Evaluation of Maintenance Procedures for Bridge Spalling on Parapet Walls

Prepared by:
Richard Miller
Norbert Delatte
Sarah Mullins

Prepared for:
The Ohio Department of Transportation,
Office of Statewide Planning & Research

State Job Number 135313

March 2017

Final Report

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.	
FHWA/OH-2017-15			
4. Title and Subtitle		5. Report Date	
Evaluation of Maintenance Procedures for Bridge Spalling on Parapet Walls		March 2017	
		6. Performing Organization Code	
7. Author(s) (include 16 digit ORCID ID)		8. Performing Organization Report No.	
Richard Miller (U of Cincinnati) Norbert Delatte (Oklahoma State U) Sarah Mullins (U of Cincinnati)			
9. Performing Organization Name and Address		10. Work Unit No. (TRAIS)	
University of Cincinnati Department of Civil and Architectural Engineering and Construction Management P. O. Box 210071 765 Baldwin Hall Cincinnati OH 45221-0071			
		11. Contract or Grant No.	
		SJN 135313	
12. Sponsoring Agency Name and Address		13. Type of Report and Period Covered	
Ohio Department of Transportation 1980 West Broad Street Columbus, Ohio 43223			
		14. Sponsoring Agency Code	
15. Supplementary Notes			

16. Abstract

Deterioration of parapet walls is a concern to the Ohio Department of Transportation. Spalling of the parapets presents a danger as pieces of deteriorated concrete may fall onto the road below. The current repair method is to chip off the deteriorated concrete, however, this process may damage the sound concrete and leaves an unprotected surface. This project used a literature search to explore methods of concrete removal and protecting/sealing the remaining surface. It was determined that hydrodemolition was the most promising method of concrete removal as it does not damage the remaining concrete. This is most efficiently done with a robot and a robot was found that may work on vertical surfaces of the parapets. Literature and research on protectants/sealants shows a number of possible solutions, but there is no long term data on performance. One protectant, polyurea, appears promising. This material may not only seal the concrete but may provide a reinforcing barrier that might retain loose pieces of concrete.

17. Keywords		18. Distribution Statement	
Concrete, Maintenance, Parapet Wall, Spalling		No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161	
19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	40	

Form DOT F 1700.7 (8-72)   Reproduction of completed pages authorized

Evaluation of Maintenance Procedures for Bridge Spalling on Parapet Walls

Prepared by:

Richard Miller

Sarah Mullins

University of Cincinnati

Norbert Delatte

Oklahoma State University

March 2017

Acknowledgments

The research team wishes to acknowledge the guidance of the Technical Committee:

Disclaimer

References to specific products or brand names in this report are for illustrative purposes only and do not represent an endorsement of any brand or product.

<u>Table of Contents</u>

Evaluation of Maintenance Procedures for Bridge Spalling on Parapet Walls

Prepared by:
Richard Miller
Sarah Mullins
University of Cincinnati

Norbert Delatte
Oklahoma State University
March 2017

ABSTRACT

Deterioration of parapet walls is a concern to the Ohio Department of Transportation. Spalling of the parapets presents a danger as pieces of deteriorated concrete may fall onto the road below.   The current repair method is to chip off the deteriorated concrete; however, this process may damage the sound concrete and leaves an unprotected surface.   This project used a literature search to explore methods of concrete removal and protecting/sealing the remaining surface.   It was determined that hydrodemolition was the most promising method of concrete removal as it does not damage the remaining concrete. This is most efficiently done with a robot, and a robot was found that may work on the vertical surfaces of the parapets.   Literature and research on protectants/sealants shows a number of possible solutions, but there is no long term data on performance. One protectant, polyurea, appears promising. This material may not only seal the concrete but may provide a reinforcing barrier that might retain loose pieces of concrete.

INTRODUCTION

The Ohio Department of Transportation and the various Ohio local governments use over 1 million tons of road salt each year.   One of the consequences of this salt usage is the deterioration of concrete structures due to the corrosive effects of that salt.   The inevitable consequence of plowing highways is that salt laden snow ends up stacked against the bridge parapets, thus providing more contact with the salt than occurs on other parts of the structure where the salt can simply wash or drain off.

Parapet walls present a particular problem. They are relatively thin concrete members and are far more susceptible to cracking than thicker members. There is less room for error in the placement of reinforcing steel, meaning that inadequate cover can often be a problem.   Taken together, this means that parapets are more susceptible to cracking and corrosion problems than other members.   Parapets are also exposed on the top of the bridges. This makes them more susceptible to thermal cracking and freeze/thaw cycling.

Deterioration of parapet walls can lead to safety problems as pieces of the parapet can fall off into traffic. Maintenance crews must remove this concrete.   It is difficult to determine the extent of the distressed concrete to remove and to verify that the repair has been taken down to sound concrete.

Then, the question becomes what to do after the concrete is removed. Ideally, the damaged surface should be sealed or repaired but there is no clear direction on how this should be done. In addition to the concrete sealing/repair, it may also be necessary to address corroded reinforcement. Maintenance

crews must close traffic lanes to conduct the repairs and this presents additional safety problems. Thus, it is desirable to have any solution to the problem be one which can be implemented in the shortest period of time.

PROBLEM STATEMENT

Ohio Department of Transportation (ODOT) county maintenance forces are responsible for removing unsound concrete (spalling) on parapet walls and deck edges from bridges over traffic. The work entails setting up extensive traffic control zones followed by removing the unsound concrete with small pneumatic jack hammers. Once the unsound concrete has been removed a new exposed surface area has been created that is left unprotected from the deicing materials used during the snow and ice season.

The purpose of this research is to determine if there is a better way to remove the unsound concrete in lieu of pneumatic tools, the extent of removing unsound concrete before jeopardizing the safety of the bridge and the best method to seal/protect the newly exposed concrete surface to prevent further deterioration.

RESEARCH CONTEXT

1) A review of ODOT and local practices for repairing spalling on bridge parapets
2) Results of an extensive literature search on the topic of concrete repair in general and bridge parapet repair in particular.   This will include information from manufacturers and 3rd parties on protective materials.
3) An analysis of current materials, products, and technology available for bridge parapet spalling repair and prevention, including a "do nothing" base line alternative.
4) A critical evaluation of 1, 2, and 3, above.

BRIDGE PARAPET CONCRETE DETERIORATION MECHANISMS

Concrete durability depends on both the exposure conditions and on the properties of the concrete and reinforcement. Bridge parapets in Ohio are subject to harsh conditions, including multiple cycles of freezing and thawing and wetting and drying. The large scale use of salt and other deicing materials contributes to the harshness of the environmental exposure. Piling up of salt laden snow against parapets, melting over the course of hours or days, increases the moisture and chloride load into the concrete.

Deterioration mechanisms are reviewed in many sources, such as Emmons (1993) and Delatte (2009). Chapter 1 by V. Penttala in Delatte (pp. 3 – 31, 2009) reviews "Causes and mechanisms of deterioration in reinforced concrete." Physically induced deterioration mechanisms include freeze-thaw and cracking due to shrinkage and temperature changes. The concrete's susceptibility to freeze-thaw damage depends on its water/cement ratio, air content, void structure, and moisture exposure. A low water/cement ratio concrete provides good protection, but that protection is easily defeated by cracks. A sufficient air content can also provide good protection, as long as the air bubbles are of proper size (e.g. 0.02 – 0.05 mm) and properly spaced. Penttala also notes (p. 12, Delatte, 2009) that salts introduced into pore water can greatly increase freeze-thaw deterioration. The effect of salts is to draw more freezable water into the concrete to fill the pores. Thus, salt can be damaging to concrete even without causing reinforcement corrosion.

The effects of shrinkage and temperature change causes non-structural cracks in concrete, although structural actions such as unintended composite flexural stresses from bridge loading may have the same effect. Once cracks form, it is much easier for moisture and salts to penetrate deeply into the concrete, accelerating the deterioration.

A dense, low water/cement ratio concrete with sufficient air content may be able to resist saturation, as long as the concrete remains uncracked. However, any deficiency in air content or the occurrence of cracking is likely to initiate freeze-thaw damage. Higher strength concretes may also be stiffer (higher modulus of elasticity) and thus more brittle.

According to Emmons (p. 32, 1993) the degree of freeze-thaw damage is increased with increased porosity of concrete, increased moisture saturation, increased number of freeze-thaw cycles, horizontal surfaces that trap standing water, and aggregates with small capillary structure and high absorption, and reduced by air entrainment.

