Evaluation of Maintenance Procedures for Bridge Spalling on Parapet Walls

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16. Abstract

Parapet wall deterioration concerns the Ohio Department of Transportation. The spalling of parapet walls presents a danger to the traveling public as pieces of deteriorated concrete may fall onto the road below. The current repair method is to chip off the weakened concrete using pneumatic chipping hammers. However, this process not only damages the sound concrete, but it also leaves an unprotected surface. This project implemented hydrodemolition as a means of removing spalled concrete. A hydrodemolition robot was utilized in the field to remove concrete on the interior and exterior face of a parapet wall. This method was determined as promising as it does not damage the sound concrete surface and exposed reinforcing steel, it mitigates silica dust, and it efficiently removes unsound concrete. Polyaspartic polyureas are a concrete protectant/sealant that may be rolled onto a prepped concrete surface using a paint roller. This material not only seals the concrete but may provide a reinforcing barrier that retains loose pieces of concrete. This material was used to coat several parapet walls in the field, and it was observed that three of the five polyaspartic products appeared effective in the field at providing a protective barrier. In contrast, all were equally effective in laboratory testing.

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ABSTRACT

Parapet wall deterioration concerns the Ohio Department of Transportation. The spalling of parapet walls presents a danger to the traveling public as pieces of deteriorated concrete may fall onto the road below. The current repair method is to chip off the weakened concrete using pneumatic chipping hammers. However, this process not only damages the sound concrete, but it also leaves an unprotected surface. This project implemented hydrodemolition as a means of removing spalled concrete. A hydrodemolition robot was utilized in the field to remove concrete on the interior and exterior face of a parapet wall. This method was determined as promising as it does not damage the sound concrete surface and exposed reinforcing steel, it mitigates silica dust, and it efficiently removes unsound concrete. Polyaspartic polyureas are a concrete protectant/sealant that may be rolled onto a prepped concrete surface using a paint roller. This material not only seals the concrete but may provide a reinforcing barrier that retains loose pieces of concrete. This material was used to coat several parapet walls in the field, and it was observed that three of the five polyaspartic products appeared effective in the field at providing a protective barrier. In contrast, all were equally effective in laboratory testing.

INTRODUCTION

The Ohio Department of Transportation (ODOT) and Ohio local government agencies use approximately 300,000 – 900,000 tons of deicing salts annually. Plowing snow on highways causes salt laden snow to stack against bridge parapets. Snow piles melt away slowly and have an extended contact period with the bridge parapets. The parapet are also subjected to salt water spray from both the roadway on the bridge and the roadway below. This exposure to salt often leads to concrete spalling and/or reinforcing bar corrosion.

Since parapet walls are relatively thin concrete members, there is less room for error in the placement of reinforcing steel during construction. As a result, inadequate concrete cover over reinforcing steel can often be a problem. Being thin members, parapet walls are especially vulnerable to thermal cracking and freeze/thaw cycling. Consequently, parapets are susceptible to cracking and corrosion problems.

Deterioration of parapet walls can lead to safety problems as pieces of the parapet concrete can fall off into traffic traveling below the bridge. Maintenance crews must remove this concrete and the conventional method is the use of pneumatic chipping hammers. This method has the following problems:

1. Maintenance workers have difficulty in determining the extent of the distressed concrete that must be removed.
2. When chipping hammers are used, it can be difficult to avoid damaging sound concrete and reinforcing bars.
3. The use of chipping hammers for extended periods of time can result in musculoskeletal problems.
4. Concrete dust generated by chipping can be a serious health hazard. The Occupational Health and Safety Administration (OSHA) has instituted new rules for worker protection from silica dust. These rules went into effect in 2017. The implementation of these rules will likely increase the cost of repairs of damaged

The surfaces damaged as a result of concrete removal should be sealed or repaired. In addition to the concrete sealing/repair, it is necessary to address corroded reinforcement, otherwise, the corrosion may progress and continue to damage the concrete.

Maintenance crews must close traffic lanes to conduct the repairs, and this presents additional safety problems to both the workers and the traveling public. Thus, it is desirable to have a solution to the problem that can be implemented in the shortest period of time possible, with minimum disruption to traffic.

Phase I of this project provided a detailed analysis of the problem with some possible solutions (Miller et al. 2017). This report details Phase II where two possible solutions, Hydrodemolition and the use of polyaspartic coatings, are evaluated.

PROBLEM STATEMENT

ODOT county/district maintenance crews are responsible for the removal of unsound concrete on bridge parapet walls located over traffic so that concrete pieces do not fall onto vehicles or pedestrians. This process involves setting up extensive traffic control zones and using small pneumatic jack hammers to remove the unsound concrete. After eliminating loose concrete, the new surface and underlying reinforcing bars are left exposed and unprotected from deicing salts utilized during the snow and ice season. The problems associated with this process include damage to otherwise sound concrete and reinforcement, potential deleterious health effects for workers.

This research team investigated hydrodemolition as an alternative means of removing spalled concrete in lieu of pneumatic handheld tools. The hydrodemolition method should be faster and do a better job of removing unsound concrete, thus improving the health and safety of the traveling public and maintenance workers. It may also prove more cost efficient. The research team also investigated polyaspartic polyureas as a better method of sealing/protecting newly exposed concrete surfaces to prevent further deterioration.

SUMMARY OF PHASE I RESEARCH

The Phase I search of literature (Miller et al., 2017) has shown that there is no easy answer for the rehabilitation and maintenance of parapet structures. There has been virtually no research on parapet repair. In fact, most research found regarding repair of deteriorated concrete bridge structures focused on decks, with some work on substructure elements. However, some of the information on bridge decks and substructures can be applied to parapet walls.

The main conclusion is that nothing done to repair the parapet walls should be considered a permanent repair. In some cases, if the underlying concrete is sound, it is possible to apply a patch and/or to seal the surface. These repairs may prevent further deterioration but are likely to only have service life of 3-7 years before they have to be replaced. It is possible that some repairs may last more than 7 years, but there is no long term data available on this subject. If the underlying concrete has any sort of deficiency (e.g. lack of freeze-thaw resistance or poor aggregates) or if extensive corrosion is present, patching and/or sealing the surface may delay the deterioration but will not prevent it. In these cases, the repair simply buys time until the structure can be extensively rehabilitated or replaced.

Figure 1: Example of the condition of a damaged parapet in District 6

Figure 1 shows examples of parapet walls in ODOT District 6 where unsound concrete has been removed. Presently, District 6 uses pneumatic handheld chipping hammers (**Figure 2**) to remove spalled concrete. Crew workers remove loose concrete generally up to the steel reinforcement, because the workers are typically unable to determine when they reach the sound concrete. After reaching the reinforcement, nothing else is done. The steel is left exposed, and no patching takes place. The combination of the inability to determine if all unsound concrete has been removed, that pneumatic chipping usually damages sound concrete and reinforcing bar, and that the chipped areas are left exposed, means that the parapet walls often continue to deteriorate and workers have to go back to the same bridges within one to two years of the initial repair. This is both inefficient and costly.

The use of pneumatic chipping hammers may present a hazard to workers. Workers may experience injury or carpal tunnel syndrome from extensive use of these tools. Chipping generates concrete dust, which now must be controlled under new Occupational Health and Safety Administration (OSHA) rules.

Figure 2: Pneumatic handheld chipping hammer

One alternative to pneumatic chipping is the use of hydrodemolition, where high pressure jets of water are used to remove unsound concrete. The water jets remove the unsound concrete without damaging the sound concrete or the reinforcing bars. Since the work is done by machine, there is less chance of injury to the workers and the water contains the concrete dust. The main drawbacks to hydrodemolition are the costs of the machines, the need to have large amounts of water on site and the need to dispose of or treat the wastewater, which is classified as a hazardous waste due to high pH and particulates. In addition, workers must be trained to properly and safely operate the equipment.

Most hydrodemolition units are designed for horizontal surfaces, but in Phase I a robot was identified that is capable of working on vertical surfaces and is able to reach over the side of the parapet wall, allowing work to be done from the bridge deck rather than from traffic lanes below.

Currently, ODOT does not have a procedure for preserving deteriorated concrete structures. The important aspect of rehabilitation to keep in mind is that cracks may still occur after the surface is coated with a particular sealing product. Therefore, a product that will bridge cracks but also be impermeable is desirable for concrete repair. From the literature review in Phase I, it has been determined that polyaspartic polyureas may be a suitable coating to be applied to parapet walls to prevent further deterioration and chloride ion intrusion. The benefits of polyaspartic coatings are that they can be applied in a range of temperatures, they are UV resistant, they cure quickly, and they have excellent bonding capabilities (Nasvik, 2016). **Figure 3** presents an outline of the performance of polyaspartic polyureas compared to other types of sealants used on concrete such as polyurethanes, polyester, and epoxies.

Performance Type	Polyurea	Polyurethane	Polyester	Epoxy
Physical Strength	low/high	low/middle	high	high
Elongation	high	low/high	low	low
Abrasion Resistance	high	middle/high	middle/high	high
Adhesion to Concrete	high	low/middle	middle	high
Cure Shrinkage	low	low	high	high
Permeability	low	middle/high	low	low/high
UV Resistance	high	low/high	middle/high	low
Temperature Limit	high	middle	low/middle	low

Figure 3: Comparison of various coating properties ("Polyurea Technology")

PHASE II TECHNICAL OBJECTIVES

The technical objectives of the research team were to answer the following questions with regards to for hydrodemolition concrete removal:

1. Evaluate if the hydrodemolition robot can be used on parapet walls or if instead does the physical shape of the parapet or the robot inhibit it from removing unsound concrete off of parapet walls.
2. Determine the feasibility of transporting the robot to the site.
3. Given that ODOT crews have limited time windows in which to work and that there is set-up and breakdown time for the robot, determine if the robot can be operated for a long enough time and over a sufficient length of parapet wall to justify its use.
4. Determine if the robot is more effective at removing concrete than utilizing a chipping hammer in terms of quality of removal, mitigation of safety hazards (such as silica exposure, and hand-arm vibration), time it takes for removal, and overall cost to remove the spalled concrete.
    a. Is the use of the robot cost effective? This must consider not only in the initial cost and operating costs of the robot, but also unquantifiable benefits of the robot (e.g. better removal of unsound concrete combined with less damage to substrate concrete means fewer return trips to the bridge).
5. Conclude if an effective system can be designed to capture/contain the wash water from the hydrodemolition robot.

The technical objectives of the research team will be to answer the following questions with regards to field polyaspartic concrete sealing:

1. Identify polyaspartic materials available for coating concrete.
2. Determine if polyaspartic materials can be easily applied by ODOT maintenance crews.
3. Determine if the material may be applied in a timely manner.
4. Visually inspect polyaspartic coated parapets to determine if the material effectively contains any loose concrete, and if any cracks have appeared to tear through the applied coating.

The technical objectives of the research team will be to answer the following questions with regards to laboratory polyaspartic concrete testing:

1. Through means of laboratory testing, determine the bond performance of the selected coating systems.
2. Through means of laboratory testing, determine the Modulus of Rupture (flexural strength) of coated concrete beam specimens and coated notched-beam specimens to see if the coatings strengthened the specimen.
3. Through means of laboratory testing, determine the ability of the coating system to confine surface deterioration.
4. Through means of laboratory testing, determine the performance of the selected coating systems under freeze-thaw and salt scaling conditions.

By accomplishing these goals, ODOT will improve the serviceability and the safety of not only the bridge infrastructure, but the safety of the traveling public as well. If the suggested strategies for bridge parapet repair are determined feasible by ODOT's District 6 Maintenance Department, a standard operating procedure will be developed for economic implementation by ODOT maintenance crews.

FIELD RESEARCH: HYDRODEMOLITION

Methodology

Phase I identified hydrodemolition as potentially the most efficient and safest alternative to pneumatic handheld chipping hammers for concrete removal. The main difficulty in using hydrodemolition is that the method is normally used on horizontal surfaces and most hydrodemolition equipment is designed for a horizontal surface. Equipment for vertical surfaces has a limited ability to reach high places, meaning platforms would be needed for bridges; an impractical situation when the bridge is over traffic. The hydrodemolition robot selected for field tests has a head on an articulated arm capable of performing hydrodemolition on both the inside and outside vertical surfaces of the parapet wall as well as on horizontal surfaces (**Figure 4**). In cases of a vandal fence, the robot is light enough to put on a lift to reach outside surfaces.

Figure 4: Hydrodemolition robot with articulated head for vertical surfaces

Depending on the pressure setting, the machine has the capability of simply removing coatings off a concrete surface at a low pressure or removing various depths of unsound concrete at higher pressures, which makes it useful in a large number of maintenance situations. The robot has an attached lance or head that moves over the surface in a zig-zag pattern. The head contains a nozzle that removes damaged concrete by shooting a jet of water out at high pressures. Different parameters may be set by the operator to control the depth and width of concrete removal along with the speed of the oscillating lance. Different tips/nozzles may be added to the lance (such as a spray nozzle or circular nozzle) to control the hydrodemolition pattern and also help direct the depth of concrete removal. In Phase II, the goal was to test this equipment and determine if it is feasible for use by ODOT maintenance crews.

Equipment Information

The first step was field testing of the equipment to determine if the equipment would be suitable for parapet wall maintenance. It was determined that hydrodemolition equipment could be rented with an operating crew for a minimum of one week. The rental included all necessary items, except that ODOT would be responsible for traffic control, supplying water for hydrodemolition, and collecting and disposing of the waste water.

Penn Hydro, a specialty subcontractor with expertise in hydrodemolition, was hired to operate all equipment necessary to remove unsound concrete on the inside and outside of bridge parapets. The test bridge is located on Gantz Road over I-270 in Grove City, Ohio, a SW suburb of Columbus (FRA 270-9.60; Structural File Number 2513021). This bridge is 311 feet in length.

A CONJET 327 robot was used. The CONJET 327 unit is compact, measuring 7'-9" by 6'-0" (**Figure 5**), which can easily fit in a 15 to 20 foot trailer. In addition to the CONJET unit, the contractor supplied a Hammelmann (**APPENDIX C**) high pressure pump and a generator (**Figure 6**). ODOT provided tanker trucks of fresh water and a vacuum truck to collect spent water from the deck.

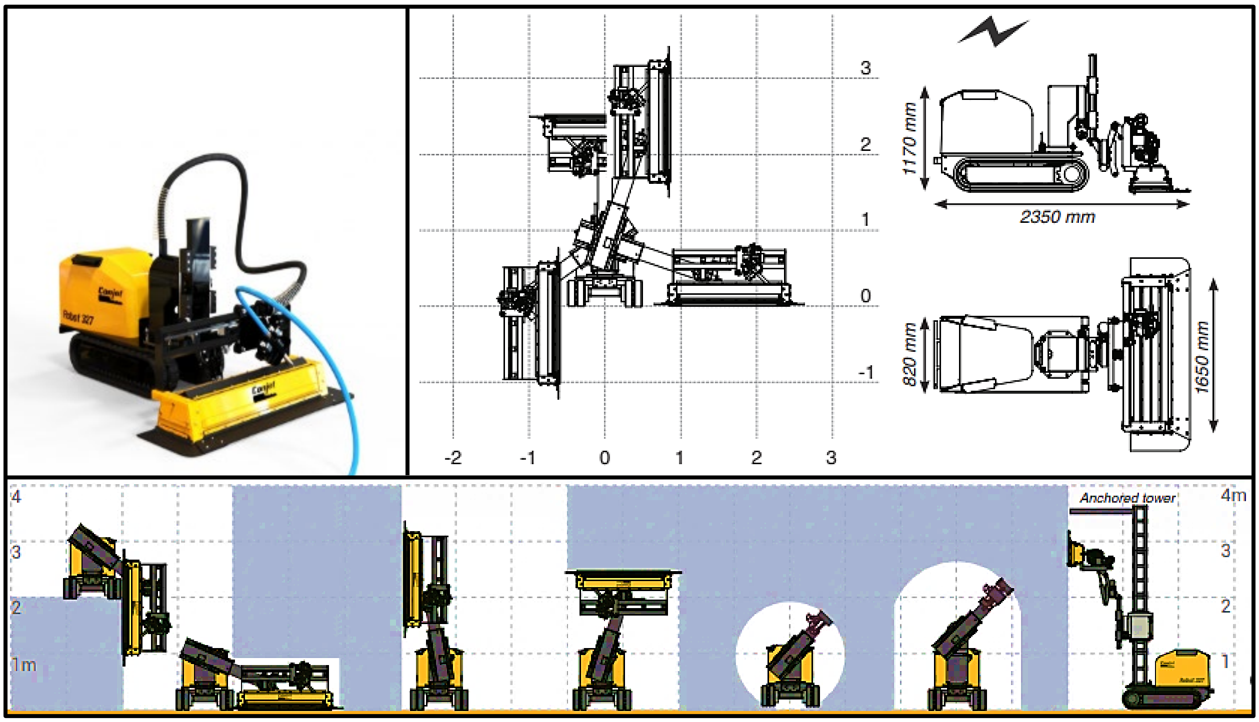


Figure 5: CONJET 327 robot dimensions and reaching capacity ("Hydrodemolition")

Testing Methods

1. Set up traffic control.
   a. ODOT set up traffic control by choosing to block the entire Gantz Rd. Bridge from 9 a.m. to 3 p.m. for testing purposes.

b. All required personal protective equipment was worn, including the following items: earplugs, hard hats, work boots, and safety glasses.

