space with steep slopes. For such a large investment it is imperative that the new lining system being applied has some evidence, from test results or otherwise, for a long service life.

The NRL have found similar issues with their new coatings applications for hulls and propellers on sub-marines and ships. In early 2017, Reclamation was contacted by NRL about previous experience with coatings testing and research facilities capable of further testing with the objective of developing a new, more representative test standard for adhesion strength. This was the beginning of a collaboration between Reclamation and NRL to develop a test method for coating adhesion strength that could be applicable to both agencies as well as the industry in general.

Literature Review

A summary of papers, reports, and recent conference presentations is outlined in Appendix A. The main finding from searching the literature is that a standard test method for “wet testing” of coatings does not exist. “Wet testing” implies that other factors have an influence on the adhesion strength of the coating besides just the dry bond between coating and surface. These factors may include rust creep and corrosion, as well as uplift forces, stagnation pressures, shear stress, and vibrations caused by the high-speed flow over the coating, all of which should be accounted for. These findings correlate with recent Reclamation experience with coating failures as most of them were due to issues with adhesion rather than durability.

All known standard tests for adhesion strength are mechanical in nature and done in the dry. Recent research by Reclamation applied these standards (namely ASTM D4541, D6677, and D3359) to wet adhesion and found no correlation in the results (Tordonato, 2018), pointing to a need for a standard wet adhesion test. NRL has tried to develop a custom adhesion test (mechanical pull) under different moisture and temperature conditions (Tagert & Martin, 2018). Their motivation for testing is due to having no correlation between standard test results and actual performance of coating systems on their equipment in the field.

Various studies were done over the years in Reclamation’s Hydraulics and Materials laboratories. Most of these focused on coating durability or resistance to cavitation. In 1953, a comparison was made between laboratory tests of various coatings and field results of the same coatings in an outlet pipe at Grand Coulee Dam (Selander, 1953). The author observed that in the field tests “several effects, such as tearing, delamination, and loss of bond………. which were not accounted for or found in the laboratory tests. These are attributed to the greater severity of the field exposure.” Adhesion seemed to be a significant factor in the failure and was not accounted for in the lab tests. None of the tests in Reclamation’s literature were completely devoted to testing adhesion strength.

A different perspective to the problem would be to treat the edge of the coating as an offset (edge could be due to imperfection in the application, defect caused by debris, etc., or an edge caused by the inside joint of the pipe). This edge may cause stagnation pressures or uplift forces as well as induce cavitation. Offsets in spillway joints were studied by Frizell (2008) with Reclamation’s High-Head Pump facility. The same approach could be applied to coatings in a way that is focused on adhesion strength by representing all the physics that contribute to delaminating a coating including stagnation, uplift and shear stress.

Collaboration with Naval Research Labs

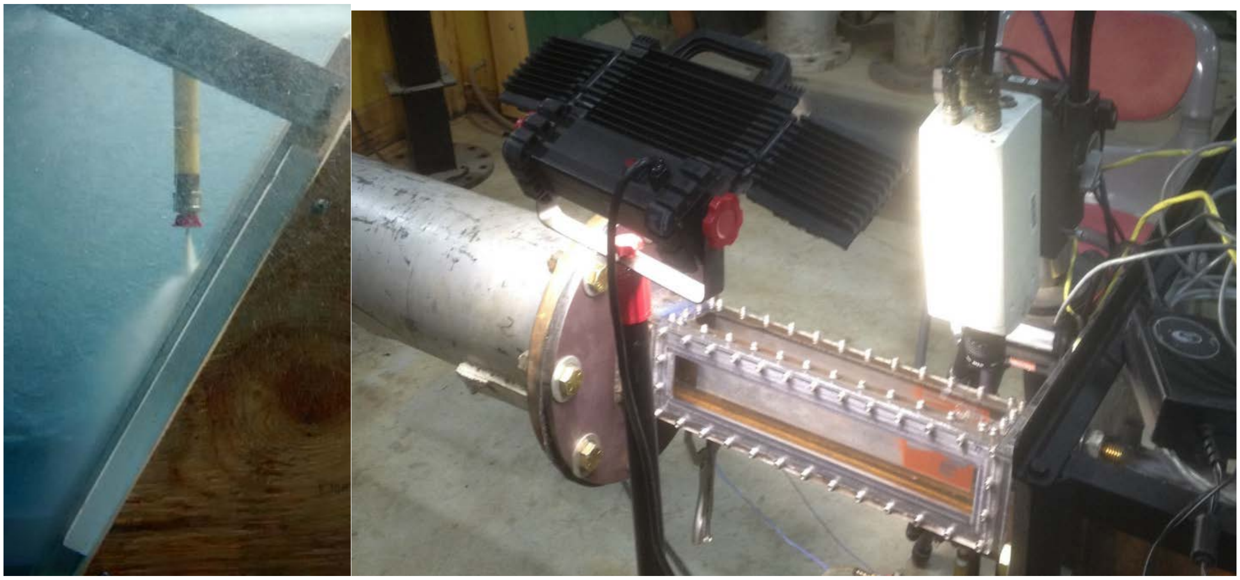
As part of the planning for the new test method approach, Reclamation met with coatings engineers and scientists from NRL. Discussions focused on the need from both agencies for a better test method and ideas for development. The group toured Reclamation's Hydraulics and Coatings Laboratories in Denver and considered different approaches and facility options for testing. A preliminary approach for wet testing was agreed upon that would allow for modifications as needed and could likely begin in Fiscal Year 2019. Further discussion is needed to clearly identify the roles of both Reclamation and NRL but testing will likely be conducted in parallel with each lab performing tests to gage the repeatability of the test method. Also, it was decided that the test method should focus on coating adhesion strength rather than durability or strength of the coating surface.