In discussing corrosion of reinforcement, Penttala discusses the importance of carbonation. "Carbonation of the surface layer of concrete does not damage concrete as such. It is important because it reduces the pH value in the pore water. This is a prerequisite for corrosion of steel reinforcement in situations when there are no chlorides in concrete pore water… if concrete is wet, carbonation of the reinforcement cover concrete can shorten the expected service lifespan considerably." (pp. 19 – 20, Delatte, 2009). Corrosion of reinforcement may be initiated either by carbonation or by chlorides.

Emmons (pp. 9 – 10, 1993) notes that corrosion is an electrochemical process that in effect makes a "battery" with an anode, cathode, and electrolyte. The electrolyte occurs within moist concrete, and different parts of the reinforcing bar create the anode and cathode. The reaction causes an increase in metal volume as iron becomes iron oxide (or rust) and the expansion is strong enough to crack concrete. Corrosion is inhibited by high quality concrete, and high pH concrete, and promoted by oxygen, water, stray electrical currents, uneven chemical environment around reinforcement, environments that lower pH, and chlorides. Cracking and spalling of the concrete over the reinforcement are influenced by the quality of the concrete and concrete tensile strength, as well as, bar size and distance to the surface. Corrosion is also increased by dissimilar metals, and perhaps differences in metal potential between reinforcement and VPF base plates could play a role.

It should be noted that freeze-thaw damage and reinforcement corrosion may be mutually reinforcing. Any cracks that open up due to either mechanism allow water and chlorides to penetrate more deeply into the concrete, thus aggravating the other mechanism.

OBSERVATIONS FROM A FIELD VISIT

On November 15th, 2016, the members of the UC research team visited District 6 to see typical examples of damage, deterioration and repair of parapet wall. The team met with Shawn Rostorfer and toured a number of bridge sites.

Figure 1 shows a typical spall. Here, the crews have simply removed deteriorated concrete. The cause of the spall appears to be that the reinforcing bar had been placed without sufficient cover and the corrosion of the bar has caused the concrete to debond.

Figure 1 - Typical spall with exposed bar

Figure 2 shows a somewhat different situation. Again, there is some exposed, corroded bar clearly placed too close to the surface.   However, there is also a large amount of spall where no corroded rebar is present. Normally, when there is a corrosion problem only, there is bar exposed behind all the spalling. Here, there are large areas of spall with no bar apparent. This does not necessarily mean corrosion is not a problem, as there may be badly rusted bar just below the surface, but the lack of exposed bar is a concern.

Figure 2 - Spalled concrete with some exposed bar, but with areas with no exposed bar.

Figure 3 another picture from the same bridge. In this case, the bar near the surface is apparent and deterioration is likely due to insufficient cover and corrosion.

Figure 3 - Damage due to corrosion

Figure 4 is a photo of another bridge. This photo is taken near the support; no concrete removal has taken place as it is not over a traffic lane. Note the occurrence of "map" cracking. Map cracking is not usually associated with rebar corrosion, but instead usually indicates a problem with the concrete itself. Map cracking is often the sign of some type of expansive failure. Common causes of map cracking are freeze/thaw deterioration, alkali/aggregate reaction (AAR a.k.a. alkali silica reaction; ASR) or delayed ettringite formation (DEF).

Figure 4 - Map cracking, no indication of corrosion

Figure 5 is another photo from the same bridge. There is corroded reinforcing bar, but it is clear that bar had sufficient cover. The corrosion may have occurred after the concrete had spalled away or it may have contributed to the failure. For bars with sufficient cover, it is usually not possible for chlorides to reach the reinforcing steel simply by permeation. Usually, it is necessary for there to be cracks which allow chloride ingress. The damage is consistent with some type of a freeze/thaw or AAR mechanism so this might have cracked the concrete, which then allowed chlorides to penetrate to the steel. Subsequent corrosion might have contributed to the failure.

Figure 5 - Severe deterioration with corrosion. The corrosion may have occurred after the concrete was damaged.

One of the more interesting bridges visited was the Sullivant Avenue Bridge. The bridge runs approximately east/west giving one side a southerly exposure and the other a northerly exposure. The side with the southern exposure was cracked and damaged as shown in **Figures 6-9**.

Figure 6 - Cracking on the parapet under a vandal fence support.

Figure 7 - Cracking on the parapet wall.

Figure 8 - Cracking on the south face of the bridge.

Figure 9 - Spalling on the south face of the bridge.

In **Figures 6-9** the deterioration does not appear to be related to any corrosion of the reinforcing bar; however, that is not possible to determine from a visual inspection. **Figure 10** is a picture of the north side of the bridge. Note the lack of damage. This was typical of the entire bridge; the north side showed no damage while the south side showed extensive damage.

Figure 10 - North side of the bridge is undamaged.

The extensive damage to the south side suggests a freeze/thaw mechanism. In Ohio, the sun is always to the south in the winter with a low declination. As a result, southern exposures are heated by the sun during the day while northern exposures are not. This will initiate many more freeze/thaw cycles for the southern exposures of structures while northern exposures receive far fewer and less severe cycles.

The field observations show a wide range of situations. In some cases, there is simple spalling of the concrete surface. In other cases, reinforcing bar is corroding due to insufficient cover. In still other

cases, there may be some fundamental problem with concrete.   These situations may require different approaches to repair.

CONCRETE SURFACE TREATMENTS

Penetrating Sealers [Includes pore liners and blockers, silanes, siloxanes, silicates, and siliconates]:

Penetrating sealers seep into the pores of concrete and then react chemically within the capillaries of the concrete to shield against moisture penetration and deicing chemicals.   They come in two basic types – pore liners and pore blockers. Pore liners (such as silane) are relatively small molecules that coat the inside of the pores to resist water penetration. Pore blockers are larger molecules that form substances that physically block the pores against penetration.   Both categories essentially protect the concrete in the same way.

Penetrating sealers are hydrophobic; that is, they cause water to bead like wax. Because they basically repel water, they prevent water intrusion into the concrete. In general, they do not seal cracks any larger than hair-line (0.002 in). Thus, their primary application of penetrating sealers is to protect and extend the life of new concrete or older concrete which has little or no damage.

It is generally believed that penetrating sealers provide excellent protection against outdoor exposure conditions. Most products are also breathable, allowing interior moisture vapor to escape. The main difficulty with penetrating sealers is that the surface needs to be cleaned and completely dried before the chosen sealant is applied (von Fey 2015).

The main advantage to penetrating sealers is that they are very inexpensive and easy to apply.   The Typical list cost of these sealers is about $40-$50 a gallon and typical coverage is 100-150 square foot/gallon; depending on the porosity of the concrete. An Illinois (Morse 2009) study found material costs of $0.10 to $0.40/sq ft.   These materials are easily applied by sprayer, brush or roller.   It is difficult to find accurate installed prices, but in general the installed price seems to be about $1.00 - $2.00 per square foot if installed by ODOT crews.

However, there is no long term durability data on penetrating sealers.   A paper by Christodoulou et al. (2013) looked at concrete pier caps that had been coated with silane approximately 20 years earlier. They found the silane was still effective, but since they had no baseline or application data, they were unable to determine how effective the material was.

Acrylics, Epoxies, Polyurethanes, HMWM and Polyureas:

Acrylics form a thin protective film on concrete surfaces. In general, acrylic coatings are thin and tend to wear faster than other coatings. Thus, they may not suitable for bridge parapet applications. While some manufactures offer acrylic coatings for bridges, it appears they are suggested for low or no traffic areas. No studies were found where acrylic coatings were tested for deck applications.

Epoxies also form a protective layer on the concrete surface, but they only penetrate about 1/16 of an inch (von Fay, 2015).   These materials can bridge and seal over existing cracks, although large cracks may need to filled with some other material prior to application of the epoxy.   Epoxies have limited ability to bridge cracks which form after application.

The cost of epoxies appears to be similar to penetrating sealers based on manufacturers' list prices, the Illinois study (Morse 2009) and data from Tennessee (Knight and Huddleston, 2016). Application is similar to the penetrating sealer in that it can be sprayed or rolled on. As with penetrating sealers, there is no long term data on epoxy durability.

There are also forms of epoxy/polymer overlays which the Illinois study referred to as "laminates". These may be anywhere from ¼ to 3/8 inch thick and are sprayed on. Data from Illinois (Morse 2009) shows they are about $2-$3 per square foot, but the Illinois study was on bridge decks and this cost includes a non-skid aggregate finish. However, the Illinois study indicated these materials did not have good performance against chloride intrusion after 5 years with delamination being a problem.