NOTE: When performing hydrodemolition, the bridge must either be shut down or a barrier set in place between the traffic and the hydrodemolition robot, because there could be some low to the ground flying debris during hydrodemolition as a result of the high pressure water. According to Penn Hydro, if it is ODOT's desire to not close the entire bridge, only one lane may be shut down if a barrier system (tall enough to protect the traveling vehicles) is put in place between the traveling traffic and the hydrodemolition robot/equipment. During the testing, the entire bridge was closed from 9:00 AM to 4:30 PM.

2. Set up equipment. The general contractor and ODOT arrived on-site with the equipment **Figure 6**. Set-up took approximately **one hour** and consisted of the following:

Figure 6: Hydrodemolition equipment setup

a. Filling the water tanker with water.
   - The water was warmed up otherwise the cold water would have broken the ceramic cylinders in the pump. This step is important, because ceramic cylinders are costly to replace. Warming the water takes approximately 15 minutes.

b. Unloading the CONJET robot and checking to see if the machine was working properly.
   - The proper nozzles were attached to the oscillating head of the robot.

c. Attaching hoses from the water tanker to the to the high pressure pump (rated between 3470 hp to 740 hp), and then from the high pressure pump to the oscillating lance attached to the CONJET 327.
   - The CONJET 327 runs on electricity supplied by a generator.

d. Setting up the water containment system (for the outside of the bridge parapet) and/or the vacuum truck (for the bridge deck and inside parapet wall) to contain the wash water produced by the demolition.

3. Using the remote controller, operate the CONJET 327 and orient the lever arm sideways in order to remove concrete on the parapet walls.

4. Utilize the CONJET 327 robot until the desired surface is covered.
    a. The vacuum truck and water containment system ran during the same time as the CONJET robot to catch the wash water.
5. Tear down equipment, and open the road to the public.
    a. Tear down took approximately 30 minutes.

The debris left behind from the hydrodemolition robot must be removed before the debris dries out so that the cement particles do not hydrate and bond to the concrete deck. Before the water is disposed, debris must be removed and the pH balance returned to the value accepted by local regulations. ODOT located a site which would accept and treat the spent water and it was taken there.

Hydrodemolition Process and Observations

The hydrodemolition test was conducted on a portion of the parapet wall and bridge deck as shown in in Figure 7. The field test lasted three days:

- 9/25/17 – Inside of Parapet Wall
- 9/26/17 – Outside of Parapet Wall
- 9/27/17 – Bridge Deck

The research team collected data regarding the amount of time it took to set up equipment, robot settings (nozzle type, pressure required, water usage), and the time it took for the robot to remove unsound concrete, and collection of water. The CONJET 327, (**Figure 8**) was first utilized on the inside face of the parapet wall to determine if the robot would be able to remove concrete on a parapet wall to a desired surface profile. **Figure 9** illustrates the parapet (inside face) condition of Gantz Rd. Bridge before hydrodemolition. Extensive cracking was observed in the general area where reinforcing steel is found in the cap of the parapet wall (see the red circle).

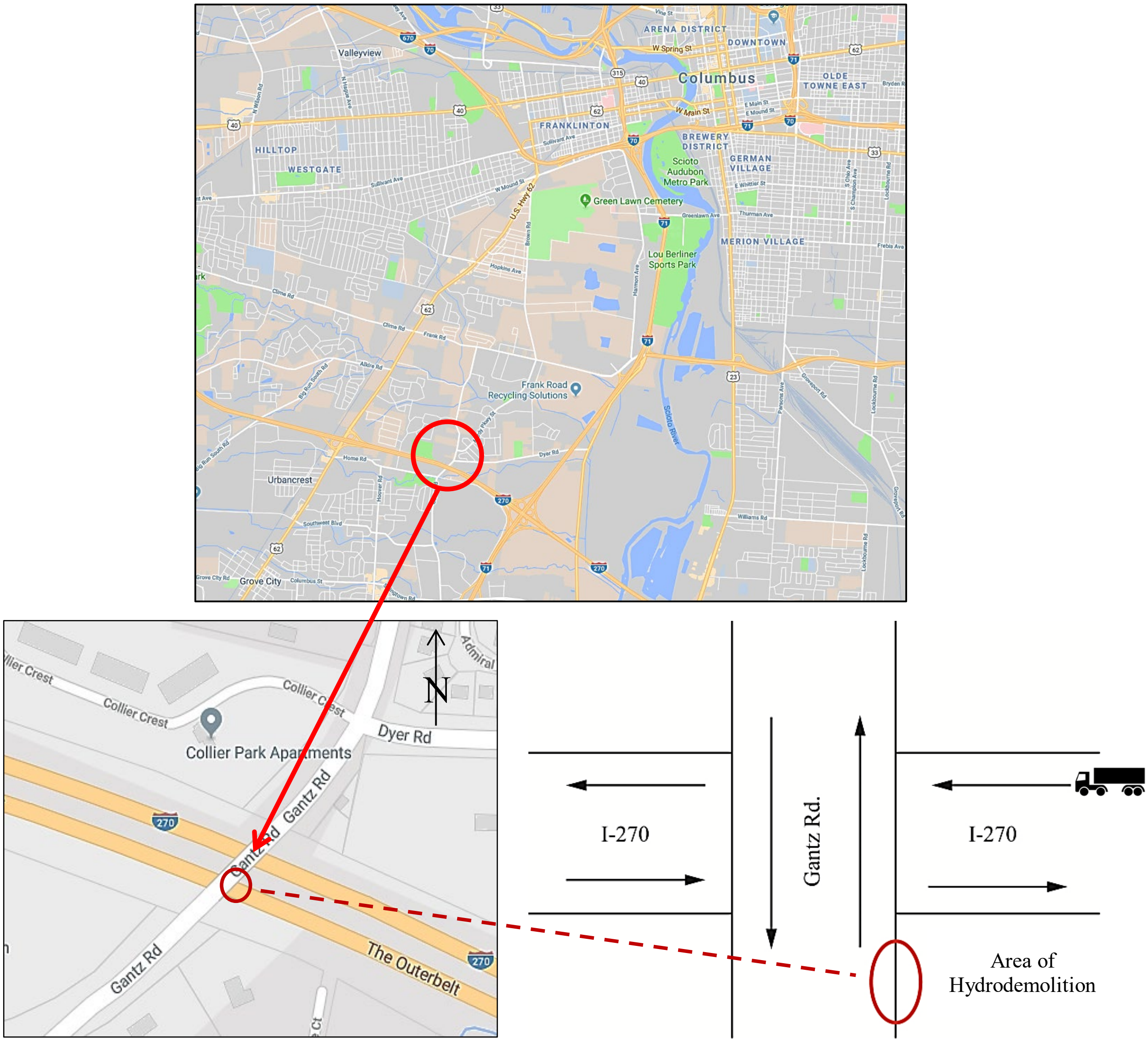


Figure 7: Location of Gantz Rd. used for hydrodemolition testing

Figure 8: CONJET 327 robot

Figure 9: Parapet wall before hydrodemolition

The robot has a head which contains a steel pipe (the nozzle is attached to the end of the steel pipe) that directs the water at the concrete surface. The head of the CONJET robot consists of the steel cage covering over the high pressure water and the rubber flaps to prevent flying debris (**Figure 8).** The steel pipe with the attached nozzle oscillates across the surface of the concrete. The oscillating system (pipe and nozzle) makes up the cutting width of the CONJET robot. The oscillating system can also be moved across the entire length of the head or over just some part of the head, depending on the size of the area to be removed. Therefore, the cutting width of the robot is variable and dictated by the operator. The nozzle oscillates back and forth even when the nozzle is stationary. There are five variables which need to be set: the pressure of water, the size and shape of the nozzle, the rate at which the nozzle oscillates, the speed at which the nozzle moves across the head, and the extent to which nozzle moves within the head. Slide refers to the number of times the oscillating system covers the concrete surface (up and down refers to one slide).

The first step during the field testing of the robot was to identify the correct nozzle and pressure. Hydrodemolition requires some adjustment of the nozzle and pressure. Hydrodemolition works by forcing water into the cracks and concrete pores. This causes concrete below a certain strength to burst. The threshold strength for bursting depends on the pressure applied and the nozzle used. Non porous materials, like steel, are not harmed but coatings may be removed. If the wrong nozzle and/or too low of a pressure is used the unsound concrete might not be completely removed. If a wrong nozzle and/or too high of a pressure is used, the process might also remove some sound concrete.

At first, a straight nozzle was used. As shown in the first photo in **Table 1,** this nozzle cut too deeply into the concrete. As a result, the nozzle was changed from a straight nozzle to a spray nozzle which has a fan type pattern. Over time, operators learn how the nozzles perform and how to choose an appropriate nozzle and pressure.

The spray nozzle has a 2.7 mm opening at a 15° angle. This type of nozzle is typically used to remove thin surfaces of concrete or even just coatings, such as an existing epoxy coating. The spray nozzle requires a higher pressure than the straight nozzle, even though the resulting concrete surface will be more intact than the straight nozzle counterpart. Picture 2 of **Table 1** displays the concrete surface of the inside face of the parapet wall after hydrodemolition using the spray nozzle. In this instance, the hydrodemolition robot oscillating lance ran from the bottom of the parapet wall to the top of the cap of the parapet (**Figure 10)**. The resulting surface was slightly roughened, and the epoxy coating was removed. Unsound concrete near the cap was completely removed (**Figure 11)**. The parapet could be left in this condition or the resulting surface was suitable for patching and/or sealing.

Figure 10: Interior parapet wall hydrodemolition

Table 1: Settings for CONJET 327 with corresponding removal surface of interior parapet wall

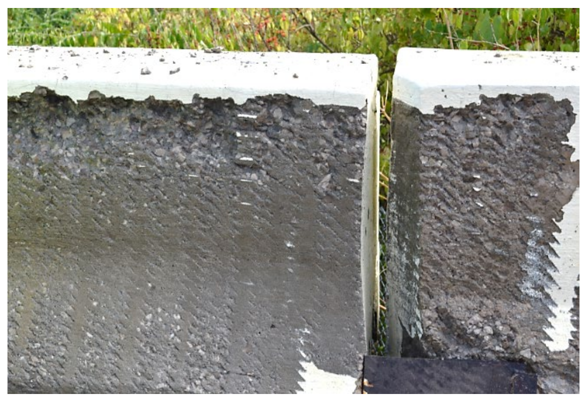
Parapet Side	Nozzle	Settings	Picture
Inside of Parapet Wall	2.6 mm Straight	Slide: Single Pressure: 14,500 psi Speed: 6.0 m/min Oscillation Speed: 157	
Inside of Parapet Wall	2.7 mm Spray @ 15°	Slide: 2-Slide Pressure: 18,500 psi Speed: 6.0 m/min Oscillation Speed: 157	

Figure 11: Interior parapet wall profile after hydrodemolition using the spray nozzle

Oscillation speed affects water penetration into the concrete. It was observed that the faster the oscillation speed of the oscillating head, the less deep the water will penetrate into the concrete surface. The slower the oscilation speed of the oscillating head, the deeper the water will penetrate into the concrete surface. Thus, the performance of the hydrodemoltion process depends on the pressure of the water, the shape of the spray from the nozzle, the rate at which the nozzle oscillates and the speed at which the nozzle moves within the head. According to the operator, with training and some practice, the operator can determine the correct setting for a given situation.

Once all of the equipment was in place and adjusted (including correct nozzle type and water pressure calibration) the speed of concrete removal was very rapid. The robot was able to perform hydrodemolition on the inside of the parapet wall at a rate of 2 linear feet of parapet wall per minute. The inside surface of a parapet wall is approximately 3.5 ft^2 per linear foot so the removal rate is approximately 7 ft^2 per minute or approximately 46.7 yd^2/hour. This is consistent with the manufacturer's stated removal rate cited in the Phase I report of this study. The Gantz Rd. bridge is 311 feet long, so the inside surface of the parapet wall could have potentially been hydrodemolitioned in under 3 hours of machine operation. This means that both inside walls of the Gantz Road Bridge (which is a fairly typical bridge over a major highway) could have been subjected to hydrodemolition within a single 8 hour shift. This includes time for both set up and break down. The machine removed only the damaged concrete while leaving sound concrete intact, an improvement over chipping. Water sequestration for removal of concrete on the inner surface was easily achieved with a vacuum truck. The water was then transported to a disposal site where it could be properly disposed.

On September 26th, the hydrodemolition robot was modified to remove unsound concrete on the outer face of the parapet wall, see **Figure 12**. The modification added an extension to the articulated arm of the machine (red circle). Unfortunately, this modification did not allow the hydrodemolition head to reach the bottom of the parapet wall and tended to cause the robot to tip slightly on account of the weight of the beam added to the arm. In areas where the arm was able to reach, it was able to remove concrete effectively and efficiently. Subsequent discussions with the manufacturer revealed that other models of the robot have arms with sufficient reach for the proposed situation.

Figure 12: Exterior parapet wall hydrodemolition set-up

Water capture on the outer surface was achieved with the help of a water catching basin mounted on the man lift, (**Figure 13)**. The system consisted of a waterproof box fitted with a mesh shield to catch debris. A JLG 800S straight boom man lift was used to hold the basin up. JLG 800S has a restricted lifting capacity of 1000 lbs. The catch basin was designed while keeping this restriction in mind. The system shown is simply a proof of concept and a more permanent system can be designed and built.

Figure 13: Water containment system for exterior parapet wall hydrodemolition

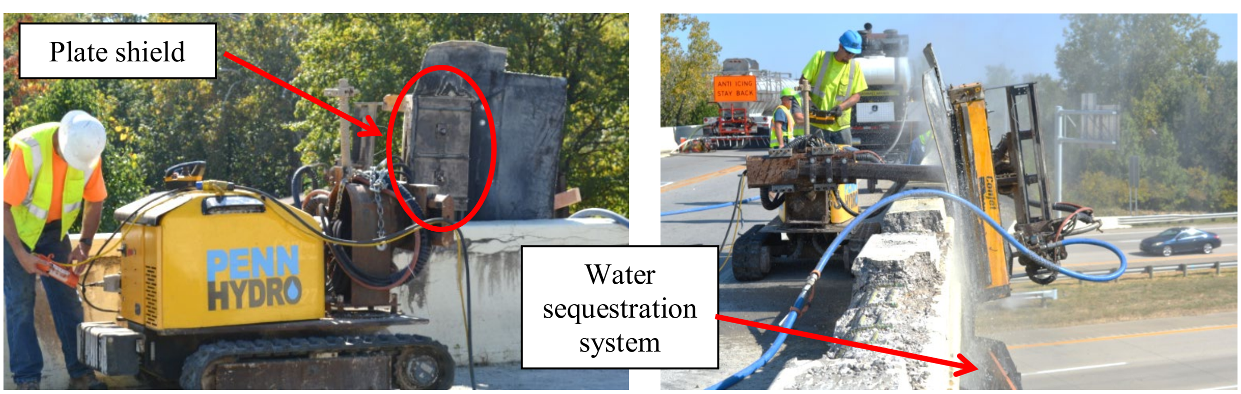


Figure 14: Exterior parapet wall hydrodemolition removal

A plate was added to the head of the hydrodemolition robot in order to prevent concrete debris from rebounding back towards the crews located on Gantz Rd. Bridge (**Figure 14**). This plate was small enough to cover the opening located above the parapet wall. **Figure 15** displays the effectiveness of the hydrodemolition robot in removing concrete off the outer face of the parapet wall.

Figure 15: Exterior parapet wall profile after hydrodemolition

Although the field test showed that a robot with a longer reach was needed and that the water sequestration system needed some improvement, the test demonstrated that hydrodemolition can be used on the critical outside face of the parapets walls. There were also two other important observations. First, the sequestration system sufficiently restrained the water and debris enough that if hydrodemolition were to be performed more than about 10 feet away from a traffic lane, no traffic control would be needed. Second, the robot was also able to remove concrete at a rate of about 2 linear feet per minute. I -270 under Gantz Road has three, 12 foot lanes in each direction. With safety lanes, the roadway width is approximately 50 feet. Thus, the robot could perform hydrodemolition on the outside of the parapet wall over traffic in approximately 25 minutes. The greatly limits the amount of time the road would need to be restricted or closed during the repair process.