Recommendations for Test Method Development

A test method is needed that is more representative of coatings in a field application where dynamic hydraulic conditions are present. To a large degree, these conditions may be created in a laboratory environment where a coating is exposed to flow conditions that are comparable to that of a penstock or pipe in the field. Two test facility options were identified for "wet testing" in the lab.

The first option is a submerged jet that impacts a coating test sample. The jet will impact the edge of the coating at an angle similar to that shown in option (a) of Figure 1. The advantages of this option are that it is easy to fabricate and reproduce for parallel testing and it can generate extremely high velocities (greater than 200 ft/s) and impact pressures on the test surface which may accelerate testing of many coating samples. However, the hydraulic conditions will likely deviate from that of a penstock because of the angle of the jet flow to the surface and the presence of cavitation implosions which is more a test of the coating's durability rather than adhesion strength. But if the jet impingement is focused on the edge of the coating surface it may serve as a screen test for a variety of coating systems.

The second option is high-speed flow parallel to the coated surface as shown in option (b) of Figure 1. The example shown in the photo is from a previous test where high speed flows (velocities in the range of 30-60 ft/s) were generated by the High-Head Pump facility in Reclamation's Hydraulics Lab. Similar equipment is also available in some of NRL's facilities. This test option will likely produce more representative hydraulic conditions where coating adhesion forces are dominated by stagnation pressures and uplift forces. The test facility can be designed for a range of "real-life flow conditions" typical of penstocks that can be tested and measured to estimate the true adhesion strength of the coatings. This is the preferable option but may limit the amount of test data that can be collected due to potentially long test runs required for each coating sample.



(a) (b)

Figure 1 Submerged jet test option (a) and high-speed test flow option (b) for wet adhesion strength testing.

After discussions with both hydraulics and coatings staff from Reclamation as well as coatings experts from NRL it was decided that both options could be used for testing. The submerged jet could be used as a more rapid screen test for multiple coating systems and the high-head pump would then be used to test selected coatings. Table 1 below outlines the preliminary approach with four main tasks for developing the new test method for coating adhesion. While this approach will likely become more refined through actual testing, the “wet testing” method proposed here is more likely to represent the physical forces acting on the coating by the flow and will hopefully produce results that more closely match field performance.

While attempts will be made to account for the dominant processes that lead to coating failure by delamination (failure of adhesion strength), it will be impossible to truly represent every condition seen in a field application. Other variables such as surface condition of the penstock during application, size and geometry of damage or flaws in the coating that initiate the delamination process, temperature variations, sediment laden flow, debris, and exposure time all contribute to the service life of a coating system. While these conditions all have an influence, the findings of this scoping-level study point to accurate test methods of adhesion strength as the greatest need for extending service life of coatings at this time.

Table 1 Preliminary approach for developing a new test method for coating adhesion strength.