Polyurethanes are also used as bridge deck sealers. From the literature it appears that the cost and performance are similar to other epoxy and polymer sealers.

High molecular weight methacrylates (HMWM) are used as crack sealers on bridges. Usually they are used on bridge decks as they are gravity fed, but they can be rolled or brushed on (von Fey 2009). Von Fey states that the material will degrade due to UV light, so it is not a surface sealant, however, it is effective as a crack sealant. Johnson et al. (2009) and von Fey note that HMWM will penetrate much deeper than epoxies, but Johnson et al. cite research that indicates that epoxies have higher bond strength. Both Johnson et al. and von Fey state that consideration should be given to apply HMWM at night or early morning when cracks are open due to cooler temperatures as this will result in less stress on the material, because cracks open and close due to temperature changes. The cost of HMWM is similar to epoxies.

All of the products cited need clean, dry surfaces for application and cracks should be cleaned out before application. Since this is often done with water, Johnson et al. recommend that 2 to 3 days of drying may be needed before application.

Polyureas are a 2-component material that develops into a polymer compound by mixing a resin with a catalyst. Polyureas come in two types – aromatic and aliphatic; the difference is the shape of the molecule (aromatics are cyclic, like benzene, while aliphatics can be cyclic or straight). There is a variation of the aliphatic polyurea known as a polyaspartic. The main difference is that both aromatic and aliphatic polyureas generally need to be sprayed on using a special mixing nozzle, because the material sets very fast (i.e. has a short "pot life"). Application requires a skilled worker and literature suggests that full body protective equipment, similar to that used in paint shops, is required. Polyaspartics are formulated to have a longer pot life allowing them to be sprayed, rolled or brushed onto a surface. Although both aromatic and aliphatic (including aspartic) are offered for use in coating concrete, it seems that the aliphatic is more common as it is does not degrade under ultraviolet light and is color stable. However, aromatics are cheaper and easier to apply. Several manufactures note that aromatic base coats can be covered by aliphatic top coats to provide color and UV stability.

Once applied, polyureas form a plastic or rubber like coating on the surface. On line literature suggests that spray on coatings can be as thick as 500 mils (1/2 inch), but most literature seems to suggest that typical thicknesses are 20 to 100 mils (0.02 to 0.1 inch).

The advantages to this type of material are as follows:

1) Polyureas are abrasion resistant and are used as sprayed or rolled on truck bed liners. This would likely make them resistant to abrasion from salt laden snow pushed up against parapet walls.
2) This material seems to exhibit a superior bond and bonds to concrete, masonry and steel. This means the material could be installed over exposed steel. Manufacturers suggest the steel should be cleaned and the coating will not necessarily stop further corrosion if the source of corrosion is internal. It will bond over existing coatings (acrylic, epoxy or urethane) if those coatings are sound (in fact, one manufacturer recommends using an epoxy primer with concrete).
3) They are resistant to most common chemicals, like chlorides, and are resistant to humidity and temperature changes. Polyureas are often used to protect marine structures.
4) Polyureas will seal the surface, preventing water, chlorides and other substances from penetrating the concrete.
5) The material can bridge and seal cracks. Specifically, the literature suggests that this material has a high level of elasticity which not only allows it to bridge cracks but to accommodate movement of the crack during normal temperature cycles. This property may be valuable for cases where some internal mechanism (freeze/thaw or corrosion) opens the cracks. Manufacturers indicate a crack sealing capacity of 1/8 inch. Larger cracks need to be filled with a joint sealing material.
6) Polyureas have been demonstrated to provide a degree of reinforcement to concrete and masonry structures. Davidson et al. (2004, 2005) showed that polyureas applied to masonry walls can provide a degree of blast resistance and several manufactures sell "blast resistant" formulas. Davidson et al. suggest that polyureas are a good substitute for carbon fiber wrapping for reinforcing existing structures against blast attack. The importance here is that polyureas may be able to contain the fragments of concrete from a deteriorating structure, thus preventing them from falling to the road below.
7) The material appears to be repairable.
8) The literature suggests that polyurea coated concrete can withstand freeze/thaw cycling and salt fogging.
9) The material can be applied over a wide range of temperatures; from -30 to +140°F. It also sets almost immediately so that multiple coats can be built up at one time.
10) Polyureas can be colored or left clear.

The drawbacks are:

1) The installed cost of the material is $3-$7.50/sq. ft. This much more expensive than other materials such as epoxies which are about $1-$2/ sq. ft.
2) For many polyureas, special spray equipment is needed for application.
3) As is true for all coatings, the surface needs to be prepared and cleaned.
4) As it true for most coatings, the material will not bond well to wet surfaces.
5) If spray on polyuria is used, training is required for the workers. Manufacturers offer this training, but the training takes 10 days.

The main problem with polyureas is the cost. It is very difficult to get accurate cost information because the cost depends on the material, application method and thickness. Aromatic polyureas are $25-$45/gallon while the higher performing aliphatics are $60-$140/gallon. Coverage depends on thickness and application method but it appears the installed material may run about $3 to $7.50 per

square foot. In fact, one of the drawbacks of the material listed by Davidson, et al. (2004, 2005) was the expense of the material.

For sprayed on polyureas, the most common machine is high pressure spray equipment which are high volume and have high heating capabilities. They cost between $20,000 - $40,000. Manufacturers recommend either using a contractor or having personnel trained.   Lower cost joint fill and "cold" spray equipment utilizes static mixers and operates with lower outputs and pressures. Average pricing is $5000 - $15000.

Although polyurea is marketed as a bridge deck sealing material, a search did not show any studies on the effectiveness or long term durability of the material.

LITERATURE SEARCH RESULTS

A review of literature did not locate any studies on concrete surface treatments for protection of bridge parapet walls. Most of the studies found were on bridge decks. One was found that focused on pier caps (Christodoulou et al. 2013). These studies largely focus on sealing the concrete against further chloride intrusion.   The main differences between the deck and parapet problems are:

- Decks are horizontal surfaces where gravity works in favor of the application, drawing the material into the surface not away from it. For parapets, gravity works to pull the material down the vertical surface. This makes it difficult to work with low viscosity materials and/or thick coatings.
- Decks are subject to tire wear and need to be skid resistant, so most of the studies had some testing related to this and may have eliminated a product due to poor abrasion or skid resistance properties. Parapets are not subject to the same type of wear and skid resistance is irrelevant.

None addressed the problem of reinforcing bar corrosion or what to do when there is an exposed reinforcing bar.   Most of the studies found address new construction and/or coating existing structures to prevent possible corrosion.   The research team was able to locate a few studies that address repair of structures with corroded reinforcing bars (FHWA 1998; FHWA 2001; Sohanghpurwala et al. 2002) and some general repair guides (ACI 1994; von Fay 2015; Emmons 1993).

In general, all of the studies on coatings followed the same methodology.   Various products were researched for their properties and possible application to the problem. A certain number of products or product types were selected for further testing.

The products were tested under laboratory conditions. These testing methods varied. In many cases, standard ASTM or AASHTO tests were used. The most popular test was ASTM C1543 (AASHTO T259), Standard Test Method for Determining the Penetration of Chloride Ion into Concrete by Ponding. Basically, standard test specimens were made and some were coated and some control specimens were not.   The specimens were then subject to the ponding test and the depth of chloride penetration was measured. In some studies (Pincheira and Dorshorst (2005)) some of the coated specimens were subjected to some type of damage (freeze-thaw or abrasion) prior to testing.   Rapid Chloride Permeability (ASTM C1202) was also used (Almusallam, et al. 2003).

Another test was the cube test, often referred to as the NCHRP 244 test (Pfeifer and Scali, 1981). Here, 4 inch by 4 inch cubes are coated with sealant and submerged in salt water. The cubes can also be broken into 4 parts and checked for depth of sealant penetration. Dunn (2005) reported on variations of this test and also tested damaged coatings.

After laboratory testing identified potentially useful products, the products were placed in the field and monitored for some time. Unfortunately, none of the studies monitored the materials for more than a few years, with about 5 years being the maximum. Christodoulou et al. (2013) did check some concrete cross beams (pier caps) that had been treated with silane 20 years earlier and similar untreated beams. Unfortunately, there were limited records on the construction of these bridges so the authors were not 100% sure when or how the sealant was applied. The results did show the silane was still provided some protection after 20 years, however the effectiveness of that protection was not stated.