On September 27th, the robot was used for removal of a patch of unsound concrete on the bridge deck. It was observed that the robot can efficiently and easily remove up to nine inches of concrete bridge deck for deck repairs (**Figure 16** and **Table 2)**. According to the contractor and the manufacturer, the robot can remove more than 9 inches of concrete, but 9 inches was the most removed in this test. The small size of the hydrodemolition head makes it ideal for removing small areas in a maintenance situation.

The positive side of using the robot for a horizontal surface is that hoses may be attached to the head of the machine and remove the water as it removes the concrete. For this particular situation (the small deck repair) a vacuum truck was used to remove all wash water, so there was no standing water anywhere onsite.

While the field test only used the robot on parapet walls and a bridge deck, discussion with contractor's crew indicated that the robot is much more versatile. With adequate access, the robot could be used for vertical surfaces of substructures, including piers.

As can be seen in **Figure 16** below, none of the reinforcing bar were damaged during the hydrodemolition process for bridge deck repair.

Figure 16: Hydrodemolition on the Gantz Rd. concrete bridge deck

Table 2: Settings for CONJET 327 with corresponding removal surface of exterior parapet wall and concrete deck

Parapet Side	Nozzle	Settings	Picture
Outside of Parapet Wall	2.7 mm Spray @ 15°	Slide: 2-Slide Pressure: 18,500 psi Speed: 6.0 m/min Oscillation Speed: 157	
Bridge Deck	2.6 mm Straight	Slide: 2-Slide Pressure: 15,370 psi Speed: 6.0 m/min Oscillation Speed: 157	

<u>**Results and Economic Analyses**</u>

One important advantage of hydrodemolition is the safety it provides for the maintenance workers and the operators. According to the Occupational Safety and Health Administration (OSHA), pneumatic chipping hammers also pose health risks regarding hand-arm vibration ("PADS - Hand-Arm Vibration"). The following three health hazards may occur:

- Vibration syndrome
- Vibration-Induced White Finger
- Carpal Tunnel Syndrome

Vibration syndrome refers to the following symptoms that occur as a result of using pneumatic handheld tools: muscle weakness and fatigue, arm and shoulder pain, vibration-induced white finger, headaches, and irritability. Vibration-induced white finger is also commonly referred to as "dead finger" or "dead hand." This injury occurs when there is loss or impaired blood circulation in the fingers. The extent of the harm depends on the length of time the worker uses the pneumatic chipping hammer and the frequency of the hammer vibration. Tingling and numbness occurring for more than an hour after ceasing hammer usage may be deemed as an early state of vibration-induced white finger. Carpal tunnel syndrome arises as a result of pressure from the handheld tool on the nerve located on the palm side of the wrist affecting (causing numbness, tingling, and possibly pain) the wrist, thumb, forefinger, and middle finger.

Additionally, the repairs utilizing jack hammers or chipping hammers depend on the skill and mobility of the operator. The operation of pneumatic tools requires several breaks in order to bypass injuries. The use pneumatic hammers also exposes workers to silica dust. OSHA has updated their regulations regarding pneumatic handheld tools, and the updated regulations can be seen in **Table 3**.

Table 3: OSHA crystalline silica standard for handheld power chipping tools ("OSHA")

	Required respiratory protection and minimum assigned protection factor (APF)	
Engineering and work practice control methods	**≤ 4 hours/shift**	**≥ 4 hours/shift**
Use tool with water delivery system that supplies a continuous stream or spray of water at the point of impact:		
- When used outdoors	None	APF 10
- When used indoors or in an enclosed area	APF 10	APF 10
OR		
	Required respiratory protection and minimum assigned protection factor (APF)	
Engineering and work practice control methods	**≤ 4 hours/shift**	**≥ 4 hours/shift**
Use tool equipped with commercially available shroud and dust collection system. Operate and maintain tool in accordance with manufacturer's instructions to minimize dust emissions. Dust collector must provide the air flow recommended by the tool manufacturer, or greater, and have a filter with a 99% or greater efficiency and a filter-cleaning mechanism:		
- When used outdoors	None	APF 10
- When used indoors or in an enclosed area	APF 10	APF 10

NOTE: APF 10 stands for an "Assigned Protection Factor" of at least 10, which refers to the level of respiratory protection necessary for the desired level of protection. Level 10 refers to filtering face pieces and half masks (OSHA).

Table 4 below displays the major differences between chipping hammers and hydrodemolition. Not only does it outline the key safety aspects, but also compares the quality of the overall processes.

Table 4: Chipping hammers vs. hydrodemolition comparison

	Hydrodemolition	**Chipping Hammer**
Silica (Concrete) Dust	Controlled	Not Controlled
Risk of Injury to Workers	Very Low	Moderate
Speed of Removal	7 ft^2 per minute	Variable with worker.
Quality of Concrete Removal	With proper setting, only unsound concrete is removed	Difficult to tell when sound concrete is reached
Depth of Removal	Provides a uniform depth of removal	Depth of removal is not uniform in a particular area
Concrete Substrate	Undamaged	May have microfractures from chipping
Reinforcing Bar	Undamaged but coatings may be removed	Often damaged
Environmental and Health Hazards	Spent water is hazardous waste due to high pH and particulants. Must be properly disposed.	Silica dust is a hazard to workers and must be controlled.

An economic analysis was conducted in order to determine the upfront costs of purchasing all of the hydrodemolition equipment and to determine the life cycle costs of the machine. As previously noted, the robot used in the field trial was unable to completely reach the outside base of the parapet wall. The manufacturer recommended a larger model, CONJET 557 that has sufficient reach. In addition, the Model 557 is a diesel operated machine which eliminates the need to have generator for the robot.

The life cycle analysis was compared to the current District 6 practices (average costs over the past three years). A summary of the analysis can be found in **Table 5**. This analysis was based on a ten year period assuming the robot would have a 10 year service life. The estimated annual usage of the CONJET over the course of one year was assumed to be 200 hours (4 hours per bridge for a total of 50 bridges in District 6). With proper planning and traffic control, using CONJET, damaged concrete on a bridge can potentially be repaired in 1 day. Thus, CONJET will be used 50 days a year to perform the repair tasks that District 6 performs annually. For rest of the days of a typical maintenance season, (150 days annually), the CONJET can possibly be used for other District 6 concrete repair needs or can be used in other districts. A boom lift is included in the cost as it is used to hold the exterior water collection system when the machine operates on the outside of the parapet walls. The boom lift is extremely versatile. District 6 crews can use it on a number of different maintenance tasks.

Table 5: Hydrodemolition economic analysis summary

	Current ODOT District 6 Practice	CONJET only for Parapet Wall Repairs (50 days of Annual Use)	CONJET for Parapet Wall Repairs + 50 days use for other concrete demolition	CONJET for Parapet Wall Repairs + 100 days use for other concrete demolition	CONJET for Parapet Wall Repairs + 150 days use for other concrete demolition
Labor Cost with Overhead (per bridge)	$4,340.40	$889.60	$889.60	$889.60	$889.60
Equipment Cost (per bridge)	$1,564.50	$2,689.34	$2,142.44	$1,956.47	$1,868.96
Total Cost (per bridge)	$5,904.90	$3,578.94	$3,032.04	$2,846.07	$2,758.56
Cost Savings	**N/A**	**39.4%**	**48.7%**	**51.8%**	**53.3%**
Time to recover the initial investment	**N/A**	**4.6 years**	**3.8 years**	**3.5 years**	**3.4 years**
Time Required	200 days	50 days	50 days for work currently done + 50 days for additional bridge repair	50 days for work currently done + 100 days for additional bridge repair	50 days for work currently done + 150 days for additional bridge repair
Time Saving (Extra Work)	**N/A**	**75%**	**75% time saving (on current work) + 50 extra days to perform other work**	**75% time saving (on current work) + 100 extra days to perform other work**	**75% time saving (on current work) + 150 extra days to perform other work**
Unintended Damage	May require additional maintenance due to damage to rebar and micro-cracking in concrete	Does not cause micro-cracking and damage to reinforcement and creates a long term repair eliminating the need to return to the same structure multiple times for additional repairs.			
Silica Exposure (per bridge)	125 Labor Hours	Silica Exposure is eliminated			
Elimination of Safety Hazard	N/A	100%	100%	100%	100%
Adverse Health Effects	May have adverse health effects.	Adverse effects on worker's health are eliminated			
Traffic Affected (Annual) (Estimated[3])	1,120,000 vehicles	280,000 vehicles	280,000 vehicles + Traffic affected due to work on additional bridges. Due to high efficiency of the CONJET, traffic impact will be significantly reduced.		
Reduction in Traffic impact (per bridge)	N/A	75%	75% reduction on the number of vehicles currently impacted + reduction in impact on traffic on any additional bridges repaired		

The initial capital cost of purchasing the CONJET, pump, trailer, and boom lift will be approximately $618,482.00 total.

Up-front Equipment Cost = $197,768 (CONJET) + $ 259,618 (Pump) + $151,096 (Boom Lift) + $10,000 (trailer) = **$618,482**

The initial upfront cost of the hydrodemolition equipment includes purchasing the following:

- CONJET 557 Robot – quote received from National Hydro (CONJET distributor)
- Hammelmann HDP 503 High Pressure Pump – quote received from National Hydro
- Boom Lift – quote received from OHIO CAT
- Trailer – allotted amount requested by ODOT District 6's maintenance crew

For the determination of the total cost to operate equipment for parapet equipment, it was assumed that running the equipment costs $17.00 / hour (totaling $8,211.00). Also, for the determination of the total cost of equipment miles for parapet rehabilitation, it was assumed that it costs $2.50 per mile (totaling $70,015.00). These rates were provided by ODOT. For a more detailed analysis regarding how numbers were obtained, please see the **Appendix A** and **APPENDIX B** of this report.

HYDRODEMOLITION EQUIPMENT: PROCUREMENT AND TRAINING

Hydrodemolition Equipment Procurement

A CONJET 327 robot was mobilized for the hydrodemolition field trials conducted from 09/25/17 to 09/27/17 at Gantz Road. The contractor selected for the work, PENN Hydro, had modified the robot's arm to achieve the depth necessary to perform hydrodemolition all the way to the outer base of the parapet wall. Although the research team was able to perform "proof of concept" hydrodemolition on the outer face of the parapet wall on the bridge at Gantz road, it was observed that the modified robot arm was unwieldy and it would be difficult to manage in production setting during day to day ODOT operations.

If ODOT were to purchase a CONJET 327 robot, it would have required extensive engineering and modification to it to make it useful for performing hydrodemolition on exterior face of parapet walls. CONJET engineers noted that the rotary actuator combined with the extension on a 327 robot will not be robust enough to withstand the weight associated with the application (hydrodemolition of parapet walls) which may create a safety hazard. Therefore, the design engineers at CONJET did not feel comfortable with recommending a 327 robot. They created 3D models of typical parapet walls and evaluated the CONJET 557 robot for the proposed application.

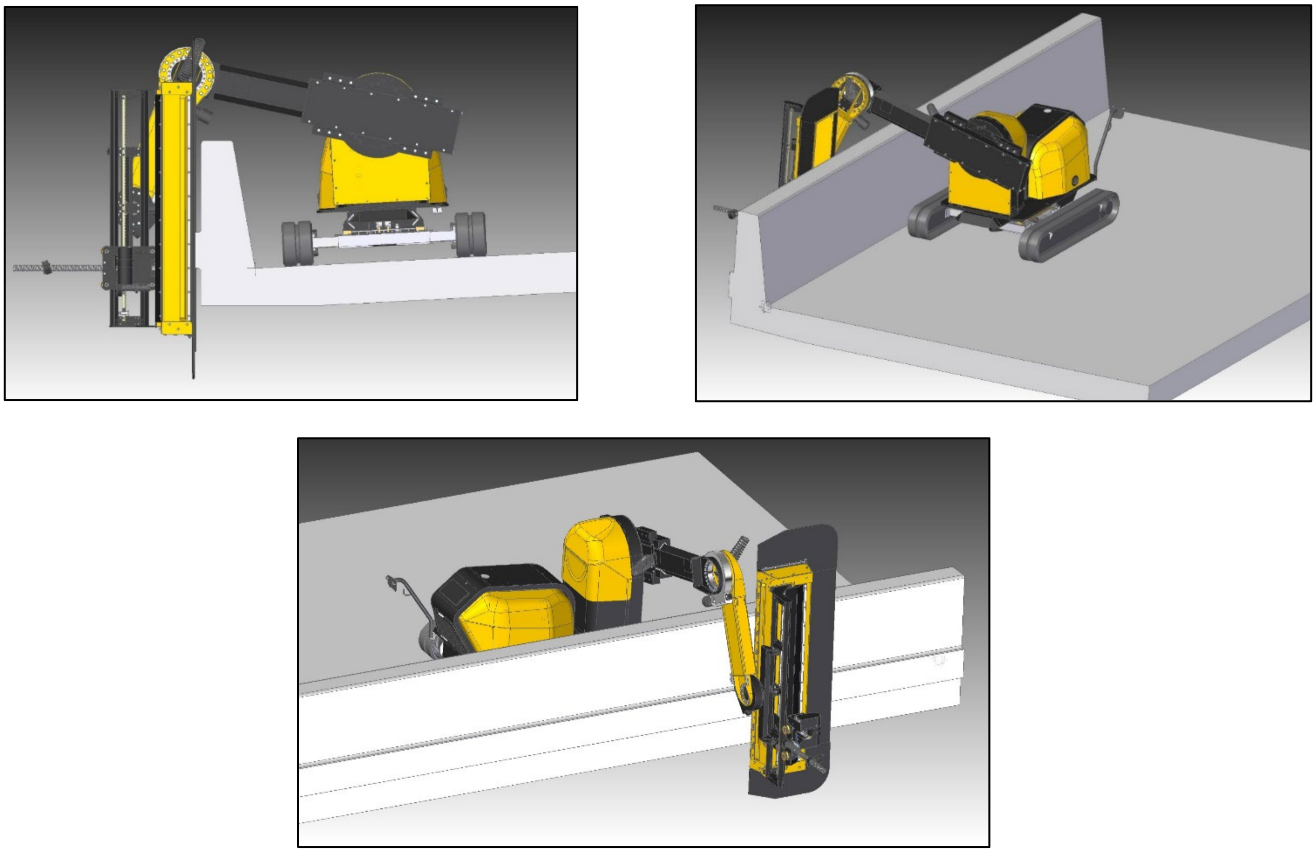


Figure 17: 3D Model of CONJET 557 operating on a typical parapet wall

As shown in Figure 17, the 557 robot would have sufficient reach to perform hydrodemolition at the base of the parapet wall. The 557 is designed to handle more weight while cutting below track level and was much more robust and suited for hydrodemolition of parapet walls. Based on conversations with the equipment manufacturer and ODOT representatives, we decided to purchase a CONJET 557 robot.

The main advantages of a CONJET 557 robot over CONJET 327 robot were:

1. Sufficient reach (7’2” for Robot 557 vs 3’3” for Robot 327) to meet the requirements of hydrodemolition of exterior faces of the parapet walls.
2. CONJET 327 uses a separate electrical generator whereas the 557 robot has a built in diesel engine. The comparison between the two robots is shown in the table below.

Table 6: CONJET Robot 327 vs 557 Comparison

Description	CONJET 327	CONJET 557
Power Supply	3 phase 380 - 480V, 16A, 50 - 60 Hz 3 phase 200V, 32A, 50 - 60 Hz	Diesel Engine, Yanmar
Maximum Raction Force	1500N	3000N
Cutting Width	4'-11"	6'-11"
Height	3'-10"	5'-3" / 4'-1"
Length	7'-8.5"	11'-2"
Operation Weight	2,293.0 lbs	5,730.0 lbs
Robot Arm Configuration	Standard, Base Extension, Tower	Multipurpose Arm (Standard), Tower, Mast
Main Body Stability Track Extension	--	47" – 47"
Main Body Stability Sliding Backwards	--	15.7"
Cutting Height Vertical	9'-10"	17'-8"
Cutting Height Overhead	7'-10"	14'-9"
Cutting Below Track Level	3'-3"	7'-2"

In addition to the CONJET 557 robot, a pump (Hammelman 303) to supply water at high pressure was purchased based on recommendations from CONJET. A boom lift for water sequestration (JLG 600s) was purchased based on discussions and recommendation from ODOT personnel. An enclosed trailer was purchased for the transportation of CONJET robot. The information data sheets for the equipment are included in Appendix D, Appendix E, and Appendix F of this report.

The equipment (CONJET robot from Sweden, Hammelman Pump from Dayton, and the JLG Boom Lift) was delivered to ODOT in the fourth quarter of 2018.