Task Name	Task Description
Task 1 - Initial Screen Testing	Preliminary screening test for all coating samples using a Submerged Jet Facility. The coating will be exposed to high shear and uplift forces which will be controlled and measured. For these tests, hydrodynamic parameters will be the variables and time will be constant. Shear and uplift forces will be recorded at the failure of each coating and compared a baseline coating (Coal Tar Enamel).
Task 2 – Compare Submerged Jet Results to Conventional Test Results	Adhesion strength results from submerged jet testing will be compared to conventional mechanical test methods (90° peel tests, knife peel tests, etc.) to determine if consistent trends exist.
Task 3 – High Velocity Testing	Selected coatings from the screen testing will be tested in a high velocity flow chamber (velocities up to 70 ft/s). The coatings will be exposed to shear and uplift forces similar to or in excess of their typical service environment. Shear and uplift forces will be measured and controlled based on screen test results. For these flow chamber tests hydrodynamic parameters will be held constant and time to failure will be the variable.
Task 4 – Data Analysis and Test Method Formalization	High velocity test results will be used to estimate the adhesion strength of the coatings compared to a baseline coating (Coal Tar Enamel). Results will also be compared to other conventional adhesion test methods. This analysis will help determine if this approach can be used as a formal test method and a standard procedure will be written.

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ASTM. (n.d.). *D4541 Standard Test Method for Pull-Off Strength of Coatings using Portable Adhesion Testers.* Retrieved 2018, from https://www.astm.org/Standards/D4541.htm

ASTM. (n.d.). *D6677 Standard Test Method for Evaluating Adhesion by Knife.* Retrieved 2018, from https://www.astm.org/Standards/D6677.htm

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Colgate, D. (1965). *Resistance of Selected Protective Coatings for Concrete to High Velocity Water Jets.* HYD-543, Denver, CO: Bureau of Reclamation.

Frizell, W. K. (2008). *Uplift and Crack Flow Resulting from High Velocity Discharges over Open Offset Joints.* PAP-976, Denver, CO: Bureau of Reclamation.

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Selander, C. E. (1953). *Resistance to Cavitation Damage, Laboratory, and Field Tests on Four Selected Coatings.* ChE-25, Denver, CO: Bureau of Reclamation.

Tagert, J., & Martin, J. (2018). Alternative Adhesion Test - Creep Test. *SSPC.* New Orleans.

Tordonato, D. (2018). Adhesion Testing - How much is sufficient? *SSPC.* New Orleans.

Appendix A – Literature Review

AUTHOR	TITLE	NOTES
Existing Methods – Mechanical and Durability		
Tagert, Jimmy Martin, James	Alternative Adhesion Test – Creep Test (Presentation given at SSPC 2018 Conference and shared with Reclamation)	Presents the use of an alternative test procedure to existing standards that could be installed to apply stress to coating during accelerated testing with the intent to identify durability of coatings under in-situ environmental conditions. Development of corrosion resistant test jig to apply stress to coating during accelerated testing. Determination of how coating properties change when exposed to different environmental conditions, IE, moisture & Temperature Test Jig installed on coated panel, Baseline adhesion determined. Preload on different location on specimen at 25% of baseline load. Panel placed in ASTM B117 (Salt Spray fog test) for 1 week, then pre-load increased to 50% of baseline. After 4 weeks, the panels that had not failed were loaded to failure.

Tordonato, Dave	Adhesion Testing – How much is Sufficient? (Presentation given at SSPC 2018 Conference)	Wet adhesion may be weaker than dry adhesion. There is NO industrial test standard for wet adhesion. (RESEARCH GAP) A corrosion performance test was performed on 8 different coatings. The coating with the highest initial adhesion was the worst performing coating for undercutting and ranked last in HAR immersion, PRO, and BOR testing with a poor rust creep rating as well. (slide 8) Eight lining systems and a control were evaluated to investigate the connection between adhesion and corrosion performance. No correlation between any type of adhesion measurement (initial pull-off, post immersion pull-off, and knife adhesion) to undercutting resistance during immersion or cyclic testing. Best performing lining systems failed with a mix of adhesion and cohesion failure (wet adhesion). The worst performer experienced 100% adhesion failure (wet adhesion). Vinyl resin which is known to exhibit long term barrier protection, produced glue failures for dry and wet adhesion and had fair undercutting resistance. Adequate adhesion is necessary for coating and lining performance but the ideal amount is still unclear. Rust creep is only one aspect of lining performance and other factors such as barrier performance and durability play an important role in determining longevity.