In general, the results from literature are mixed.   Bahsheer et al. (1997) did a comprehensive literature search of the studies conducted up to that point, looking at different characteristics of sealants. The common method of assessing a sealant's resistance to water penetration is to coat a specimen, submerge it in salt water and then measure weight gain (basically the NCHRP 244 test). There were a number of reported variations on this method. The NCHRP 244 (Pfeifer and Scali 1983) report recommends a sealant to be considered effective if it reduces absorption by 75% over a control specimen. However, Basheer et al. note that this is not universally accepted value for this test and various agencies simply make up their own value.

For chloride penetration, the usual testing methods are ponding tests (AASHTO T259 or similar), rapid chloride permeability (AASHTO T277), saltwater spray tests or shallow immersion in a salt water solution (the entire specimen is not submerged, just some portion of it).   The chloride intake of sealed specimens is compared to unsealed, control specimens.   Again, the authors note that there is no accepted standard for determining the effectiveness of the sealant and cite different sources using anywhere from a 25% to 95% reduction of chloride intake as acceptable. Bahsheer et al. also noted that reported laboratory results differed significantly from actual field performance, and they cautioned the reader against relying solely on laboratory studies.

For corrosion protection, Bahsheer et al. concluded that there was insufficient research available to make a conclusion on the ability of a surface sealant to prevent corrosion. Another consideration was durability of the sealer. One suggested criterion is surface penetration. However, this is only applicable to those sealants (such as silane) that actually penetrate the surface. Most sealants are coatings with no appreciable penetration.   The other criterion is resistance to weathering. This would include resistance to UV light, abrasion, freeze/thaw cycles, repeated wetting and drying and temperature. Bahsheer concluded that there are no accepted criteria for determining the weathering resistance of coatings. Finally, as noted above, Bahsheer et al. stated that there is a lack of long term durability field testing on these materials so the long term reliability is not known.

The summary by Bahsheer et al. was published in 1997. A few more recent reports have been found. A Colorado DOT report (Liang, et al. 2014) tested silane, two different epoxies and a high molecular weight methacrylate (HMWM) for sealing bridge decks. The report concluded silane was the least effective. The epoxies were effective but showed some loss of effectiveness after one year. The HMWM was judged best, but, again, the study time was short; about 3.5 years.

A more thorough and perhaps more relevant, study was done in Wisconsin (Pincheira and Dorshorst 2005). Here, a number of different surface sealers and crack sealers were tested. There are two main conclusions that are particularly relevant to this study:

1) Depth of penetration is important. Not only have previous studies shown that deeper penetration provides better protection, but also sealants with shallow penetration depths tend to not survive abrasive environments.
2) Freeze/thaw testing is necessary. The study found that many sealants that passed standard laboratory tests failed when exposed to freeze/thaw cycles.

Unfortunately, the Wisconsin study was only a laboratory study, so actual field performances or the sealants were not assessed.

Dunn (2005) tested four epoxies and one sodium silicate sealer. All were tested under laboratory conditions using the NCHRP cube test and variations on the cube test. The significance of this study is that it tested the sealers using three different mix designs, representing a historical Alabama DOT bridge deck mix and two modern ALDOT mixes, one with and one without fly ash. One conclusion was that there was variation of sealer performance with the different concrete mixes. This is logical if the different concrete mixes have different porosity structures.

There was little information and no studies found regarding the application of sealers to deteriorated concrete structures.

Based on the literature, the conclusions on sealant protection are:

1) There are no accepted criteria for determining the effectiveness of a sealer for any given application.
2) There are no accepted criteria for determining the ability of a sealant to resist environmental factors such as abrasion or weathering.
3) There does not appear to be any reliable correlation between the results of laboratory tests and actual field performance.
4) Data on the long term durability or performance of sealants is practically non-existent.
5) Data on particular types of sealants is inconsistent, that is, one study may conclude a particular type of sealant is effective and the next may draw an opposite conclusion. This may be due to a number of variables which might affect the sealant performance. Various studies have noted that the concrete mix design and/or moisture content are factors. Additional factors include surface condition, surface preparation, application method, number of coats and temperature/weather conditions at time of application.

Repair of Areas with Corroded Reinforcing Bars

Two studies were located on repair of deteriorated areas due to corrosion, both by FHWA (1998, 2001). Both concluded that patching concrete over corroded reinforcing bar was, by itself, ineffective, even if the patches contained corrosion inhibitor (FHWA 2001). The 2001 study concludes that the problem is that the patches shrink and crack, thus allowing chloride laden water to penetrate the patches.

This is supported by several general studies and guides on corrosion of reinforcing bars (Bertolini et al., 2013; Vaysburd and Emmons, 2000 and 2004; von Fay, 2015). An additional problem, noted in these

same studies, is electrochemical incompatibility. If the patching material and the original concrete have different electrical potentials and a bar is partially embedded in both materials, an electrochemical corrosion cell can be created; especially if water and chlorides penetrate the perimeter of the patch.

Vaysburd and Emmons (2000) suggest different methods of addressing repair of corroded rebar.

1) The bar can be cleaned and the area patched. This is the easiest repair, but as noted above, the least effective.
2) The bar can be cleaned, coated with epoxy and the area patched. This is a fairly simply repair that provides a protective coating to the bar. This cannot be accomplished in one step as the epoxy needs to cure before the patch is applied.   While better than doing nothing to the bar, epoxy coating has its difficulties. If there are any voids or pinholes in the epoxy (holidays), corrosion at these sites may be accelerated. Epoxy is also known to reduce bond strength to the patch.
3) The bar can be cleaned, coated with a cement mortar and the area patched. This is a fairly simply repair that provides a protective coating to the bar. If a fast setting coating is used, this could be accomplished in one day. The protection works by providing a highly alkali layer around the bar. The coating also bonds well to the patch. However, this material is still permeable to chlorides.
4) The bar can be cleaned, coated with a sacrificial coating and the area patched. The coating is usually a zinc rich primer that provides a level of cathodic protection. However, the effectiveness of this repair is not known.
5) The bar can be cleaned and the area patched with a mortar containing corrosion inhibitor. As previously noted, FHWA (2001) did not find this to be effective but this was only one study and it was found that problem was shrinkage of the patches. If low shrinkage material is used better results may be obtained.

Use of surface applied corrosion inhibitors has also been studied (ElHacha et al. 2011; Zheng et. Al. 2012).   Surface-applied corrosion inhibitors work in two phases. One phase, usually amino alcohol, migrates to the steel surface to form a protective layer. Another phase, usually an acid, reacts with the cement to form calcium salts that block the pores.   Zhang et al. (2012) tested cubes for water absorption, chloride penetration and carbonation.   As would be expected, the inhibitors were less effective for higher w/c cement ratios where pores are larger. El Hacha (2011) both cracked and uncracked concrete specimens containing rebar. They concluded that the products were effective even in cracked specimens, but the cracks were hairline so there is no information about larger cracks. They found all of the products delayed, but did not prevent, corrosion. Initial chloride contamination of the concrete was a factor with more corrosion occurring in specimens with higher initial concentrations. Both studies were laboratory studies and stated that more research should be conducted to determine the effectiveness of surface-applied corrosion inhibitors.

Removal of Existing Concrete

The most common method for removing failing concrete is an impact method (e.g. jackhammering) (ACI 546R-04, 2004; von Fay, 2015). Other methods include high pressure water methods, such as water jet hand lances and hydroblast/ hydrodemolition, and abrasive removal, such as sandblasting or shotblasting. Many of these systems are designed for flatwork, e.g. bridge decks, slabs and pavements, and are not really suitable for vertical surfaces such as parapets.

Impact methods are probably the most practical for parapets.   The equipment used is small and handheld.   It is noted (ACI, 2004; Bertolini, et al. 2013; Von Fay, 2015) that the problem with impact methods is that they tend to damage to sound concrete by causing micro-fractures. Thus, any repair may fail because the damaged substrate may eventually fail due to this micro-fracturing. Impact hammers may also damage reinforcing bars. Von Fay recommends the use of a 15 to 30 pound hammer. Both Von Fay and ACI note that anything larger tends to damage the base concrete. The use of a sharp, pointed bit is also recommended over a spade bit. Spade bits are only recommended near saw cuts.

Von Fay notes that shotblasting is very effective at removing damaged concrete, but it is completely impractical for vertical surfaces (a search showed that all shotblasting equipment is made for horizontal surfaces) and is most effective at removing less than ½ inch of concrete.   Sandblasting can be used, but it is only economical for removing less than ¼ inch of concrete, and there is the problem of how to contain the sand (ACI 2004).