Hydrodemolition Equipment Training

The commissioning and training of ODOT personnel was conducted by Mr. Conny Tangring (CONJET representative from Sweden) and Mr. Steve Toms (National Hydro, CONJET Dealer in the US) from Monday, 05/06/2019 through Thursday, 05/09/2019. The training was attended by:

1. ODOT District 6: Maintenance crew, Mr. Dan Wise and Mr. Bruce Mayes
2. Mr. Jeremy Price and Mr. Mike Stuber from ODOT District 11,
3. Dr. Richard Miller and Dr. Abhijeet Deshpande from the University of Cincinnati.

The activities completed during commissioning and training are described below:

Monday 05/06/2019

Conny Tangring and Steve Toms inspected the CONJET robot and the high pressure pump. They updated the robot's operating system. This new operating system is supposed to make it easy to setup and operate the Hydro-demolition system as a whole. They also established the Bluetooth communication between the pump and the robot.

Figure18 : CONJET 557 Robot

Figure 19: Hammelman 303 Pump

In the second part of the day, CONJET conducted theoretical training in a computer lab in ODOT's District 6 office in Delaware. Some of the topics covered during this training included:

1. Safety: PPE for hydrodemolition and safety precautions that need to be taken at the site when performing hydrodemolition. Mr. Tangring emphasized the importance of taking every precaution when dealing with high water pressure systems close to traffic.
2. Robot Components: Tracks, Boom System and its movement, feed beam, connections to the robot.
3. Robot Movement: Starting the robot, remote control functions, selecting functions, setting parameters
4. Parameters for Hydrodemolition: Setting parameters on the robot (passes, step length, oscillation, lance angles, lance speeds etc.) and setting pressure on the pump
5. Setting up parameters for a test cut at the beginning of the hydrodemolition operation
6. Hydraulic and Electrical Systems
7. Alarms on the robot and the pump
8. Daily, weekly and seasonal maintenance on the robot and the pump.

Tuesday 05/07/2019

On Tuesday, ODOT personnel (Steve Conner, Andrew Kandel) received hands on training from CONJET at the District 6 garage on:

1. How to move the robot using the remote control
2. How to make connections between the pump and the robot
3. How to set hydrodemolition parameters on the pump and the robot

Under CONJET representative's supervision, ODOT operators performed hydrodemolition on a concrete pad at the District 6 garage. This gave them the opportunity to experiment with different pressures, nozzle angles, lance speeds etc. in a controlled setting.

Figure 20: Hydrodemolition training at ODOT District 6 Garage: Demolition of a slab in the District 6 yard.

Wednesday 05/08/2019

On Wednesday, ODOT personnel performed hydrodemolition on a bridge deck on US-23 in Marion county under the supervision of trainers from CONJET.

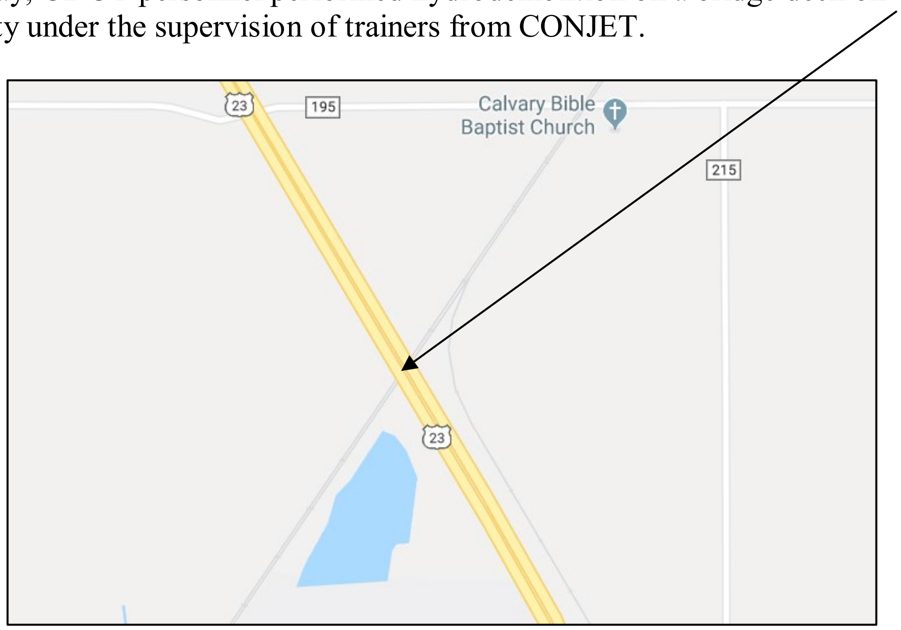


Figure 21: Hydrodemolition Training – US-23

ODOT mobilized the following equipment for the field training: CONJET robot, Hammelman Pump, water tanker, and a vacuum truck. The damaged portion of the concrete deck was successfully demolished. This was an excellent opportunity for ODOT personnel to learn how to operate the equipment in the field under live traffic conditions.

Figure 22: Hydrodemolition Training US-23 Bridge Deck

Additionally, ODOT personnel also learned how to use the CONJET 557 robot's reach to repair the outside face of the parapet wall. This bridge is located over railway tracks. We didn't perform any repairs on the parapet wall on this occasion.

Figure 23: CONJET 557 Reaching over the Parapet Wall

<u>Hydrodemolition by ODOT Crews</u>

After the training, ODOT organized hydrodemolition of a bridge deck on Route 257 on 08/07/2019. This had dual purposes: to complete a much needed repair on a bridge deck and to give ODOT personnel experience in independently planning and executing hydrodemolition in a live traffic situation.

Figure 24: Hydrodemolition on SR 257

Figure 25: Deck Hydrodemolition on SR 257

The crews were able to successfully set up and operate the hydrodemolition equipment but the work could only be partially completed because the Vacuum truck filled up earlier than anticipated. Approximately 140 ft^2 of deck were removed and replaced.

After the work on the Route 257 bridge, the ODOT crews performed hydrodemolition on several other bridges without the research team present. The ODOT crews were able to successfully perform all operations. The District 6 Maintenance Engineer estimates that hydrodemolition removes concrete at approximately double the rate of hand chipping/jackhammering. This allows for more work to be completed in a shift and/or reopening the road to traffic sooner.

Issues with the CONJET

During training, the robot arm would not move through the full range of motion. This was traced to a bad valve, which CONJET replaced.

There was a leak in the diesel tank. ODOT District 6 elected to repair this on their own.

During operations in SR 257, the one tread of the CONJET kept moving slightly after being told to stop. This caused the robot to sometimes be at an angle to the original line of movement. At first it was thought to be a bad remote control, but was later traced to another valve problem. This was repaired by CONJET.

Issues with Water Treatment

Hydrodemolition water is highly alkaline and must be either disposed of in an environmentally sound manner or treated. ODOT District tried to treat the water. A recommendation from the Research Team (after consulting with the UC Chemical and Environmental Engineering Department) was to use muriatic acid for treatment. ODOT regularly stocks muriatic acid as it is used to clean concrete off equipment. Attempts were made to treat the water in the vacuum truck, but the pH could not be lowered. Additional attempts were made to lower the pH after the water was placed in a large vat at the District office and the pH could not be lowered. Samples of the water were taken to the Environmental Laboratories at UC and tested. It was found that the problem was the presence of concrete solids in the water. These solids react immediately with the acid. When the solids were allowed to settle and the water was decanted, a very small amount of acid was needed to bring the pH below 8.

FIELD RESEARCH: POLYASPARTIC POLYUREAS

Field Testing Methodology

Phase I identified polyurea/polyaspartics as a type of product that could be applied to parapet walls, but information obtained from manufacturers indicated that each manufacturer has their own unique formulation of the product; thus, it was necessary to identify specific brands for testing. The testing was intended to determine if the materials are easy to apply in the field and if they have the capability to contain loose concrete. The tasks for this part of the research were:

1. From the laboratory results, identify and obtain three or more different products to apply to bridge parapets by roller or brush, and determine compatible base coat (primer) materials necessary to build the protective system.

2. Obtain polyaspartic samples.
3. Work with the Ohio Department of Transportation to identify bridges that the polyaspartic coating could be applied to by district maintenance crews.

After identifying polyaspartic products from a variety of manufacturers, choosing which products to apply in the field, and obtaining the samples; the next step was to apply the products in the field at two different bridges. The following steps outline the process of applying these materials in the field.

4. Apply 1'-0" to 1'-6" strips of polyaspartic samples to two different bridges within District 6, Columbus, OH.
    - Prepare substrate according to manufacturer specifications (Moisture Content (MC) < 5%)
    - Mix and apply products according to manufacturer specifications (have maintenance workers apply the polyaspartic material, and ask questions regarding the feasibility of application)
    - Apply material over an area whose substrate has been prepped (by hydrodemolition)
    - Apply material over an area whose substrate has not been prepped
    - Apply material over exposed aggregate
    - Apply the material before winter, so that it goes through one winter before visual inspection the following spring
5. Record the time it takes for the primer and top coats to cure.
6. Determine how many coats may be applied in the course of one working day.
7. Determine the feasibility of using polyaspartic polyureas for parapet walls.
8. After one winter, by visual inspection, determine if the polyaspartic coating holds loose concrete, resists deterioration, and adheres to the concrete.
9. Create a final report detailing the results.

The field test results of the polyaspartic material were used to determine the practicality of using this material along with the cost effectiveness. The results were used to develop an operating procedure.

Product Information and Manufacturers

Five different products from four polyaspartic manufacturers were used to coat the surface of bridge parapets (1'-0" to 2'-0" strips starting at the bottom of a parapet wall to the top of the parapet wall) on two different bridges (**Table 7**). The following manufacturers were identified in the laboratory phase and provided polyaspartic information and samples:

Table 7: Polyaspartic manufacturers

Manufacturer
Citadel Floor Finishing Systems
Creative Material Technologies, Ltd.
Mirabel Coatings
VersaFlex, Inc.

The bridge parapets on the bridges in **Table 8** below were chosen for application of the polyaspartic materials on the specified repair dates:

Table 8: Bridges identified for polyaspartic preservation in District 6, OH and dates of repair

Date	Bridge	Structural File No.
November 2, 2017	Gantz Rd. Bridge over I-270	SFN: 2513021
November 14, 2017	SR142 Bridge over I-70	SFN: 4902793

List of Materials for Polyaspartic Application

- Polyaspartic / Polyurea Primers (See **Table 9**)
- Polyaspartic / Polyurea Top Coats (See **Table 9**)
- Protective Gloves. If MEK or Acetone is used Butyl gloves are resistant to ketones, and latex gloves are not recommended.
- Large Clear Plastic Measuring Cups (2 quart – 1/2 gallon size)
- Paint Trays
- Paint Liners (Plastic Disposable Liners)
- Paint Sticks (Stirrers)
- Paint Sponges (Hand Brushes)
- 9” Paint Rollers with Rollers of a 3/8” nap
- Trash Bags
- Personal Protective Equipment
- Traffic Control

Before disposing the polyurea / polyaspartic products, the material on the roller and in the pan must harden and dry. They may be temporarily discarded in a bag until the product cures and then the bag may be put in the trash. In a wet state the product is an EPA controlled substance; in the hardened state, the material is not. The rollers, clear plastic measuring cups, and the pan cannot be reused after coming into contact with the material, so it is recommended to use a pan liner or disposable pan during application. It is suggested to keep paper towels and cleaning products in line with chosen products’ SDS onsite to remove the polyaspartics off the skin or other surfaces.

Table 9: Chosen polyaspartic products and product descriptions

Manufacturer	#	Product	Type	Description / Notes	Mixing (A:B)	Layer Thickness	Cost
VersaFlex	1	VF20	Primer	Primer compatible with Aliphatic clear Coat to promote adhesion.	1:1	10 mils	$50 / gallon
		Aliphatic Clear Coat	Top Coat	Top coat that contains a higher elongation necessary for vertical surfaces. More flexible and resistant to cracking. May not be clear; the product is pigmented.	1:2	10 mils	$120 / gallon
Citadel Floor Finishing Systems / Rust-Oleum	2	Polyurea 350	Primer	98% solids basecoat that cures in 1-3 hours.	1:2	6-8 mils	$310 / 2 gallon kit
		Polyurea Polyaspartic RG-80X	Top Coat	Top coat comes in clear, but may be colored by adding a compatible grey tint to the top coat.	1:1	4-6 mils	$320 / 2 gallon kit
Creative Material Technologies	3	DYNA-PRIME N-23	Primer	100% solids, unpigmented, water chasing primer. Seals damp concrete for top coat application.	1:1	5-10 mils	$230 / 2 gallon kit
		DYNA-PUR 7416BL	Top Coat	Has a 20 min. – 40 min. working time dependent on temperature and humidity. Product is pre-tinted.	1:1	5-10 mils	$278 / 2 gallon kit (Gray)
	4	DYNA-PRIME N-23-NT6	Primer	NT6: Nanotechnology Modified	1:1	5-10 mils	$300 / 2 gallon kit
		DYNA-PUR 7416BL-NT6	Top Coat	NT6: Nanotechnology Modified	1:1	5-10 mils	New Product - Cost Not Available ~$350)*
Mirabel Coatings	5	Polyaspartic Slow	Primer	The primer is the same as the top coat. If the primer is too thick, the material will need to be diluted from 84% solids to 60% solids by using methyl ethyl ketone (MEK).	1:1	5-10 mils	$95 / gallon $228 / 3 gallon kit
		Polyaspartic Slow	Top Coat	Top coat shall not be diluted.	1:1	5-10 mils	$95 / gallon $228 / 3 gallon kit

Table information received from Product Data Sheets and personal communication—*Estimated by Creative Materials Technologies

Table 10: Polyaspartic behavior application details

Manufacturer	#	Product	Important Notes	Coverage Rates	Curing Window (at 25°C)
VersaFlex	1	VF20	Has a pot life of 20-25 minutes. Application temperature greater than 25°F; however, cure times will be extended with colder temperatures. High moisture content will affect coating adhesion. Substrate must have moisture content below 5%.	@ 6-10 wet mils, 1-gallon will cover 160-240 sq. ft.	Gel Time: **45min.-2 hrs.** Working Time: **45 min.** Recoat Window: **72 hrs.**
		Aliphatic Clear Coat	May be applied in temperatures as low as 20°F, and has a pot life of approximately 20-25 minutes. Has a shelf life of one year.	@ 10 mills, 1-gallon will cover 160 sq. ft.	Tack Free: **1.5-2 hrs.** Dry to Recoat: **2 hrs.** Recoat Window: **4 hrs.**
Citadel Floor Finishing Systems / Rust-Oleum	2	Polyurea 350	The product is clear, but may be custom colored; tint packets are sold separately.	@ 10 mil, 1-gallon will cover 160 sq. ft.	Hard Dry: **2-4 hrs.** Mar Free: **4-6 hrs.** Recoat: **12 hrs.**
		Polyurea Polyaspartic RG-80X	Can be sprayed or rolled in temperatures ranging from -20°F-120°F. Only use solvent resistant, natural or synthetic fiber rollers with a nap of 1/4" – 3/8". Larger naps may cause bubbling.	@ 10 mil, 1-gallon will cover 160 sq. ft.	Surface Dry: **30-120 min.** Hard Dry: **2-4 hrs.** Mar Free: **4-6 hrs.**
Creative Material Technologies	3	DYNA-PRIME N-23	Penetrates and seals concrete with little bubbling, but bubbling may occur. The pot life ranges from 20-40 minutes, and a 6 month shelf life. Application condition of substrate: 50°F - 95°F.	@ 10 mil, 1-gallon kit will cover 320 sq. ft.	Working Time: **45 min.** Dry to Touch: **2-4 hrs.** Recoat Window: **2-24 hrs.** Return to Service: **4-24 hrs.**
		DYNA-PUR 7416BL	May come in several tints. The pot life ranges from 20-40 minutes, and a 6 month shelf life. Application condition of material: 40°F - 100°F. Application condition of surface and air: 0°F - 120°F.	@ 10 mil, one 2-gallon kit will cover 320 sq. ft.	Working Time: **20-40 min.** Dry to Touch: **30-45 min.** Recoat Window: **4-8 hrs.** Return to Service: **2-24 hrs.**
	4	DYNA-PRIME N-23-NT6	There is currently no data sheet published for the Nanotechnology Modified Polyaspartics Primer	--	--
		DYNA-PUR 7416BL-NT6	There is currently no data sheet published for the Nanotechnology Modified Polyaspartics Pure Polyurea	--	--

Manufacturer	#	Product	Important Notes	Coverage Rates	Curing Window (at 25°C)
Mirabel Coatings	5	Polyaspartic Slow (Primer)	For multiple coats, decrease the amount of solvent in subsequent coats. Xylene or MEK can be substituted for the Acetone. For the acetone, be sure to get low water content acetone. Acetone sold in a big box at local hardware stores tend to have high water content in their acetone, which can cause flash curing and bubbles in the cured resin.	Dilute Primer 20%, 1-gallon will cover 250 sq. ft.	Dry Time: **30 min.** Dry to Touch: **60-90 min.** Dry Through: **2-4 hrs.**
		Polyaspartic Slow (Top Coat)		Dilute Top Coat 12%, 1-gallon will cover 400 sq. ft.	Dry Time: **30 min.** Dry to Touch: **60-90 min.** Dry Through: **2-4 hrs.**