ASTM D3363	Standard Test Method for Film Hardness by Pencil Test https://compass.astm.org/EDIT/html_annot.cgi?D3363+05(2011)e2	Rapid, inexpensive determination of film hardness of an organic coating on a substrate. Pencil held at 45° angle and pushed away from operator in a 6.5-mm (¼”) stroke. Start with hardest pencil to softest until reach one of two endpoints; 1) the pencil that will not cut or gouge the film (gouge hardness) or 2) the pencil that will not scratch the film (scratch hardness).
ASTM D4541	Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers https://www.astm.org/Standards/D4541.htm	The general pull-off test is performed by securing a loading fixture (dolly, stud) normal (perpendicular) to the surface of the coating with an adhesive. Attaching a testing apparatus to the loading fixture to apply tension normal to the test surface. The force applied to the loading fixture is then gradually increased and monitored until either a plug of material is detached, or a specified value is reached. When a plug of material is detached, the exposed surface represents the plane of limiting strength within the system. The nature of the failure is qualified in accordance with the percent of adhesive and cohesive failures, and the actual interfaces and layers involved. The pull-off strength is computed based on the maximum indicated load, the instrument calibration data, and the original surface area stressed. Pull-off strength results obtained using different devices may be different because the results depend on instrumental parameters (see Appendix X1 of standard).
ASTM D6677	Standard Test Method for Evaluating Adhesion by Knife https://www.astm.org/Standards/D6677.htm	Procedure for assessing the adhesion of coating films to substrate by using a knife. Adhesion is determined by making an *“X”* cut into the coating film to the substrate and by lifting the coating with a knife. Adhesion is evaluated qualitatively on a 0 to 10 scale.

ASTM D3359	Standar Test Methods for Rating by Tape Test https://www.astm.org/Standards/D3359.htm	Use of a tape peeling off the coating - referred to by Jimmy Hagert and James Martin from Navy.
ASTM G134-17	Standard Test Method for Erosion of Solid Materials by Cavitating Liquid Jet[1] https://compass.astm.org/EDIT/html_annot.cgi?G134+17	This test method can be used to compare the cavitation erosion resistance of solid materials. A submerged cavitating jet, issuing from a nozzle, impinges on a test specimen placed in its path so that cavities collapse on it, thereby causing erosion. The test is carried out under specified conditions in a specified liquid, usually water. This test method can also be used to compare the cavitation erosion capability of various liquids. This test method specifies the nozzle and nozzle holder shape and size, the specimen size and its method of mounting, and the minimum test chamber size. Procedures are described for selecting the standoff distance and one of several standard test conditions. Guidance is given on setting up a suitable apparatus, test and reporting procedures, and the precautions to be taken. This test method provides an alternative to Test Method G32. In that method, cavitation is induced by vibrating a submerged specimen at high frequency (20 kHz) with a specified amplitude. In the present method, cavitation is generated in a flowing system so that both the jet velocity and the downstream pressure (which causes the bubble collapse) can be varied independently. This method is not a good option for looking at coating adhesion – only coating resistance to cavitation or other forces at its surface.

Hydraulic Laboratory Studies and Field Experience		
Schuster, J. C.	Cavitation Tests of Protective Coatings PAP-84 Hardcopy is located in 1300 wing BLDG 56.	Test of Protective Coatings for Navy in 1953. Ten cone specimens, 2 bare metal and two each of four different coating materials were tested for their relative resistance to cavitation-erosion. Velocities ranged from 70 ft/s to 72.8 ft/s. Description of duration of tests and types of damage are included. A drawing of the cavitation apparatus is included. (Fig 1) Photographs of the test apparatus and cones before and after testing are included. (Fig 2-25)
Carlson, E. J.	Operation of pump in which impeller was covered with epoxy and neoprene protective coatings PAP-133 https://www.usbr.gov/tsc/techreferences/hyraulics_lab/pubs/PAP/PAP-0133.pdf	A 6-inch Worthington vertical pump was dismantled, and the impeller was coated with two different coatings epoxy and neoprene. The pump was then run periodically from May to October. It was started and stopped 16 times, run for an average of 47.3 hours each time, for a total time of 757 hours. Each time Q was set at 2.16 cfs, V=11.0 ft/s in a 6-in pipe. The average concentration of fine uniform sand that passed through the impeller was 361 parts per million by weight, and the total sediment passed was 63 tons. During testing, the average temperature of the water/sediment mixture was 66° F. More of a resistance test to abrasion rather than coating adhesion.

Colgate, D.	Design, Construction, and Calibration of a Rotating Disc Apparatus for Testing Protective Coatings PAP-198 https://www.usbr.gov/tsc/techreferences/hydraulics_lab/pubs/PAP/PAP-0198.pdf	This report documents the design and construction of a portable, easy to use testing apparatus that was capable of simultaneously testing 4 coatings on 4 spinning metal discs that were submerged in a tank, to study the effect of flowing water on the coatings. Instrumentation measured pressures in the ¼" space between the rotating discs at 4 locations from the center of the discs, which allowed a plot to be developed of velocity head at all points on a radius of the discs. At 780 rpm max relative velocity 17.2 ft/s between water and disc and 13.7 ft/s between water and walls. At 1520 rpm, velocity 35 ft/s between water and disc. Test run for 300 hours and did not damage red lead coating. A note referencing a Chemical engineering branch report No. ChE-25, describes how red lead was used adjacent to the test boundary at Grand Coulee outlet conduits which were subjected to up to 1,012 hours of exposure under a velocity of 96 ft/s without distress. Red lead was too durable for this testing apparatus. Test approach may be used for coating adhesion if hydraulic characteristics such as velocity, etc. can be produced in the same range as field conditions.