Hydrodemolition is very effective at removing deteriorated concrete. It has the added advantage of not damaging the concrete substrate or reinforcing bars. Most hydrodemolition equipment is made for horizontal surfaces. Robotic equipment for vertical surfaces is available but these are expensive and many have limited height range (< 25 feet).   Hand held lances are also available, but they are not as effective as the robots and are, in general, recommended for small area removal or for areas that are hard to access. The limitation is that humans can tolerate less reactive force than mechanical devices. One manufacturer noted that the maximum reaction for hand held lances is 250N (56 pounds) whereas robots are designed for forces of 1000 to 4000N (225 pounds to 900 pounds). ACI does note that hand held lances can be used but provides no guidance on their effectiveness.   One drawback to hydrodemolition is that the waste water must usually be controlled and treated (von Fay) and this may make the systems impractical for parapets.

Some recently developed hydrodemolition equipment may be suitable for parapet walls.   As noted, hydrodemolition generally needs to be done by a robot to be most effective. Three products have been found that may work with parapet walls: the CONJET 327, 367 and 557.   The 327 model is shown in **Figure 11**. **Figure 12** shows the accompanying power unit, and **Figure 13** shows the 327 model in use on a bridge.

Figure 11: CONJET 327 (Graphic courtesy of National Hydro, Inc.)

Figure 12: Power Unit (Graphic courtesy of National Hydro, Inc.)

Figure 13: CONJET 327 used on a bridge railing (Photo courtesy of National Hydro, Inc.)

All three robots have a flexible arm which gives them the capability to reach over the side of the bridge for hydrodemolition of the outside of a parapet wall if no vandal fence is present. If a vandal fence is present, the machine can be modified with a boom that will reach about 22 feet so that the outside of the parapet can be accessed from below.   A manufacturer's representative indicates that the CONJET 327 is small enough to place on a scissor lift platform to extend the vertical reach. The demolition head is about 7 feet wide, but the width of the cut can be adjusted to fit the parapet wall (see Figure 13). The difference between the three units is size, tracks vs. wheels and the 557 is available as diesel or electric unit whereas the 327 and 367 are only electric.   The 327 would likely be the best choice as it is the least expensive, has the largest vertical reach at 22 feet and is small enough to place on a lift for higher surfaces.

The manufacturer indicates the unit will operate under pressures at the head 11000 to 22000 psi.   The actual removal depends on how high the pressure is and how long the pressure is applied to a given spot.   The lower end of the pressure rating with a short time of application might be suitable for surface preparation before a coating is applied.

The unit is completely remote controlled, and a power unit is required. This power unit is about the size of a 20 foot shipping container. It contains the generator and water pumping units (Figure 12).

The main drawback to these units is in regards to the control of water and debris. The manufacturer's representative did indicate that some contractors use large, suspended buckets under the unit to catch the water and debris, but the practicality of this for a bridge would need further study.

Spent water is considered a hazardous waste by the Ohio Environmental Protection Agency. The spent water must be collected so it does not drain into streams or waterways.   Ohio EPA requires the water to be treated or allows land application with proper permits.   CONJET sells a water treatment/recycling system but it must be determined if this meet regulatory requirements.

It should be noted that the CONJET units can be used for other applications such as bridge decks, abutments and piers.

APPROXIMATE COST:
Robot - $115,000- $190,000
Pump Unit - $225,000
Miscellaneous Equipment (hoses, spare parts) - $10,000

It does appear the equipment can be rented but the closest rental place is in Michigan near Ann Arbor.

Determination of the Depth of Removal

All of the repair guides require removal of unsound and contaminated concrete. Unsound concrete is concrete that is cracked and/or debonded. Ideally a concrete removal method will remove all unsound concrete while leaving sound concrete in place. In practice, this is difficult to achieve as there may not be a clear boundary between sound and unsound concrete, but rather a more gradual transition zone. To determine when the concrete becomes sound, von Fay (2015) recommend the simple use of a hammer or large metal object.   Unsound concrete will usually sound hollow or "drummy".   The difficulty with this method is that it will not detect any deep delaminations, but it may be acceptable for maintenance situations.   Von Fay notes "Good quality concrete develops a distinct ring from a hammer blow, and the hammer rebounds smartly. Low quality concrete resounds with a dull thud and little rebound of the hammer." The Schmidt Rebound Hammer may also be useful. This device uses a spring loaded impactor and a weight. The rebound of weight gives an indication of the relative quality of the concrete; high rebounds indicate better quality. The Schmidt Hammer is not particularly accurate in determining concrete strength, but is very useful for comparisons within a structure. Thus, a rebound reading in an area known to be sound can be compared to the rebound in the repair area to see if sound concrete has been reached.

Contaminated concrete presents a totally different situation. There are two basic mechanisms for corrosion – carbonation and chloride intrusion.   When cement particles hydrate, calcium hydroxide (CaOH) is formed as a byproduct.   This makes the concrete alkali and the alkalinity causes the formation of a "passive layer" around the reinforcing steel.   Over time, exposure to carbon dioxide in air will cause the calcium hydroxide to convert to calcium carbonate ($CaCO_3$). This reduces the pH and the passive layer will be lost.   To prevent corrosion, carbonated concrete should be removed. Fortunately, there is

23

a simple test for carbonation. An alcohol based solution of phenolphthalein is sprayed on the concrete. Carbonated areas do not change color but non-carbonated areas (pH $\geq$ 9) turn pink.

Chloride contamination is a more difficult problem. It is assumed that chlorides will cause corrosion of reinforcing bars when a certain concentration of the chlorides, called a "threshold" value, is reached. However, there is no accepted standard for this threshold and it may be variable depending on the concrete (Bertolini, et al. 2013). Even if a threshold value were available, there is no easy or practical method of determining chloride content in the field. Chloride contents are usually determined by laboratory analysis. The problem is that if the chloride contaminated concrete is not removed, corrosion of the reinforcing bar may continue (FHWA 1998). In a rehabilitation situation, where the structure can be closed for a period of time, it might be practical to try to determine when chloride laden concrete is removed, but in this is not practical in a maintenance situation. Thus, the possibility of further corrosion due to chloride contamination might simply have to be accepted in this case.

Analysis and Recommendations

The problem with parapet walls is largely due to cracking, which occurs after the walls are cast. The problems seem to be:

1) Shrinkage and temperature cracking not controlled by the saw cut joints which leads to corrosion of the reinforcing bars.
2) For some older parapets, cracking of the cap due to a poor detail (since corrected) (Bazzo, et al. 2013a and 2013b)
3) Freeze/thaw deterioration of the concrete.

Recommendations:

1) Continue to seal new parapets with epoxy. This is a cost effective sealer and immediate sealing will help to prevent chloride intrusion. Silanes are not recommended as they have no ability to bridge cracks and may prevent bonding of future surface treatments. It is important that the surface be properly prepared prior to application. However, it must be noted that epoxies have a limited ability to bridge cracks which form after application. As experience has shown, epoxy coated parapet walls will exhibit open cracks in service.
2) After a year when most of the shrinkage will have occurred, reseal cracked areas of the parapets with epoxy. It is recommended this be done during cooler temperatures when the cracks are open. Cracks could be sealed with high molecular weight methacrylate, but while studies show HMWM penetrated deeper, epoxy bonds better, is compatible with the current coating and is easier to apply. Wide cracks should be washed out prior to application. The parapet needs to be clean and dry prior to application of epoxy.
3) If there areas of spalling, remove the spalling with a chipping hammer and reseal with epoxy.
4) Studies have shown that not all epoxy coatings are freeze/thaw resistant. It is recommended that the Office of Materials Management qualify (or request qualification) of epoxy coatings. Specimens should be coated with epoxy and subjected to AASHTO T161 (ASTM C666) – Resistance of Concrete to Rapid Freezing and Thawing. It is recommended that both coated and uncoated specimens be tested for comparison. Note that the research shows that simply qualifying epoxies, in general, is not sufficient. It is necessary to qualify specific products.
5) Parapets should be recoated periodically. Estimates of the life span of epoxies vary from 5 years to 20 years but these are estimates – there is no long term data on epoxy life.

6) For parapets that exhibit extensive cracking, spalling or deterioration, consider using a polyurea coating. Ideally, polyurea could be an excellent coating for all parapets, but it is expensive compared to other systems. Depending on the application and material used, it can be 3 to 7 times as expensive as epoxy. Thus, polyurea might be an excellent choice for parapets with more damage than an epoxy can seal but not so much damage that replacement is necessary. Polyureas will bond over existing coatings, fill and bridge cracks. Polyureas will also provide some level of exterior reinforcement with some studies likening them a carbon/fiber wrap. This may temporarily prevent loose concrete from falling from the parapet until a repair can be made. The material is "repairable" and can be reapplied to deteriorated areas. It is recommended that polyaspartic polyureas be explored first. These are easily applied with brushes or rollers. Spray-on polyurea may provide better protection, but the application process is more complex.