Testing Methods of Polyaspartic Field Applications

The field testing of these materials consisted of the following steps:

1. Set up traffic control.
   - Block off one lane of traffic (the lane closest to the parapet wall).
2. Wear all required PPE according to manufacturer directions and product SDS sheets.
   - This includes plastic gloves, safety glasses, hardhat, etc.
3. Check the mixing ratio for the chosen primer.
   - If mixing ratio is 1:1, then mix 1 part A to 1 part B
   - See specific mixing ratios in **Table 9**
4. Mix together part A and part B of the primer in a plastic measuring container with a paint stirrer stick back and forth for 2 minutes.
   - Be sure that parts A and parts B are completely mixed together to form one color; do not leave swirls of color left in the mixing container.
   - Remember to scrape the sides and the bottom of the mixing container.
5. Pour the mixture into a plastic disposable paint liner tray that is already placed into the paint tin.
6. It was necessary to check the surface moisture content of the parapet wall. The parapet walls must have a surface moisture content that does not exceed 5% in order to meet manufacturer directions. The polyaspartic coating will not adhere to the concrete surface if there is too much moisture present, and the excess moisture may cause outgassing in the coating. Therefore, the moisture content of the concrete parapet walls was checked with a moisture reader. For areas with moisture content greater than 5%, a large torch was used to dry the concrete surface until the reader displayed a value smaller than or around 5%. One exception was the Creative Material Technologies. The primer is a "water chasing" technology which prefers a wet surface.
7. Using a paint roller with a 3/8" nap, roll the polyaspartic coating material onto the bridge parapet wall; starting from the bottom of the parapet (just above the bridge deck) to the top (slightly over the cap) of the parapet (only one side and top of parapet will be coated) for a width of 1'-6" (**Figure 26**).
   - Using sponge brushes apply the primer on areas of the concrete surface that are too small or too tight to cover with a roller. This is especially important over the exposed, rough aggregate.
8. Allow parapet to dry until tacky (no material comes off on a glove when the coat is touched, but it sticks when lifting up the hand) before applying the polyaspartic top coat.
   - See **Table 10** for approximate drying times for the applied primer (these also can be found on the product specification sheets).
   - The recoat window time will vary depending on the temperature and humidity.
9. Once the primer material has dried in the disposable tray and roller, it may be disposed of into a trash bag.
   - Be sure to follow the SDS sheets for each particular product and follow all EPA rules and guidelines.
10. Repeat steps 1-8 three times for the top coat. Therefore, there shall be a total of four applications for each of the five polyaspartic products. This shall include one coat of primer and three top coats applied to the parapet wall.

Figure 26: Rolling on of the primers of the polyaspartic products

Steps 1-9 were repeated for five different polyaspartic products on a total of two different bridges: Gantz. Rd. over I-270 and SR142 over I-70. There were two applications on the Gantz Rd. Bridge: Application No. 1 was over a prepped concrete surface (prepped by the hydrodemolition equipment explained in the previous section), and Application No. 2 was over an unprepped parapet wall that still had epoxy on the surface.

Tints were added to the top coats for product 1 (Aliphatic Clear Coat) and product 2 (Polyurea Polyaspartic RG-80X). These tints were provided by the manufacturer, and are compatible with the polyaspartic top coat and primer. The amount of tint was added according to the provided manufacturer directions (typically outlined as a percentage of the overall mixture amount).

<u>Polyaspartic Application Process and Observations</u>

The weather conditions during the time of the polyaspartic application on Gantz Rd. Bridge on November 2, 2017 were as follows:

- Cloudy with 0.01" of rain.
- Average Temperature: 58°F
- Average Relative Humidity: 86%
- Observation: The parapet walls were damp from the 0.5" of rain received the day before (November 1, 2017).

Figure 27 below illustrates the area in District 6, Columbus, OH where the polyaspartic products were applied. This first area was chosen, because this was the same area that the hydrodemolition equipment was used to clean the inside of the parapet wall.

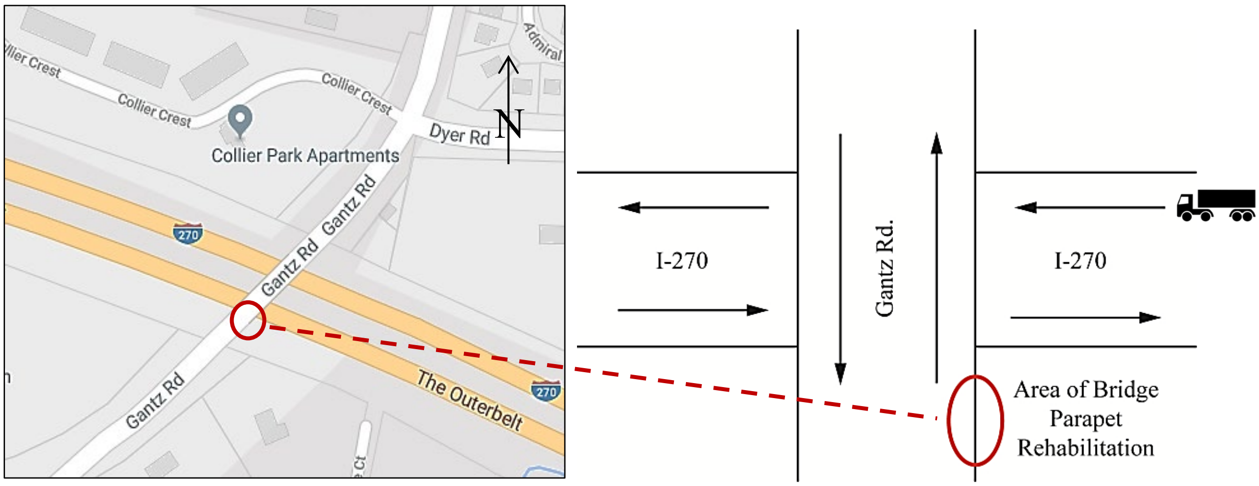


Figure 27: Location of Gantz Rd. Bridge parapet wall rehabilitation

Figure 28 shows how a torch was used in order to get moisture content below 5% for application, because the parapet surfaces were wet from rain the day before and earlier in the day.

Figure 28: Drying the surface of the parapet walls

After utilizing a torch to dry the surface of the parapet walls, a moisture reader was used to determine the moisture content on the concrete surface. **Figure 29** displays a graph that reflects the four moisture content readings per parapet section. Each section ranged an average reading of 2.6 - 3.0 %, which falls below the maximum moisture content of 5% specified by manufacturers and the products' specification sheets.

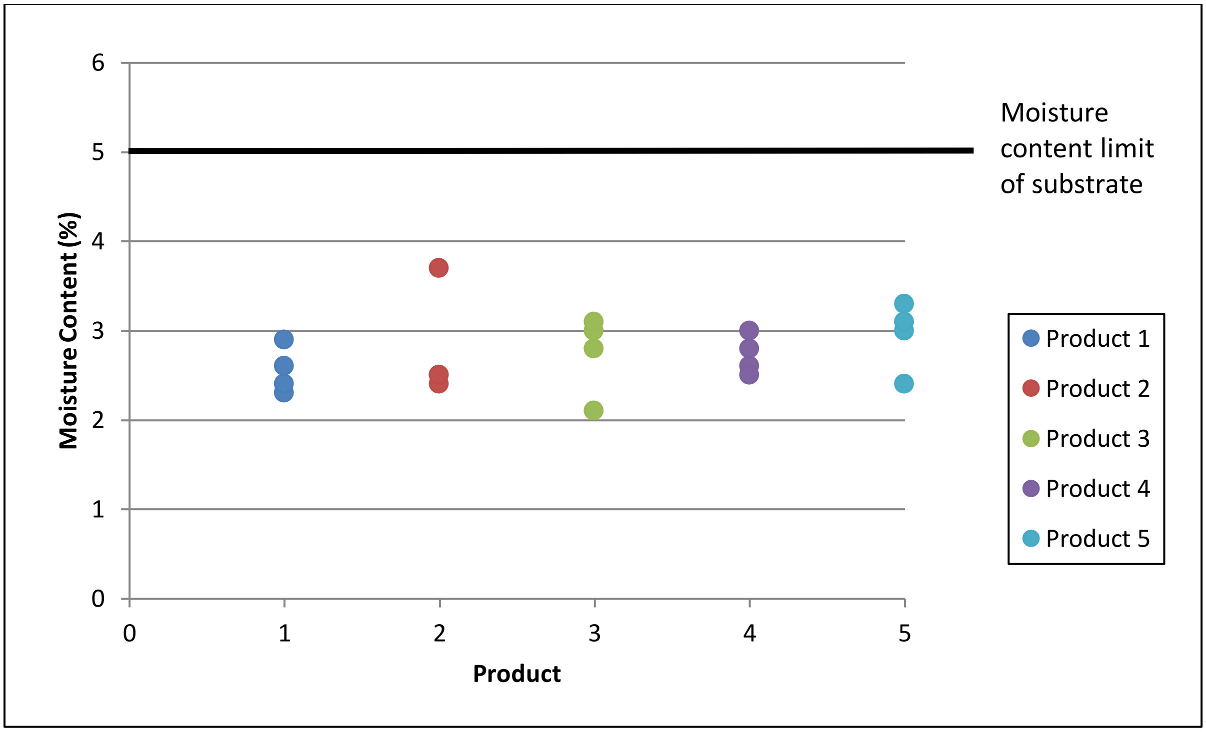
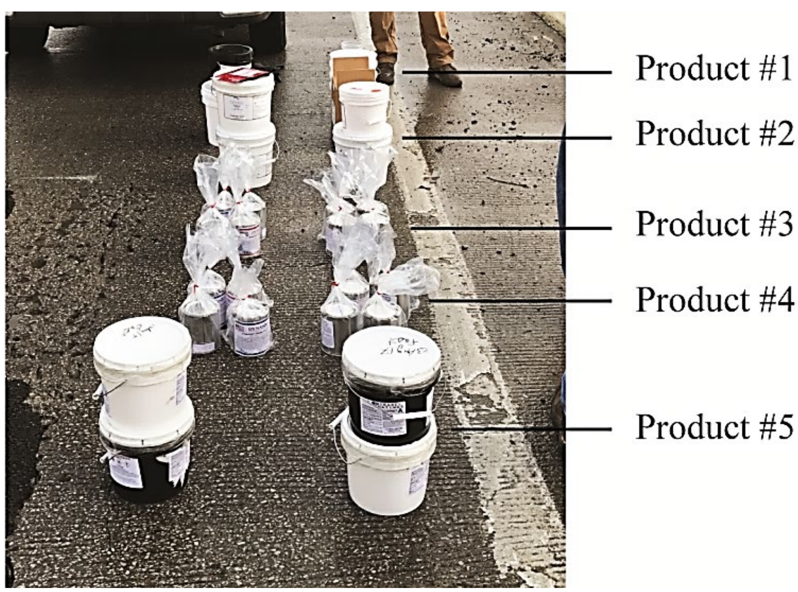
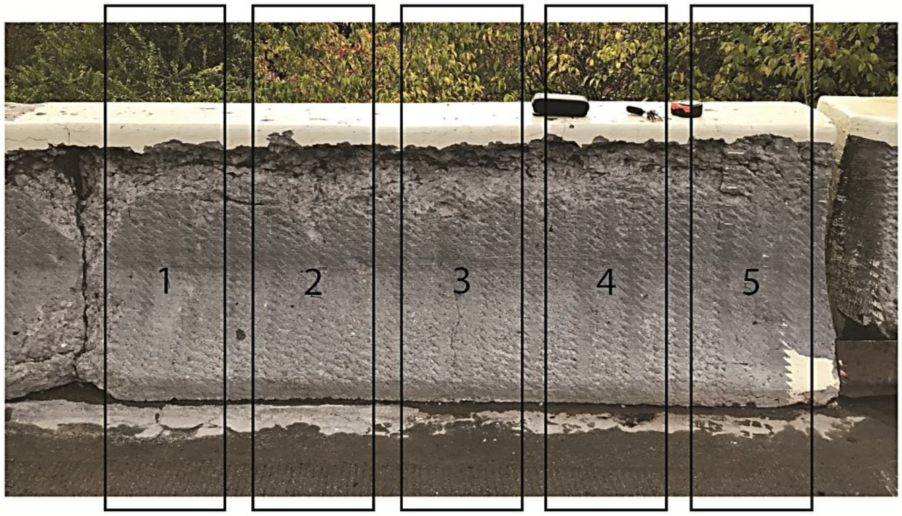


Figure 29: Moisture content of parapet wall sections for Gantz Rd. Bridge (11.02.17), Application No. 1

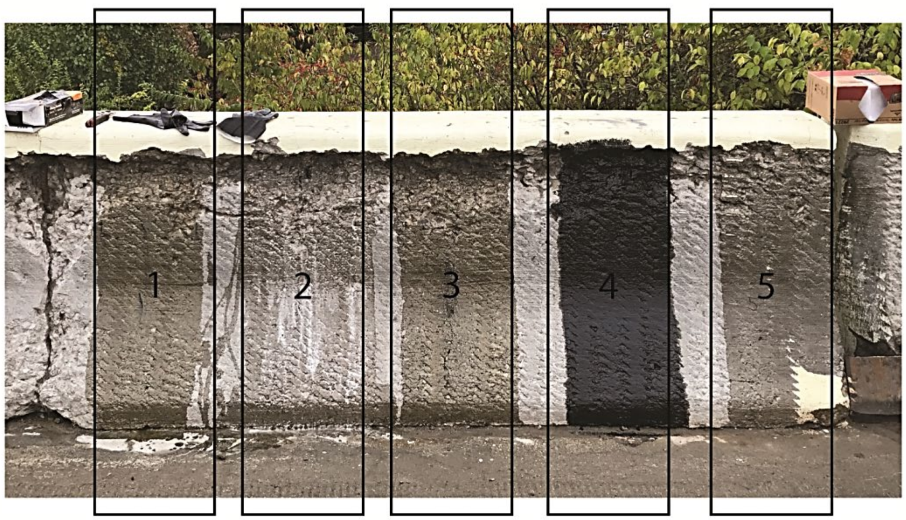
The following figures, **Figures 30 a-f** display the process of applying the five polyaspartic products including the primers and top coats for a total of four layers.