Frizell, K. W. DSO-07-07	Uplift and Crack Flow Resulting from High Velocity Discharges Over Open Offset Joints PAP-976 https://www.usbr.gov/tsc/techreferences/hydraulics_lab/pubs/PAP/PAP-0976.pdf	This report investigates uplift pressures caused by high velocity flow encountering a vertical offset joint. The joint was adjustable and included instrumentation and allowed for flow to penetrate into the joint (reducing uplift) or be sealed (max uplift). Pressures were measured on the top surface of the downstream slab. Differential pressure measurements and particle image velocimetry were utilized to capture the uplift pressure and movement of water particles during testing. These observations were compared to results from a computational, Flow3D model. Aspects of the test setup may be applicable to the current coatings standard development. I.E. the use of the high head pump, utilizing the pumps ability to deliver 6.5 cfs through a closed conduit section to created velocities in the 55 ft/s range. Determined that slab movement is caused by uplift forces (reduced pressures on top surface and stagnation pressures from beneath). Stagnation is a function of velocity and distance between offsets. Did not measure turbulent fluctuations which could have an effect on uplift pressures. Mentions this is more likely with gaseous entrainment (Bollaert, 2002). Bollaert does mention uplift observed in rock joints goes up significantly due to hydrodynamic forces. There is a decrease if the % air is greater than about 10%.

Mortensen, J.D.	Resistance of Protective Coatings to High Pressure Water Jets for Invasive Mussel Removal PAP-1074 https://www.usbr.gov/tsc/techreferences/hydraulics_lab/pubs/PAP/PAP-1074.pdf	The objective is to determine an operations range for utilizing a high-pressure water jet to remove mussels without damaging the protective applied coating. Description of submerged jet characteristics and equations to predict impact pressures and shear stress may be useful. Still not sure how to deal with cavitation which will be difficult to avoid with a submerged jet. Use a larger orifice to obtain more flow impact with less cavitation? Possible with the pressure pumps we have? Get extremely close so that impact velocities can be assumed the same as orifice velocity (dist. < 6 x orifice dia.)?? Test is a good option as its cheap and fast, however it would be difficult or impossible to produce the needed velocities at a parallel angle without cavitation.
Colgate, D.	Resistance of Selected Protective coatings for Concrete to High-Velocity Water Jets HYD-543 https://www.usbr.gov/tsc/techreferences/hydraulics_lab/pubs/HYD/HYD-543.pdf	Tests were conducted to determine the resistance of two coatings for concrete to a 1-inch-diameter, 100 ft/s (unsubmerged) water jet that struck the coatings at an angle of 45°. The coatings were a random-glass-filament reinforced thermosetting polyester resin (plastic) and a flexible neoprene (synthetic rubber) membrane. The coatings were 1/8 inch thick and the testing was conducted on undisturbed coatings as well as on a sharp cut exposed edge and on an epoxy protected cut edge. The test time ranged from 5 minutes (exposed plastic edge failure) to 4 ½ hours (typical for un-failed coating). A few tests on an “unprotected cut edge of the coating (simulating a cracked or broken surface) the coating was removed from the concrete surface in less than 5 minutes”.

Selander, C.E.	Resistance to Cavitation Damage, Laboratory and Field Tests on Four Selected Coatings ChE-25	Report No. ChE-25, compared cavitation resistance test results from lab and field testing at Grand Coulee outlets on 4 selected coating types. Results did not correlate from the lab to the field. Coatings performed relatively well in the lab but did not hold up at all in the field tests. This was likely due to “several effects, such as tearing, delamination, and loss of bond……….which were not accounted for or found in the laboratory tests. These are attributed to the greater severity of the field exposure.” From photos of the field test it seems that those samples would be exposed to high shear & impinging flows as well as surface cavitation.

Data Sets that Support the Final Report

If there are any data sets with your research, please note:

- \\bor\do\Home\J\JMORTENSEN\Active Files\Research\Active Projects\Coatings Adhesion Test Development
- Josh Mortensen, jmortensen@usbr.gov, 303-445-2156:
- Spreadsheets, word doc literature review and report
- Keywords: Adhesion, coating system, hydrodynamics, penstock, pressure, uplift
- Approximate total size of all files: 14.8 MB