7) For concrete removal in small areas, literature shows that simple chipping hammers are best. Other forms of removal (sandblasting, shotblasting or hand held hydrodemolition) will only remove small amounts of concrete and are more cumbersome than chipping.

8) For removal of large areas of damaged concrete, robotic hydrodemolition can be used. There are robotic hydrodemolition machines which can work on the interior vertical surfaces of the parapet and reach over the side of parapet walls without a vandal fence. For parapets with fences, the robot can reach as high as 22 feet. For larger heights, it can be placed on a scissor lift. The equipment is expensive; the complete system runs about $350,000. It does appear the equipment can be rented but the closest rental appears to be in Michigan. The problem of containment of water and debris from the demolition needs to be solved. In Florida, large buckets were hung from the side of the bridge to contain debris.

On the next four pages, two matrices compare alternatives for concrete removal and for parapet surface treatment. For concrete removal, the "do nothing" option is not available because leaving the deteriorated concrete in place represents a risk to the traveling public. The two alternatives are the current practice (chipping hammer) and the hydrodemolition robot. Hand lances are not practical for this application. The comparison criteria are worker safety, public safety, and cost, and the advantages and disadvantages of the two approaches are enumerated.

Matrix two compares alternatives for treating the parapet once the concrete has been removed. All of the alternatives could be used following either chipping or hydrodemolition. The comparison criteria are worker safety, public safety, cost, and projected service life following the treatment (if any) and the advantages and disadvantages of the two approaches are enumerated. The cheapest and easiest practice is to do nothing, which is often the current practice, but parapet deterioration may continue or even accelerate due to the newly exposed surfaces. Another alternative is to contain falling concrete with netting, as was observed at one bridge during the field visits. Finally, epoxy sealers and polyurea are compared. It should be noted at this point that polyurea, while technically very promising, has yet to be proven in the field for this application.

(This page intentionally left blank)

MATRICES

Matrix 1: Concrete Removal

Alternatives	Comparison criteria			
	Worker Safety	**Public Safety**	**Cost**	**Advantages/Disadvantages**
Chipping hammer (current practice)	Higher risk – 1. Workers must be at arm's length from parapets to use hand tools; 2. Workers must be on lifts for exterior surfaces; 3. More workers are required.	Higher risk – 1. Chipping damages substrate concrete increasing the risk of pieces coming loose in the future. 2. Chipping damages reinforcing or the bond between the reinforcing and the concrete; limiting the ability of the steel to properly reinforce the structure.	Estimated $5,890 per night, estimated 1 to 4 nights for removal: Total $5890 - $23,560. Because chipping damages the concrete, this cost is likely to reoccur every 1-3 years.	Advantages 1. Initial equipment costs, operating costs and equipment maintenance costs are low. 2. Equipment is currently available in the ODOT inventory. 3. Equipment is easily transported. 4. Debris is not hazardous. 5. Most cost effective for removing small areas of deterioration. Disadvantages 1. May not remove all the unsound concrete or may remove sound concrete. 2. Likely to damage reinforcement. 3. May be difficult to adjust depth of removal. 4. Damage to sound concrete may lead to continual deterioration resulting in the need to revisit the same structure within 1-3 years.

Alternatives	Comparison criteria			
	Worker Safety	**Public Safety**	**Cost**	**Advantages/Disadvantages**
Hydrodemolition robot	Lower risk – 1. Robot is remote controlled, operator can be out of traffic and away from demolition; 2. Workers do not need to be on the lift with the robot for outside surfaces; 3. Fewer workers are needed.	Lower risk – 1. Hydrodemolition limits damage to substrate concrete making it less likely pieces of concrete will fall off in the future. 2. Hydrodemolition does not damage reinforcing or the bond.	Estimated $6780 per night, but removal time is 2 to 3 nights per bridge. Total $13560 - $20340. Because hydrodemolition does minimal damage to the concrete, this far less likely to be a reoccurring cost	Advantages 1. High pressure water can reliably remove deteriorated concrete only without damage to sound concrete. 2. Pressures and dwell time can be adjusted to optimize removal. 3. Does not damage reinforcing. 4. Since damage to sound concrete is limited, hydrodemolition may increase the time before it is necessary to return to the bridge for more maintenance. 5. Most cost effective for removing large areas of deterioration. Disadvantages 1. Initial equipment costs, maintenance costs and operating costs are high. 2. Equipment not currently in inventory; must be purchased. 3. Equipment is large and harder to transport. 4. Spent water is considered a hazardous waste which must be treated or disposed of properly.

Matrix 2: Surface Treatments

Alternatives	Comparison criteria				
	Worker Safety	**Public Safety**	**Cost**	**Projected service life**	**Advantages/Disadvantages**
Do nothing	No exposure	Higher risk – pieces of concrete can fall on traffic.	None	Short – exposed concrete and rebar starts deteriorating rapidly. Loose pieces of concrete can fall into traffic.	Advantages 1. Zero cost. Disadvantages 1. Does not stop deterioration. 2. Does not contain falling pieces of concrete.
Netting	Relatively short term – depends on time to attach and install net. Shorter exposure time than coatings.	Moderate risk – netting catches falling concrete but does not stop deterioration of the parapet.	Recent ODOT contract - $27/sq. ft installed.	Short – exposed concrete and rebar starts deteriorating rapidly. However, loose pieces will not fall into traffic.	Advantages 1. Low cost. 2. Contains falling concrete. Disadvantages 1. Does not prevent deterioration. 2. Aesthetically unpleasing.
Epoxy Sealer	Moderate risk – workers must be at arm's length from parapets to spray or brush on liquid materials but material is not hazardous.	Higher risk – sealers do not prevent pieces of concrete from falling on traffic.	Relatively low at approximately $2-$3 per square foot, applied	Probably 5 years or less. Little information available on long term performance. Some brands perform poorly under freeze thaw cycles.	Advantages 1. Low cost. 2. Easily applied. 3. Will seal existing cracks. 4. Repairable Disadvantages 1. Limited ability to bridge cracks which form after application. 2. Will not contain loose concrete. 3. Limited service life (perhaps 5 years).

					4. Very sensitive to application conditions – requires a clean, dry surface. May peel if surface is not prepared properly.
Polyurea	Higher risk – workers must be at arm's length from parapets to spray or brush on liquid materials. Workers need protective garments.	Lower risk (?) – Research indicated that polyureas may behave as an exterior reinforcing material. This may contain loose concrete.	High at $ 3 to $ 7.50 per square foot, applied	Projected 10 years (+). No data are available on lifetime of these products for this application	<u>Advantages</u> 1. Forms a protective coating. Thickness can be chosen to fit application. 2. May be reinforcing and contain loose concrete. 3. Has high elasticity and can bridge cracks which form after application. 4. Adheres to concrete and steel; can be placed over existing coating. 5. Repairable. <u>Disadvantages</u> 1. Much more expensive than other coatings. 2. Some forms require special spray guns for application and the use of protective suits.

REFERENCES

ACI 546R-04 (2004); "Concrete Repair Guide," American Concrete Institute, Farmington Hills, MI.

Almusallam, A. A.; Khan, F. M; Dulaijan, S. U.; Al-Amoudi, O. S. B (2003); "Effectiveness of surface coatings in improving concrete durability"; Cement & Concrete Composites, 25, 473–481

Basheer, P. A. M; Basheer, L.; Cleland D. J.; Long, A. E. (1997) "Surface treatments for concrete: assessment methods and reported performance," Construction and Building Materials Vol. 11, NOS 7-8, pp. 413-429.

Bazzo, J., Delatte, N., Kalabon, A. (2013a), "Uncontrolled Concrete Bridge Parapet Cracking," State Job No. 134602, Federal agreement number E111176, Ohio Department of Transportation, June 2013.

Bazzo, J.; Delatte, N.; Kalabon, A., (2013b) "Forensic Investigation of Uncontrolled Concrete Bridge Parapet Cracking," TRB 92nd annual meeting, January 2013.

Bertolini, L.; Elsener, B.; Pedeferri, P.; Redaelli, E.; Polder, R.; (2013) *Corrosion of Steel in Concrete: Prevention, Diagnosis, Repair, Second Edition,* Wiley-VCH Verlag GmbH & Co. KGaA.