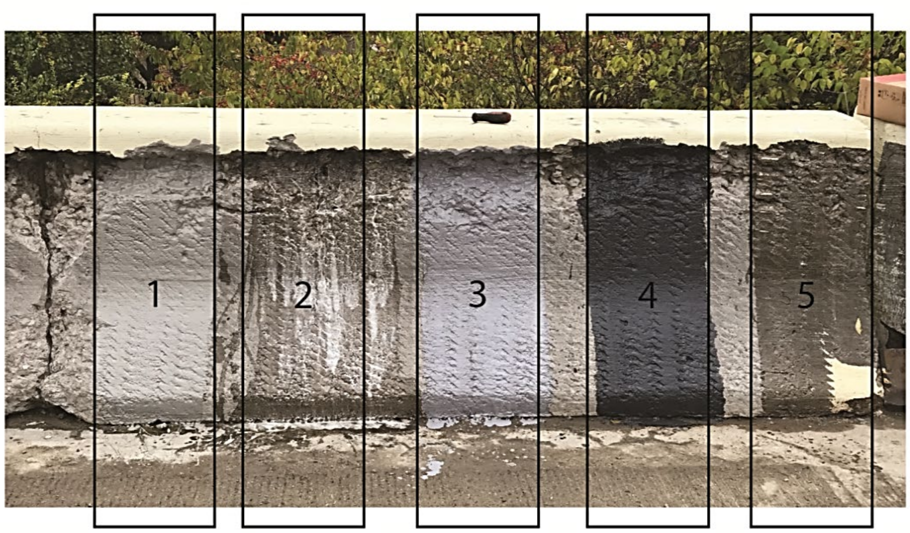
a) Product Identification



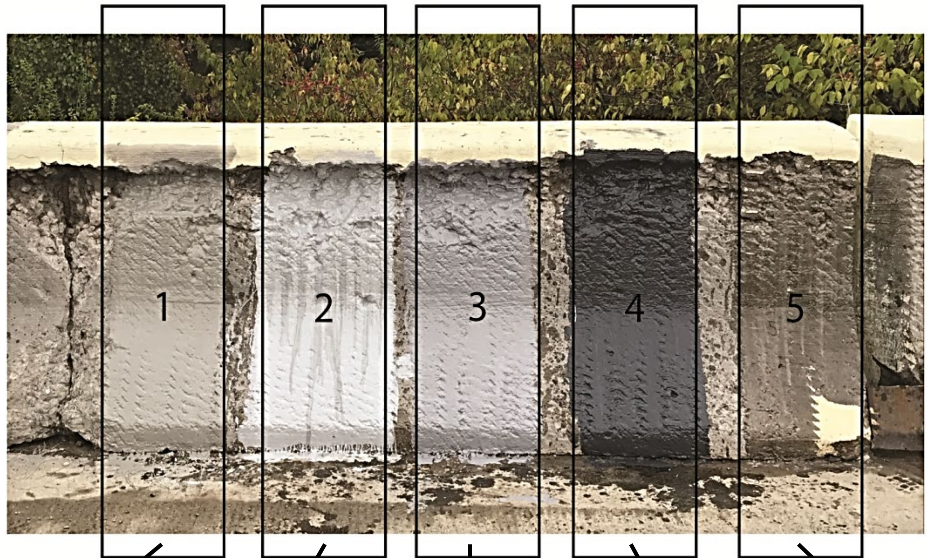
b) Designated Coating Areas



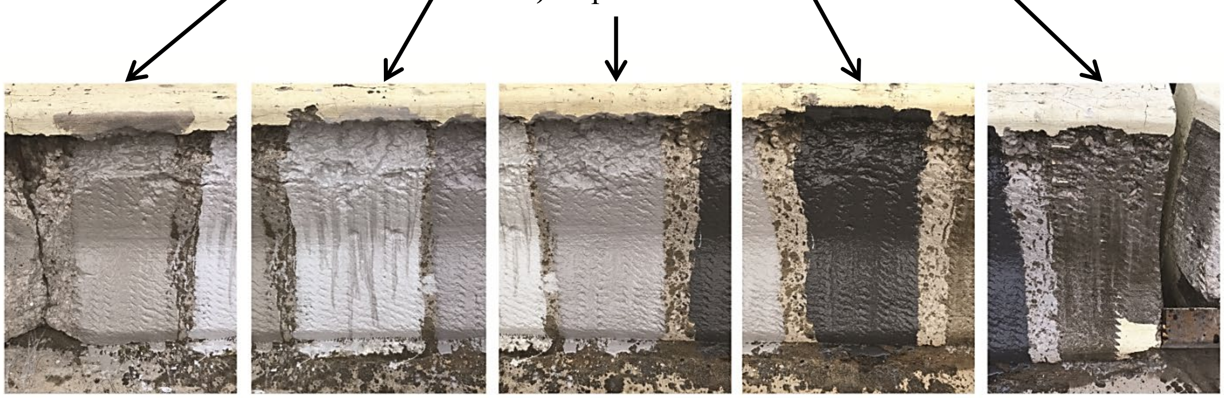
c) Primer Coat



d) Top Coat #1



e) Top Coat #2



f) Top Coat #3

Figure 21 Application No. 1: Primer and top coat polyaspartic applications on Gantz Rd.

The coatings were applied over the bridge parapets that underwent hydrodemolition during the week of September 25, 2017. For polyaspartics there is a desired concrete surface profile (CSP) of 2-3 CSP. This is similar to that of a 40-80 grit sand paper. However, the goal of this research is to determine if the product can be applied as a protectant over concrete that has been subjected to hydrodemolition or pneumatic chipping. The products were applied over the exposed aggregate as that replicated the anticipated field condition. The maintenance workers used a sponge brush to get into the cracks of the coarse aggregate. Before application the ODOT workers removed loose concrete from application areas.

After application, ODOT workers observed that all of the polyaspartic products were easy to apply; however, they stated they preferred the products that had color or tint to them, because it was easier to spot the areas that they missed with the roller. They used sponge brushes in order to get the missed uncoated areas. Additionally, the workers stated they would prefer a faster process, but they did note that they were applying five different products, and that affected the application time. **Figure 21** illustrates the cure times for the polyaspartic primers and top coats.

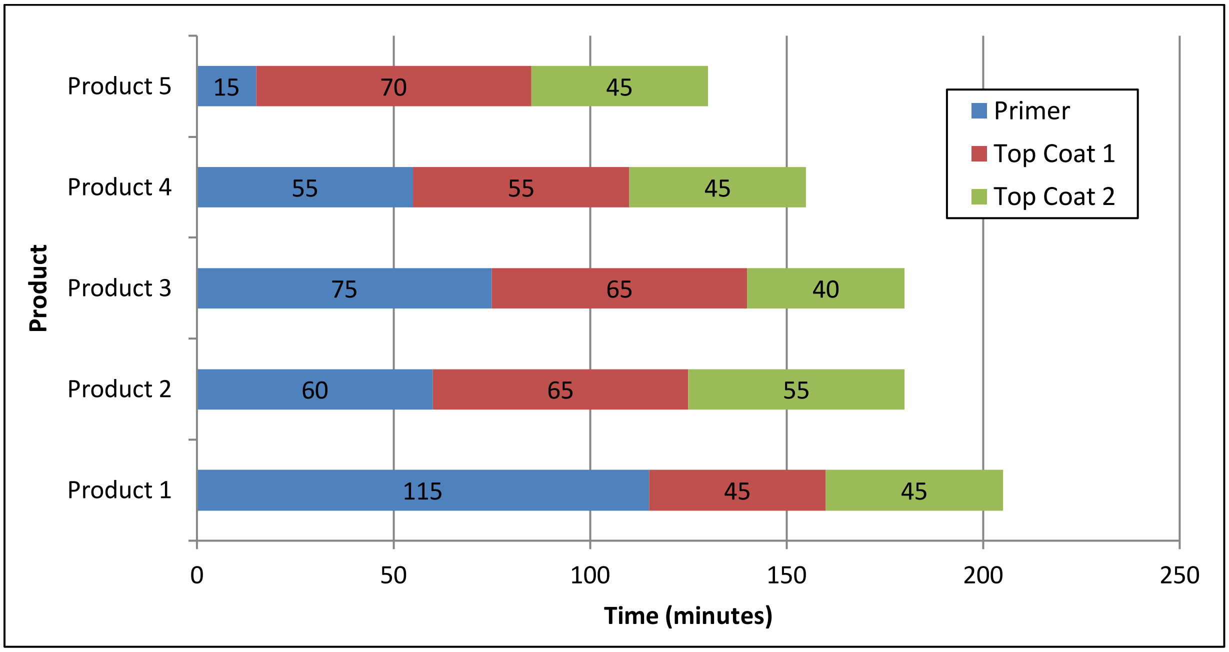


Figure 31: Field curing times of polyaspartics on parapet wall sections for Gantz Rd. Bridge (11.02.17), Application No. 1

In **Figure 31** there is no data for the third top coat, because the third top coat was left to cure indefinitely. Due to the cold and damp weather conditions, the products took longer to set than expected. The primers took much longer to cure than the top coats. The cure times shown in Figure 25 are likely a "worst case" condition and curing times will be much faster in warmer temperatures.

The following two figures, **Figure 32** and **Figure 33**, compare the field curing times to the manufacturer estimated curing times. Each coating cured (to a tacky state) within the recoat window outlined on the product data sheet provided by the polyaspartic manufacturers, except for product 3. Product 3 was ready for an additional top coat seven minutes outside of its expected recoat window (it took 53 minutes instead of the suggested 45).

The products must be tacky but dry to touch before application of additional coats; otherwise, the additional coats will pull off the bottom coating layers. This was seen during the application of the first top coat for product 5. The coating was not completely tacky before painting on another coat of the polyaspartic and the primer coat began to separate. Therefore, the maintenance workers waited longer before reapplication, and applied more of the polyaspartic material to be sure that the concrete surface of the parapet was fully covered. There wasn't any data for the cure time of the NT6 products (Product 4), because Creative Material Technologies has not yet released their product data sheets.

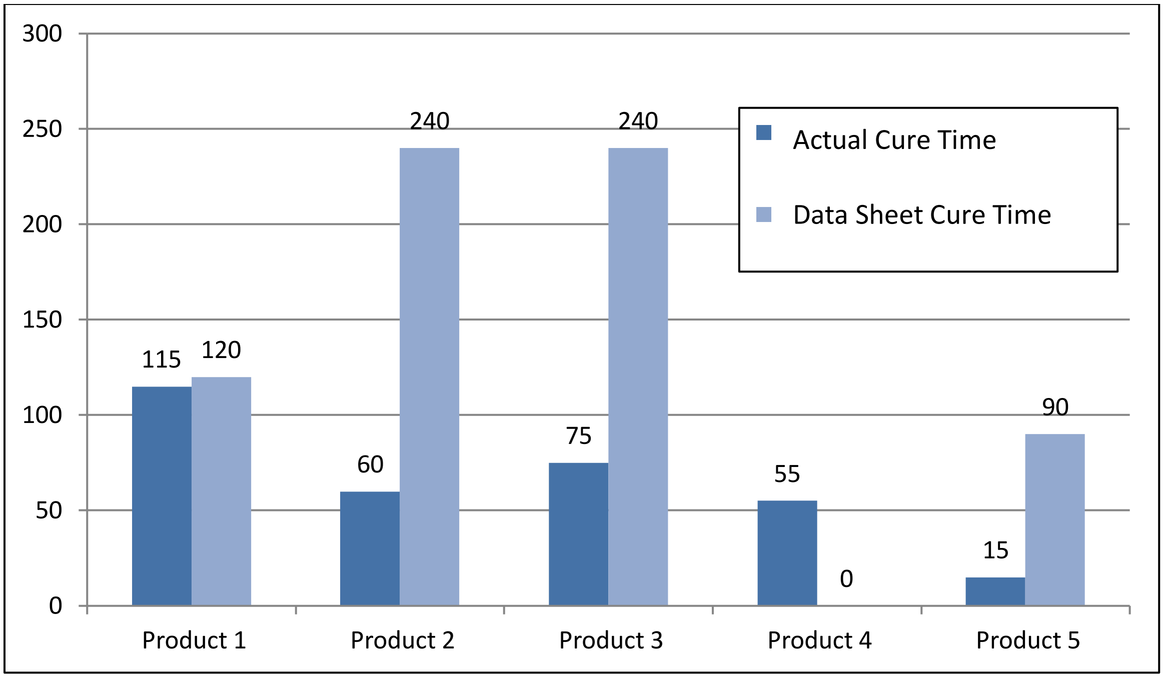


Figure 32: Curing time comparisons (actual to estimated) for Application No. 1 of the polyaspartic primers for Gantz Rd. Bridge (11.02.17)

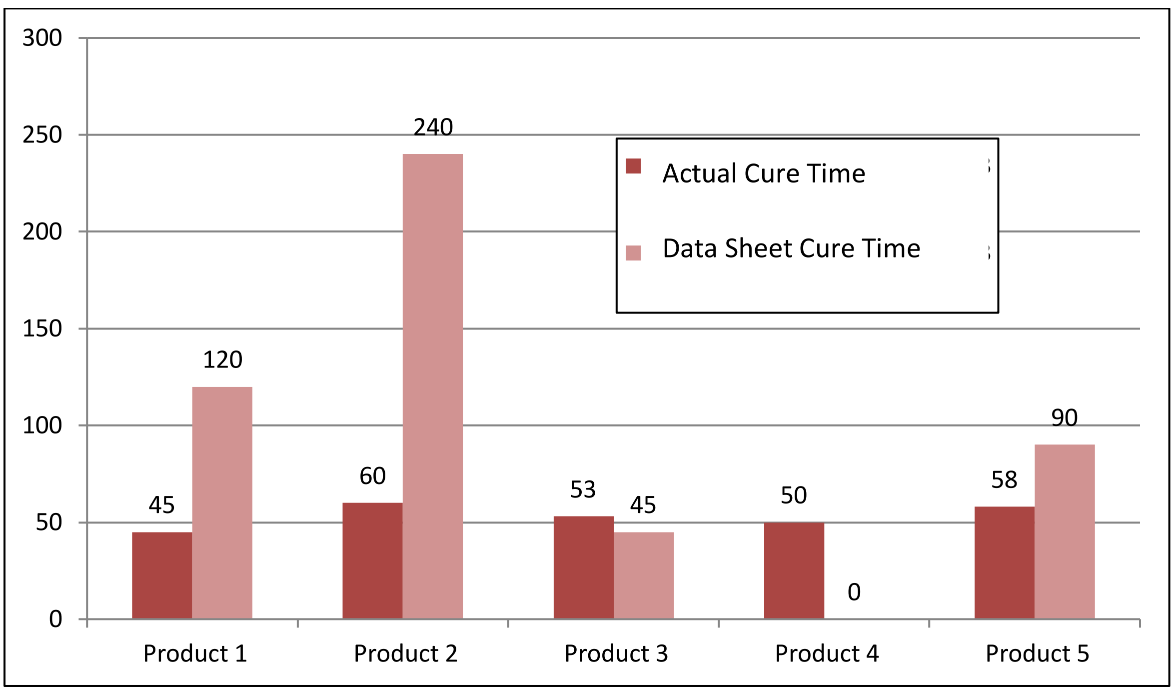


Figure 33: Curing time comparisons (actual to estimated) for Application No. 1 of the polyaspartic top coats for Gantz Rd. Bridge (11.02.17)

On the same day the same polyaspartics were applied to another section of the bridge, approximately 50 feet away from the first section (Gantz Rd. Bridge over I-270: Application No. 2). The purpose of the second application was to apply the polyaspartics over a section of the bridge that had not received any sort of concrete removal or any other prep work. This was done in order to see if the products could keep spalled concrete bridge pieces together, bridge cracks greater than 1/8”, and to mostly observe the behavior of the products after one winter if applied with poor substrate preparation. The primer applications of the second section on Gantz Bridge can be seen in **Figure 34** below, along with the application tools used during testing. Moisture contents are in **Figure 35**. The products are in opposite order compared to the first application on Gantz Bridge.

Figure 34: Application No. 2 of polyaspartic primer coatings

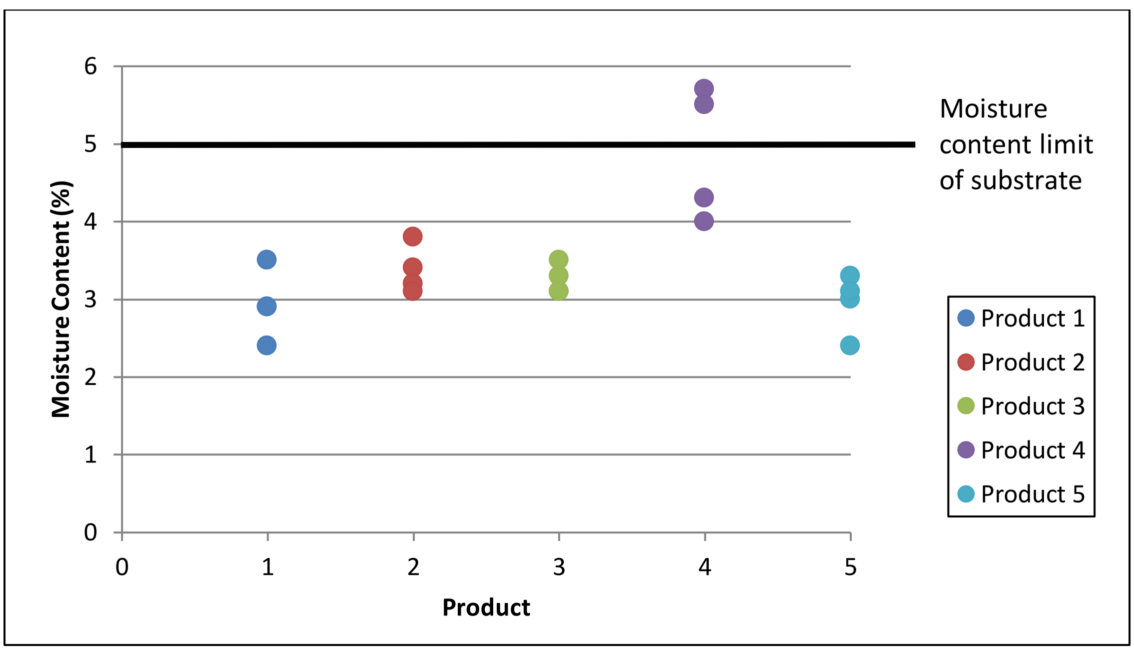


Figure 35: Moisture content of parapet wall sections for Application No. 2

The second location of polyaspartic application occurred on November 14, 2017 at the SR142 Bridge over I-70 in Madison County, OH. The location of the bridge and where the polyaspartics were applied can be seen in **Figure 36** below. The weather conditions during the time of the polyaspartic application on Gantz Rd. Bridge on November 14, 2017 were as follows:

- Clear with 0” of rain, but received 0.28” of rain over the previous two days.
- Average Temperature: 37.5°F
- Average Humidity: 84
- Observations: The parapet walls were damp from the cold and icy conditions.