Christodoulou, C; Goodier, C. I.; Austin, S. A.; Webb, J.; Glass, G. K. (2013) "Long-term Performance of Surface Impregnation of Reinforced Concrete Structures with Silane," Construction and Building Materials 48 708–716.

Davidson, J. S., Porter, J. R., Dinan, R. J., Hammons, M. I. and Connell, J. D., (2004) Explosive Testing of Polymer Retrofit Masonry Walls, Journal of Performance of Constructed Facilities, Vol. 18, No. 2.

Davidson, J. S., Fisher, J. W, Hammons, M. I., Porter, J. R. and Dinan, R. J. (2005) Failure Mechanisms of Polymer-Reinforced Concrete Masonry Walls Subjected to Blast; Journal of Structural Engineering, ASCE Vol. 131, No. 8.

Delatte, N.J. (2009) Failure, distress, and repair of concrete structures, Woodhead Publishing Limited/CRC Press LLC

Dunn, J. R. (2015) *Performance of Concrete Bridge Deck Sealers*, A Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in the Department of Civil, Construction, and Environmental Engineering in the Graduate School of The University of Alabama, Tuscaloosa, Alabama.

El-Hacha, R; Mirmiran, A.; Cook, A.; Rizkalla, S, (2011) "Evaluation of Surface Applied Corrosion Inhibitors for Concrete Bridges", Journal of Materials in Civil Engineering, Vol. 23; No. 3.

Emmons, Peter H. (1993) *Concrete Repair and Maintenance Illustrated,* R.S. Means

Federal Highway Administration (1998); *Corrosion Protection – Concrete Bridges;* Publication No. FHWA-RD-98-088; (no authors listed); http://www.fhwa.dot.gov/publications/research/infrastructure/structures/98088/index.cfm#toc.

Federal Highway Administration (2001); *Long-Term Performance of Corrosion Inhibitors Used in*

Repair of Reinforced Concrete Bridge Components; Publication No. FHWA-RD-01-097; (no authors listed); https://www.fhwa.dot.gov/publications/research/infrastructure/pavements/ltpp/reports/01097/pdf/01097.pdf

Johnson, K., Schultz, A. E., French, C. E., and Reneson, J.; (2009) *Crack and Concrete Deck Sealant Performance*, Minnesota Department of Transportation, Report MN/RC 2009-13.

Knight, M. and Huddleston, J. (2016); Use of Thin Overlays on Tennessee Bridges; presentation; http://midcon2016.engr.wisc.edu/wp-uploads/2016/11/5-C-Knight.pdf

Liang, Y.; Gallaher, B; Xi, Y. (2014) *Evaluation of Bridge Deck Sealers,* Colorado Department of Transportation, Report CDOT 2014-6.

Morse, K. L, (2009) *Effectiveness of Concrete Deck Sealers and Laminates for Chloride Protection of New and In Situ Reinforced Bridge Decks in Illinois*, Illinois Department of Transportation, Report PRR-155.

Pfeifer, D. W. and Scali, M. J. (1981); *Concrete Sealers for Protection of Bridge Structures*, National Cooperative Highway Research Program Report 244, Transporation Research Board, National Research Council, Washington, DC.

Pincheira, J. A.; Dorshorst, M. A. (2005) *Evaluation Of Concrete Deck And Crack Sealers;* Wisconsin Highway Research Program Report # 0092-03-09

Sohanghpurwala, A. A.; Scannell, W. T.; Hartt, W. H (2002); *Repair and Rehabilitation of Bridge Components Containing Epoxy-Coated Reinforcement, NCHRP Web Document 50 (Project D10-37C): Contractor's Final Report*; National Cooperative Highway Research Program; Transportation Research Board; National Research Council; Washington, DC. http://onlinepubs.trb.org/Onlinepubs/nchrp/nchrp_w50.pdf

Van Der Werf, Alex. "Corrosion Protection and Repair of Reinforced Concrete." *Truesdell Corporation.* http://www.truesdellcorp.com/index.php/services/articles/429-corrosion-protection-and-repair-of-reinforced-concrete

Vaysburd, A. M.; Emmons, P. H.; (2004); "Corrosion inhibitors and other protective systems in concrete repair: concepts or misconcepts," Cement & Concrete Composites 26, 255–263

Vaysburd, A. M.; Emmons, P. H.; (2000) "How to make today's repairs durable for tomorrow corrosion protection in concrete repair," Construction and Building Materials 14, 189-197.

Von Fay, K. F. (2015); *Guide to Concrete Repair*, US Department of the Interior, Bureau of Reclamation, Washington, DC.

Zhifu, Y; Brown, H.; Huddleston, J.; Seger, J.; (2016). "Performance Evaluation of Rapid-Set Prepackaged Cementitious Materials for Rehabilitation of Surface Distress of Concrete Transportation Structures." *PCI Journal,* March-April 2016, pp. 81-96.

York, Bill. "Plain-Language Answers to the Top 10 Sealer Questions." *V-Seal Concrete Sealers.* ConcreteNetwork.com. https://www.concretenetwork.com/products-sealer/frequently-asked-questions.html

Zheng, H.; Li, W; Ma, F,: Kong Q.; (2012): "The Effect of Surface-Applied Corrosion Inhibitor on the Durability of Concrete", Construction and Building Materials. 37, p36.

Appendix A – Estimates for Hydrodemolition:

General Information

Initial Cost (estimate from manufacturer's representative):

With all necessary equipment to operate:

High pressure pump	$225k
Robot 367	$190k
Robot 327	$115k
Spare parts	$4.5k
High pressure hose 150'	$5.250k
Water recycling attachment	$40k

Operation and maintenance training included as well as a few days of on the job training. Cost for service technician travel and housing not included.

Operating Costs (estimate from manufacturer's representative).

Fuel consumption of the pump is estimated to be 30-35 gallons per hour.

Cost of operation/maintenance over time is 10-15.00 per running hour. This includes consumable items such as nozzles and protective wear plates. The total cost is generated over time. You may find over the first 1,000 hours you have not spent that much. However over the years you will eventually find this estimate to be quite close. With that said we like to error on the high side.

Water: Production rates are based on 50 gpm @ 20k. In general it is always best to use the lower end of the estimated rate. These are conservative rates in general.

Estimated Service Life:

The diesel engines' estimated useable service life is 10,000 hours. The robots are estimated at 10-15 years and 6-7,000 high pressure hours (from the manufacturer's representative).

Assumptions:

The hydrodemolition equipment cost $390,000 – this includes the robot at $115k, the pump unit at $225k, the spare parts at $4.5k, hoses at $5.25k and water recycler at 40k.

At 2.5% interest, the annual cost amortized over 10 years is about $44,000/year.

ODOT chips 30-35 bridges per year. Average bridge length for a bridge over a highway in an urban area is about 300-350 feet (random check of bridges in Franklin County using Office of Structural Engineering data; only bridges over roads are considered).

So 18,000 – 24,000 linear feet/year (=30*300*2 low and 35*350*2 high)

A parapet wall has a surface area of 7.6 sq. ft/linear foot. This includes an assumed 8.5 inches for the deck edge. This is 0.85 sq yd/linear foot of parapet.

Production rates (from manufacturer's representative):

Removal	Production
0-3/4 inch	40-60 sq yd per hour
1 inch	35-50 sq yd per hour
2 inch	20-35 sq yd per hour
3 inch	15-25 sq yd per hour
4 inch	10-20 sq yd per hour

Light removal is about 47 to 70 linear feet/hour.

Heavy removal (Assumed 2 inch – would get down to rebar) is about 24 to 41 feet/hour.

To complete one side of a 350 foot bridge in a 7 hour time, it would be necessary to average 50 sq yds/hour. Note that:

1) 350 foot long is a reasonable upper limit to the bridge length; many bridges are shorter;
2) Only about 25-50% of the pier would need heavy removal;
3) Areas not over the roadway may or may not be hydrodemolitioned.

However:

1) Movement of traffic control must be considered;
2) For bridges with vandal fences, the unit must be lifted to the outside of the pier;
3) Debris must be removed.

So some bridges could be finished in 2 days but some may require 3: use 2.5 days/bridge as a reasonable average.

30 bridges x 2.5 days x 7hours/day = 525 hours

$44,000/year / 525 hours = $83.80/hour use $84 for ownership cost.