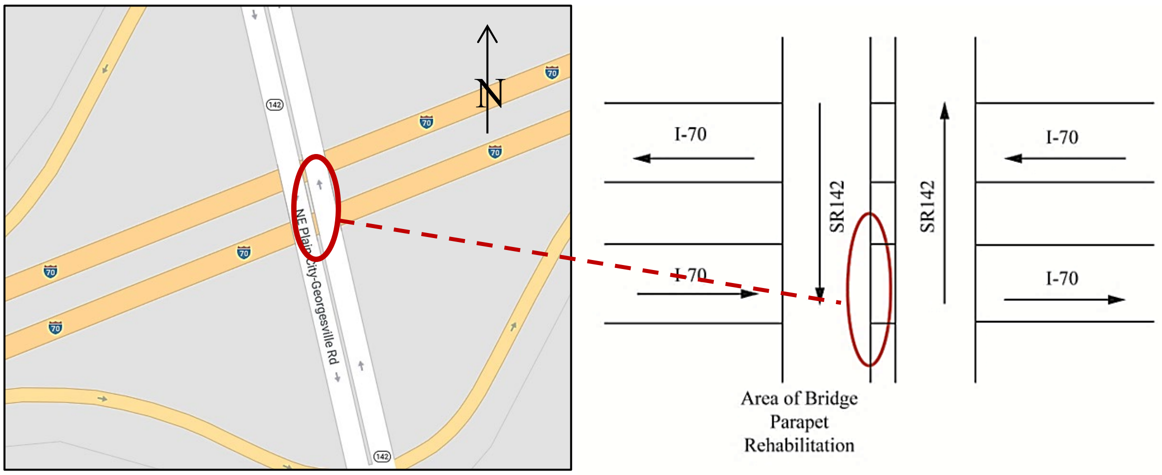


Figure 36: SR142 over I-70 in Madison County, OH

The same process was followed as the Gantz Rd. Bridge applications outlined in the section above (Testing Methods of Polyaspartic Field Applications). A total of four coats (one primer and three top coats) were applied to the parapet walls. **Figure 37** displays the curing order of the applied polyaspartics and corresponding primers. It appears that products 2 and 5 were the quickest products to cure. Product 3’s primer took the longest to reach its tacky state, it was not reached until products 5 and two were receiving their second coats, but its top coat was quick to cure. Product 1’s top coat appeared to take the longest to cure, while Product 4 closely trailed that trend. In **Figure 37** there is no data for the third top coat, because the third top coat was left to cure indefinitely. Due to the weather conditions, the products took longer to set than expected, but there was high humidity as noted above in the weather conditions above. **Figure 38** shows the application process.

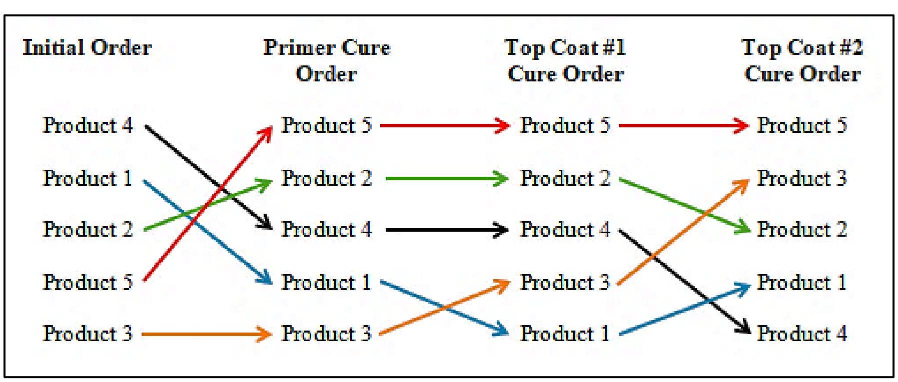


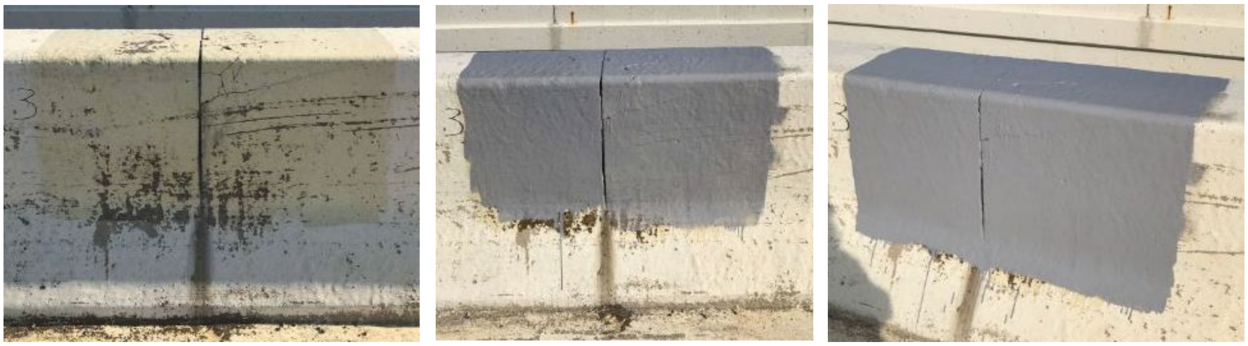
Figure 37: Polyaspartic product curing order

a) Product 4: Primer → Top Coat

b) Product 1: Primer → Top Coat

c) Product 2: Primer → Top Coat

d) Product 5: Primer → Top Coat



e) Product 3: Primer ⟶ Top Coat

Figure 38: Photos of polyaspartic primer and top coat applications on SR142

After application the ODOT workers noted that application was easy, but suggested an air sprayer. They did not want to bend over to coat the parapets. They appreciated the products with tints, because they could easily coat over any graffiti. Additionally, after the second application tiny air bubbles appeared in the coatings (**Figure 39)**. This is known as outgassing. Outgassing refers to the action of air or gas releasing from the concrete which causes pinhole bubbles (Lux, 2014). This condition is typically temporary, but usually occurs if the concrete has excessive air, or when moisture is leaving the surface, and/or the air is moving in and out of the slab as a result of temperature changes (Lux, 2014). This is why the manufacturers typically require moisture content in the concrete at a level below 5%.

Figure 39: Air bubbles found in product 1 and product 4 after Application No. 1 on SR142

Polyaspartic Field Results after one Winter Season (Nov. 2017 – May 2018)

On May 16, 2018, the University of Cincinnati research team went to Columbus, OH to take field observations of the polyaspartic polyureas that were applied on two different bridge parapet walls during the previous year (November 2nd and 14th of 2017).

Along with field observations, a few field tests were conducted to see how the polyaspartic material adhered to the concrete substrate. The first test, the V-notch bond test (known as "The Standard Test for Evaluating Adhesion by Knife") from ASTM D6677-07 (2012), consisted of using a box cutter with a sharp blade to cut an upside down "V" shape into the coating. The angle between to the two lines of the "V" ranged from 30-45 degrees. The edge of the blade was used to try and pry up the coating from the corner of the V-shape. A well-bonded coating will not pry up or it will pull the concrete off along with the pried polyaspartic material. Meanwhile, a coating that has not bonded to the concrete parapet wall will separate. **Figure 40** shows sample cuts made onto the coatings under laboratory conditions according to ASTM D6677-07 (2012).

Figure 40: Example V-notch cuts on polyaspartic samples in the laboratory

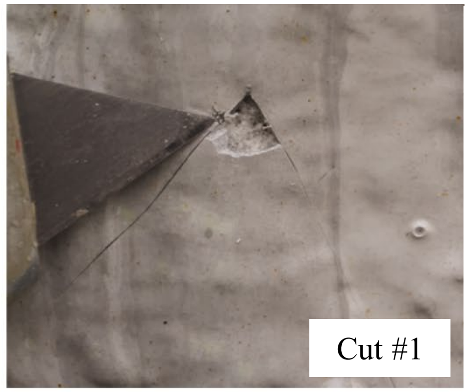
The following figures (**Figures 41-46**) will outline the V-notch bond test conducted on the five polyaspartic products applied during application no. 1 on Gantz Rd. Bridge on November 2, 2017. Products 2, 3, and 4 outperformed products 1 and 5.

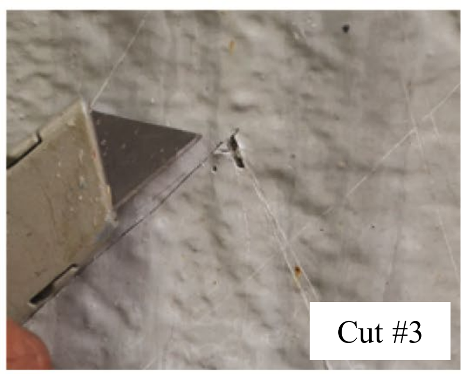
Product 1: Versaflex

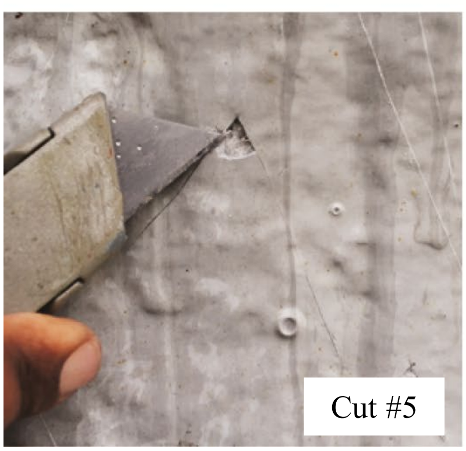
Photos of the polyaspartic coating (Application No. 1) after one winter on Gantz Rd. Bridge.

Primer: VF20

Top Coat: Aliphatic Clear Coat







<u>Observations</u>:

Product 1 performed well, but did not perform as well as products 2, 3, and 4, because more of the product was peeled off than the products listed above. However, when peeled, the surface of the concrete and aggregate came off with the small piece of polyaspartic that was pulled off (substrate failure). Therefore, the polyaspartic adhered properly and well to the substrate. The coating peeled off all of the five notch cuts.

This surface had been prepped weeks earlier with the CONJET 327 hydrodemolition equipment.

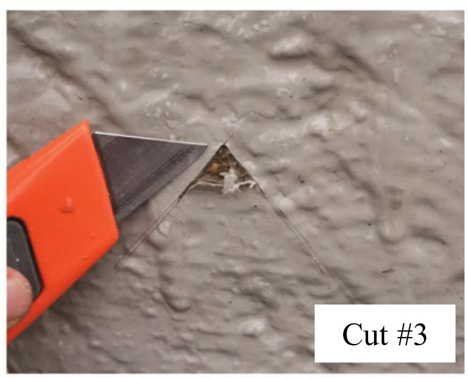
Overall, this polyaspartic coating successfully sealed the concrete bridge parapet for one winter, but did not outperform products 2, 3, and 4.

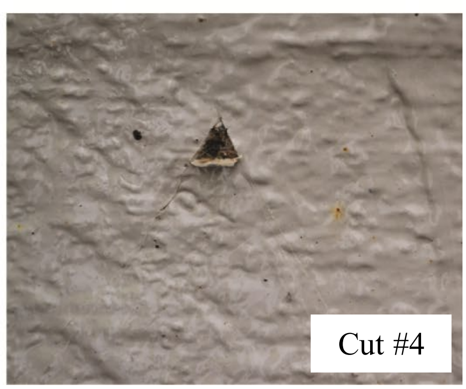
Figure 41: Testing: Five V-notch knife cuts were made with a box cutter on product 1

Product 2: Citadel Floor / Rust-Oleum
Photos of the polyaspartic coating (Application No. 1) after one winter on Gantz Rd. Bridge.

Primer: Polyurea 350

Top Coat: Polyurea Polyaspartic RG-80X





<u>Observations</u>:

Product 2 also performed well regarding the fact that when peeled, the surface of the concrete and aggregate came off with the small piece of polyaspartic that was pulled off (called substrate failure). Additionally, the polyaspartic adhered properly and well to the substrate. The coating peeled off the concrete surface for only two of the five notch cuts.

This surface had been prepped weeks earlier with the CONJET 327 hydrodemolition equipment.

Overall, this polyaspartic coating successfully sealed the concrete bridge parapet for one winter.

Figure 42: Testing: Five V-notch knife cuts were made with a box cutter on product 2

Product 3: Creative Material Technologies
Photos of the polyaspartic coating (Application No. 1) after one winter on Gantz Rd. Bridge.

Primer: DYNA-PRIME N-23

Top Coat: DYNA-PUR 7416BL

Observations:

Product 3 also performed well regarding the fact that when peeled, the surface of the concrete and aggregate came off with the small piece of polyaspartic that was pulled off. Despite the substrate failure, there was one notch cut where no aggregate was attached to the coating. However, overall the polyaspartic adhered properly and well to the substrate. The coating peeled off the concrete surface for only two of the five notch cuts, and was not attached to only one cut.

This surface had been prepped weeks earlier with the CONJET 327 hydrodemolition equipment.

Overall, this polyaspartic coating successfully sealed the concrete bridge parapet for one winter.

Figure 43: Testing: Five V-notch knife cuts were made with a box cutter on product 3

Product 4: Creative Material Technologies

Photos of the polyaspartic coating (Application No. 1) after one winter on Gantz Rd. Bridge.

Primer: DYNA-PRIME N-23-NT6

Top Coat: DYNA-PUR 7416BL-NT6

Observations:

Product 4 performed well regarding the fact that when peeled, the surface of the concrete and aggregate came off with the small piece of polyaspartic that was pulled off. This is called a substrate failure, meaning that the polyaspartic adhered properly and well to the substrate. The coating peeled off the concrete surface for only two of the five notch cuts.

This surface had been prepped weeks earlier with the CONJET 327 hydrodemolition equipment.

Overall, this polyaspartic coating successfully sealed the concrete bridge parapet for one winter.

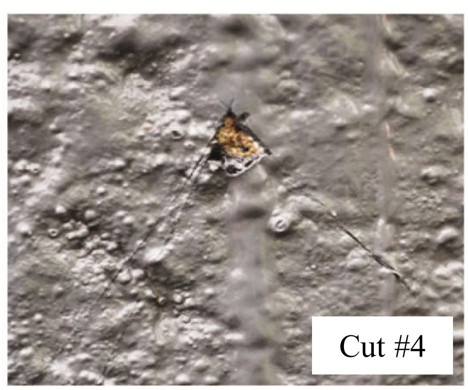
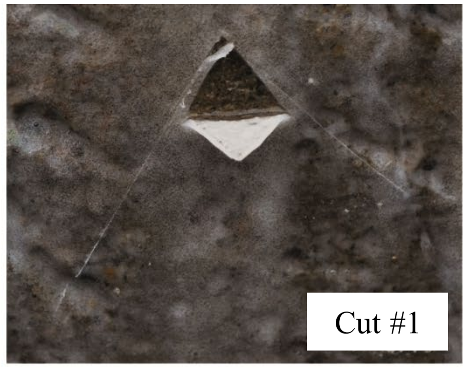
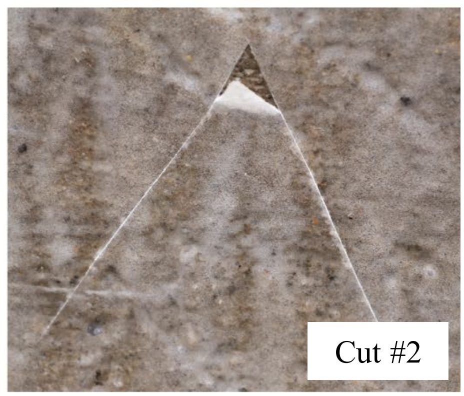


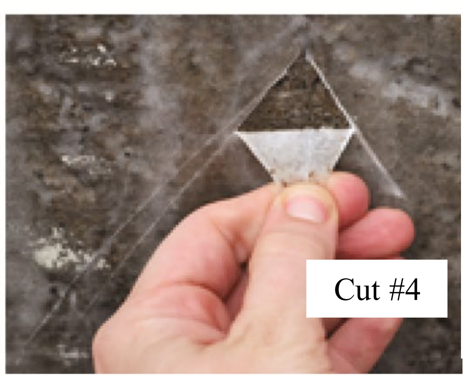
Figure 44: Testing: Five V-notch knife cuts were made with a box cutter on product 4

Product 5: Mirabel Coatings
Photos of the polyaspartic coating (Application No. 1) after one winter on Gantz Rd. Bridge.

Primer: Polyaspartic Slow
Top Coat: Polyaspartic Slow







Observations:

Product 5 performed the worst out of all five products. The coating peeled straight off of the concrete for all of the five notch cuts. Since the coating peeled straight off of the concrete, it was apparent that there was no adhesion between the concrete substrate and the polyaspartic coating. This coating had the same formula for the primer and the top coat.

This surface had been prepped weeks earlier with the CONJET 327 hydrodemolition equipment.