Operation - $15/hour (from manufacturer's rep)

Fuel = 35gal/hour @ $3/gal = $105/hour (consumption from manufacture's rep; fuel price assumed)

Total cost = $204/hour

Transporting the unit - Truck Tractor ($50.57/ hour + $1.84/mile) + Trailer ($15/hour)

Transporting some water – Water Tank Truck is $12.50/hour from ODOT standard charges

Water vacuum system – ODOT Cleaner/Flusher/Vacuum - $86.94/hour from ODOT standard charges

Water catching system – needs to be designed.

Assumed Crew:

Traffic Control – 5 (no change)

Operate Robot – 1 person

Operate pump/recycle unit – 1 person

Clean debris, assist with operation – 2 persons

Water Disposal:

Ohio EPA considers the water a hazardous waste. The manufacturer makes a water cleaning/recycling system. However, it would necessary to be sure this will meet Ohio EPA standards.

Estimated cost of chipping.   This is for one night.

Force Account Project Assessment Form (Estimate)

Ohio Revised Code 117.16 requires the Auditor of State to develop a force account project assessment form to be used by each public office to estimate or report the cost of a force account project. The form shall include costs for employee salaries and benefits, any other labor costs, materials, freight, fuel, hauling, overhead expense, workers' compensation premiums, and all other items of cost and expense, including a reasonable allowance for the use of all tools and equipment used on or in connection with such work and for the depreciation on the tools and equipment.

This form is to be completed as provided in Auditor of State Bulletin 2003-003.

| Project Name/Number: | FRA-70-16.56 SFN2505134 Bridge Chipping estimate |
| Project Description: | crew of 12 one night of work |

| Proposed Start Date: | 10/1/2016 | **Proposed End Date:** | |

STANDARD HOURLY RATES OBTAINED FROM PERSONNEL OFFICE

ESTIMATED LABOR (please complete the shaded fields)

Description	Base Wage		Hours Worked		Total
Traffic Control crew of 5	$19.00	X	40	=	$760.00
Labor crew of 7	$19.00	X	56	=	$1,064.00
				=	
		X		=	
		X		=	
		X		=	
		X		=	
		X		=	
		X		=	
		X		=	
		X		=	
		X		=	
		Total Base Wages			$1,824.00
	30	% of base wages (fringe benefits, BWC, etc.)			$547.20
	38	% of wages and fringe benefits for overhead			$901.06
		Total Labor Estimate			**$3,272.26**

ESTIMATED MATERIALS (please complete the shaded fields)

VALUES OBTAINED FROM EMS DATABASE

Description	Cost per Unit		Quantity	Unit Type		Total
		X			=	
		X			=	
		X			=	
		X			=	
		X			=	
		X			=	
		X			=	
		X			=	
		X			=	
		X			=	
		X			=	
		X			=	

				Base Materials	
	15	% of base materials for overhead			

		Total Materials Estimate	

ESTIMATED EQUIPMENT (please complete the shaded fields)

Each piece of equipment used in a project must be assigned an hourly rate. For equipment owned by the public entity, this rate must reflect the original purchase price of the equipment, maintenance costs, time in service, depreciation, freight, fuel, and hauling. The public office may use any generally accepted rate that reflects all of the aforementioned considerations, or it may use the statewide rates as published by the Ohio Department of Transportation and updated on a quarterly basis; however, the office must use the same rate source for all equipment used in a project. Any equipment rented by the public entity must be listed in the form and reflect the actual rental rate. *STANDARD RATES USED FOR CALCULATIONS. RATES OBTAINED FROM STANDARD FY-11 UNIT RATES ISSUED FROM OEM WEBSITE.*

Description	Rate per Hour/Mile		Hours/Mile		Total
2 stake body trucks for TC barrels 50 mile each	$1.70	X	100	=	$170.00
3 PU's at 30mile each	$0.65	X	90	=	$58.50
2 dump trucks 20 each	$2.85	X	40	=	$114.00
stake bodys hours 7hrs each	$27.17	X	14	=	$380.38
PU's hours 7hours each	$16.00	X	21		$336.00
Dump hours 7 hours each	$50.15	X	14	=	$702.10
Light plant x2 at 7hrs	$6.49	X	14	=	$90.86
debris dump x1 hours	$50.15	X	1	=	$50.15
debris dump x1 miles	$2.85	X	30	=	$85.50
compressor x2 7 hours each	$30.70	X	14	=	$429.80
Miscellaneous tools	$200.00	X	1	=	$200.00
		X		=	
		X		=	

	Total Equipment Estimate	**$2,617.29**

TOTAL ESTIMATED PROJECT COST	**$5,889.55**
(labor + materials + equipment)	

Estimated Cost of Hydrodemolition. This is for one night.

Force Account Project Assessment Form (Estimate)

Ohio Revised Code 117.16 requires the Auditor of State to develop a force account project assessment form to be used by each public office to estimate or report the cost of a force account project. The form shall include costs for employee salaries and benefits, any other labor costs, materials, freight, fuel, hauling, overhead expense, workers' compensation premiums, and all other items of cost and expense, including a reasonable allowance for the use of all tools and equipment used on or in connection with such work and for the depreciation on the tools and equipment.

This form is to be completed as provided in Auditor of State Bulletin 2003-003.

Project Name/Number:	FRA-70-16.56 SFN2505134 Bridge Chipping estimate
Project Description:	crew of 9 one night of work

Proposed Start Date:	10/1/2016	Proposed End Date:	

STANDARD HOURLY RATES OBTAINED FROM PERSONNEL OFFICE

ESTIMATED LABOR (please complete the shaded fields)

Description	Base Wage		Hours Worked		Total
Traffic Control crew of 5	$19.00	X	40	=	$760.00
Labor crew of 4	$19.00	X	28	=	$532.00
				=	
		X		=	
		X		=	
		X		=	
		X		=	
		X		=	
		X		=	
		X		=	
		X		=	

		Total Base Wages	$1,292.00
30	% of base wages (fringe benefits, BWC, etc.)		$387.60
38	% of wages and fringe benefits for overhead		$638.25

	Total Labor Estimate	**$2,317.85**

ESTIMATED MATERIALS (please complete the shaded fields)

VALUES OBTAINED FROM EMS DATABASE

Description		Cost per Unit		Quantity		Unit Type		Total
			X				=	
			X				=	
			X				=	
			X				=	
			X				=	
			X				=	
			X				=	
			X				=	
			X				=	
			X				=	
			X				=	
			X				=	

	Base Materials	
15 % of base materials for overhead		
	Total Materials Estimate	

ESTIMATED EQUIPMENT (please complete the shaded fields)

Each piece of equipment used in a project must be assigned an hourly rate. For equipment owned by the public entity, this rate must reflect the original purchase price of the equipment, maintenance costs, time in service, depreciation, freight, fuel, and hauling. The public office may use any generally accepted rate that reflects all of the aforementioned considerations, or it may use the statewide rates as published by the Ohio Department of Transportation and updated on a quarterly basis; however, the office must use the same rate source for all equipment used in a project. Any equipment rented by the public entity must be listed in the form and reflect the actual rental rate. ***STANDARD RATES USED FOR CALCULATIONS. RATES OBTAINED FROM STANDARD FY-11 UNIT RATES ISSUED FROM OEM WEBSITE.***

Description	Rate per Hour/Mile		Hours/Mile		Total
2 stake body trucks for TC barrels 50 mile each	$1.70	X	100	=	$170.00
3 PU's at 30mile each	$0.65	X	90	=	$58.50
2 dump trucks 20 each	$2.85	X	40	=	$114.00
stake bodys hours 7hrs each	$27.17	X	14	=	$380.38
PU's hours 7hours each	$16.00	X	21		$336.00
Dump hours 7 hours each	$50.15	X	14	=	$702.10
Light plant x2 at 7hrs	$6.49	X	14	=	$90.86
debris dump x1 hours	$50.15	X	1	=	$50.15
debris dump x1 miles	$2.85	X	30	=	$85.50
Hydro Demo	$204.00	X	7	=	$1,428.00
Miscellaneous tools	$200.00	X	1	=	$200.00
Truck Tractor 7 hours	$50.57	X	7		$353.99
Truck Tractor 30 miles	$1.84	X	30		$55.20
Trailer 7 hours	$15.00	X	7		$105.00
Vaccum Truck 7 hours	$22.50	X	7	=	$157.50
Water Tank (2) for 7 hours	$12.25	X	14	=	$171.50

	Total Equipment Estimate	**$4,458.68**

TOTAL ESTIMATED PROJECT COST	**$6,776.53**	
(labor + materials + equipment)		