Overall, this polyaspartic coating did not successfully seal the concrete bridge parapet wall for one winter.

Figure 45: Testing: Five V-notch knife cuts were made with a box cutter on product 5

An additional note regarding product 1, chunks of the polyaspartic coating appeared to be missing from the parapet wall. The failure of the coating appeared to be a substrate failure. It was hoped that the coating would restrain any pieces of concrete that had come loose and prevent them from falling. This did not appear to be the case.

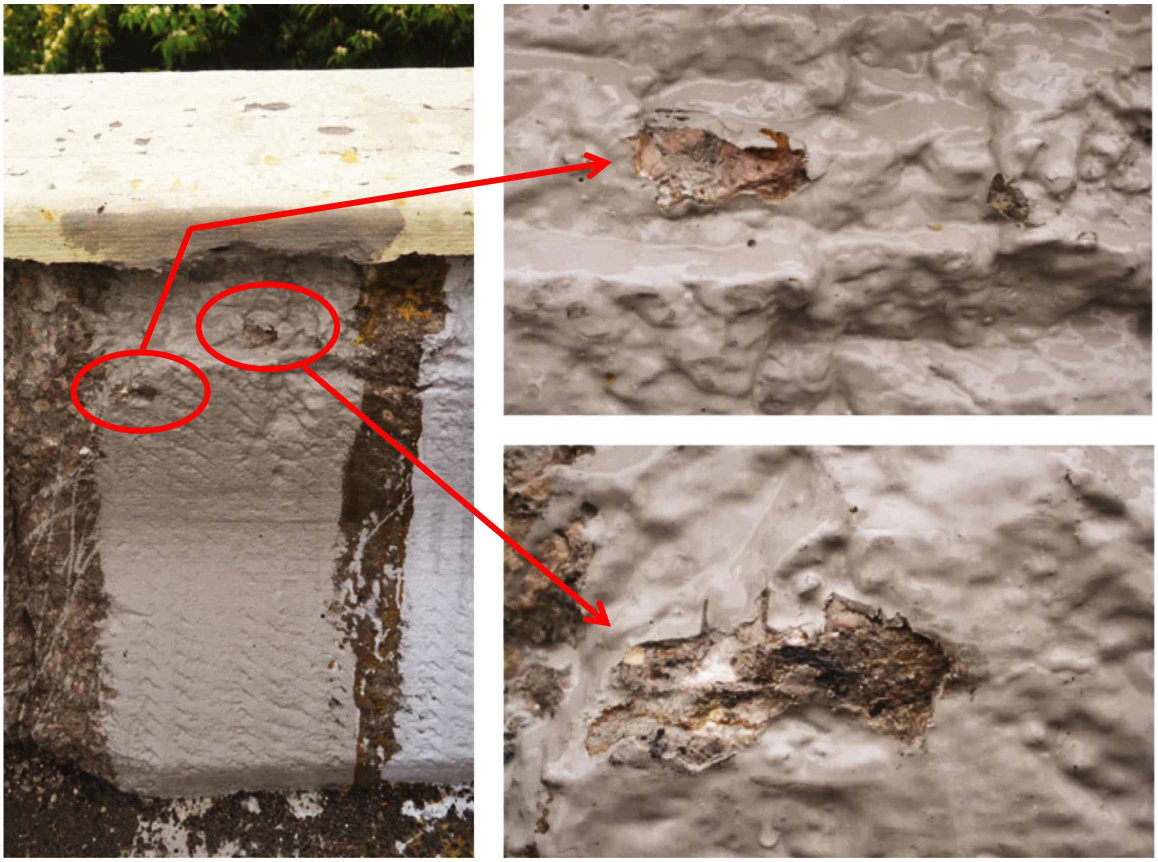


Figure 46: Product 1 substrate and polyaspartic coating failure

After completing the V-notch test on the first application the research team went to the second application on the same bridge. These parapets were not prepared before applying the polyaspartics, so coatings were applied straight onto the existing epoxy.

The first observation is that proper preparation is important. During application back in November, a second coat was applied to product number 5 before the primer was tacky and the coating came off onto the paint roller instead of sticking to the concrete surface. This likely led to a failure of the coating. As shown the photos below, the polyaspartic polyurea was missing from most of the parapet wall after one winter. It appeared as if the coating had just flaked off as shown in **Figure 47**. This could be a result of the problems with the application of product 5, the cold/wet weather or that the product just does not adhere well to unprepared concrete surfaces.

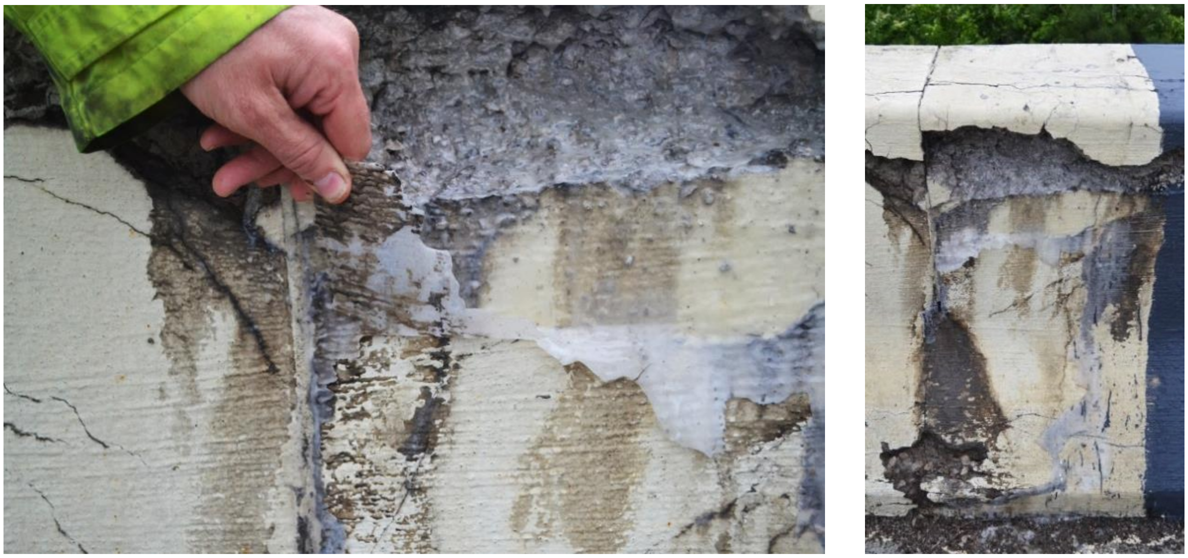


Figure 47: Failed product 5 of Application No. 2 on Gantz Rd. Bridge

For the coatings which did adhere, it was noted that there was some reflective cracking that occurred through the coating (**Figure 48)**. This only appeared to occur in the area where the coating was applied over the existing epoxy coating. This may be caused by a lack of bond.

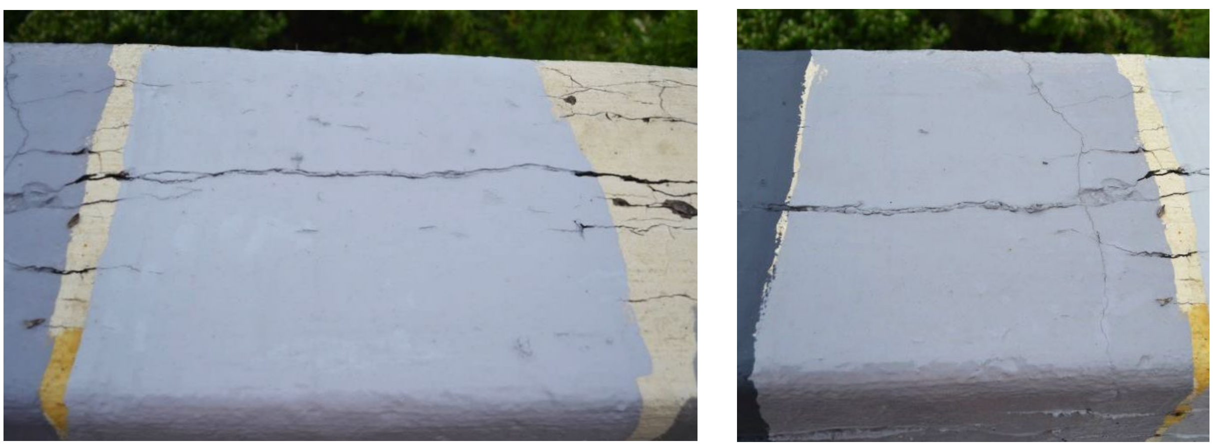


Figure 48: Surface cracking through the polyaspartic coating placed over existing epoxy on the top of the parapet wall (the cap)

For the four coatings which did appear to bond to the epoxy, the notch test was used. Here the coating pulled off the existing epoxy surface, but it was observed that the epoxy came off with the polyaspartic. The polyaspartic appeared to bond very well to the epoxy and the failure was in the bond of the epoxy to the concrete. It was noted that if there were any reasonably large gaps in the epoxy, the polyaspartic bonded well to the concrete beneath. Therefore, the prior application of the epoxy did not appear to affect the bond of the polyaspartic in areas where the epoxy had come off. The polyaspartic applied over the epoxy seemed to stay intact. It was not separated until it was pulled off with the notch test. This may still provide a protective coating, but is likely to be a short term solution. The polyaspartic may provide protection for a year or two until a permanent repair is made.

Figure 49: V-notch test on unprepped parapets with existing epoxy from Application No. 2 on Gantz Rd. Bridge

Later on May 16, 2018, the University of Cincinnati research team went to the second bridge, SR142 over I-70 in Madison County, OH to take field observations of the polyaspartic polyureas that were applied. These parapets were not prepared before coating application, so the polyaspartic coating was applied straight over the existing epoxy. **Figure 49** displays the condition of the coatings from the V-notch test. The results were identical to Gantz Road. The polyaspartic bonded to the epoxy, but the epoxy then debonded from the parapet wall. In those places where polyaspartic was bonded directly to concrete, either because deterioration of the concrete left exposed aggregate or the epoxy had deteriorated, the polyaspartic seemed to bond quite well.

The impact test consisted of using a stake and hammer to impact the sides of the parapet (**Figure 50**). The intent of striking the parapets with the stake was to dislodge some concrete see if the coating would hold loose pieces of concrete after impact. The photo below displays how a stake and hammer was used to impact the coated parapet walls. For some of the walls, the stake was struck five times. For others, the stake was intentionally placed in areas and struck until a chunk of the concrete parapet became detached. However, the detached chunks were held to the parapet wall by the coating itself.

Figure 50: Impact test on parapets with stake and hammer

After completing this test in the field, it was observed that the polyaspartic does in fact hold the loose concrete pieces to the parapet wall after impact, see **Figure 51**.

Figure 51: Impact test on parapets with existing epoxy from Application No. 1 on SR142 Bridge over I-70

Additionally, small cracks were observed in some rough aggregate areas, see **Figure 52** below. However, the bond seemed unaffected.

Figure 52: Small cracks observed in rough aggregate areas of the coated parapet walls

During application product number 3, some bubbles were noticed in the coating due to outgassing. As a result, some bubbles were found in the polyaspartic coatings on the parapet where water bubbled out of the cracks. However, other than looking unsightly, it did not seem to impair performance, see **Figure 44**.

Figure 53: Bubbled polyaspartic product observed after one winter

LABORATORY RESEARCH FINDINGS: POLYASPARTIC POLYUREAS

Laboratory Testing of Polyaspartic Products

For this portion of the research project, various polyaspartic coating materials were investigated under laboratory conditions. The goal of this investigation was to investigate the performance of the coatings after being subjected to the following tests: ASTM D7234 "Standard Test Method for Pull-Off Adhesion Strength of Coatings on Concrete Using Portable Pull-Off Adhesion Testers", ASTM C78 "Standard Test Method for Flexural Strength of Concrete" for crack resistance propagation", ASTM C469 "Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression" for confining deterioration, and ASTM C666 "Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing" to replicate freeze-thaw conditions in Ohio. In addition, a wet-dry test was performed simulating a 30-minute rain event with a recurrence period of 1 in 5 years for the state of Ohio. The purpose of the laboratory tests was to determine whether the polyaspartic polyureas are effective at containing loose concrete and preventing further deterioration, and if so, which products would perform the best compared to each other. This information was used to choose products for field testing. Manufacturer application guidelines were followed during testing and are provided later in this report.

An experimental research program that comprised of several types of mechanical testing and durability testing was devised to meet the stated objectives. Details of the materials studied and the procedures followed are presented in the **Laboratory Research Methodology** section. The results along with a discussion are presented the **Laboratory Results and Discussion** section.

Laboratory Research Methodology

Manufacturer and Product Selection

For the first part of the study, the research team identified four manufacturers of polyaspartic polyurea coating systems for concrete. The following tables list the products evaluated along with manufacturer's recommended layer thicknesses and comments for specific products observations (**Table 11** to **Table 15**).

It should be noted that the manufacturers supply the materials by batch, so for field use it is relatively easy to combine on container of one part with one of the other part to get the correct proportions. For laboratory scale testing, however, it is more difficult to get the correct proportions with small batches. This may affect laboratory results.

Table 11: VersaFlex product thickness and application information

VersaFlex Product	Mixing Ratio (A:B)	Recommended Layer Thickness	Notes
VF20 (Primer)	1:1	10 mils	The Quick Mender product had a short pot life once mixed (5 to 10 minutes). For this reason, it was not considered for further analysis.
Aliphatic Clear Coat	1:2	10 mils	
Clear Seal	1:1	--	
Quick Mender	1:1	--	

Table 12: Citadel Floor Finishing Systems / Rust-Oleum product thickness and application information

Citadel / Rust-Oleum Product	Mixing Ratio (A:B)	Recommended Layer Thickness	Notes
Polyurea 350 (Primer)	1:2	6-8 mils	--
Polyurea Polyaspartic RG-80X	1:1	4-6 mils	

Table 13: Mirabel Coatings product thickness and application information

Versaflex Product	Mixing Ratio (A:B)	Recommended Layer Thickness	Notes
Polyaspartic Clear Coat (Fast Curing)	1:1	--	The same product is used for both primer and top coat. However, the product can be diluted with methyl ethyl ketone (MEK) to reduce the viscosity of the product permitting better absorption by the porous concrete. Part A and Part B contain 84 percent solids. A reduction up to 60% solids is recommended. Depending on the volume prepared, dilute the product up to 1.4 times the initial volume prepared. Ex: (1) 500 ml of Part A and 500 ml of Part B are mixed for a total of 1000 ml. (2) Dilute the product to 1400 ml (1.4 x 1000). Therefore, 400 ml (1400-1000) of MEK is added to dilute the product.
Polyaspartic Clear Coat (Slow Curing)	1:1	--	

Table 14: Creative Material Technologies product thickness and application information

Versaflex Product	Mixing Ratio (A:B)	Recommended Layer Thickness	Notes
DYNA Prime N-23 (Primer)	1:1	--	--
DYNA-PUR 7416 Aliphatic Clear Coat (Top Coat)	1:1	--	
DYNA Prime N-23-NT6 (Primer)	1:1	--	
DYNA-PUR 7416-NT6 Aliphatic Polyurea (Top Coat)	1:1	--	

Concrete Surface Preparation

The International Concrete Repair Institute (ICRI, 1997) guidelines were instrumental in defining adequate surface preparation prior to application of coating. The surface must be clean, free of dust and debris (ICRI, 1997). According to product manufacturer recommendations, the surface moisture content must be below 3-5% (concrete scale) prior to application of the primer, which was checked with a concrete surface moisture meter. For this study a TRAMEX device was used.

Since hydrodemolition was not possible to conduct on small-scale laboratory samples, a pneumatic needle scaler was the chosen surface preparation method since it produces a similar concrete surface profile has that obtained with hydrodemolition. This required the removal of approximately 1/8" to 1/4" of concrete from the sample's surface exposing the coarse aggregate. The concrete surface profile (CSP) achieved was approximately 6 to 8 CSP (ICRI, 1997).

Product Application

For preparation, mixing and product application, manufacturer instructions were followed. The following general procedure was used:

1. Accurately measure the required volumes for Part A and Part B in separate containers.
2. Pour both products into a plastic disposal pan (paint tray is recommended for easy rolling/application).
3. Hand mix the product thoroughly for approximately two minutes. Do not use a mechanical mixer. It was found that mechanical mixing generated an excessive number of air bubbles.
4. Apply the product onto the prepared surface using a lint free (low lint) roller. A release or flow control roller is recommended for even application. The nap size will depend on surface profile of concrete. A 3/8 inch nap was used for this study due to coarse surface profile (CSP ranges from 6 to 8).

5. Allow the product to cure prior to the next application. The surface must be tacky (barely sticky to the touch without any product sticking to the finger) before applying the following coat. Time between coats depends on ambient environmental conditions.
6. Repeat steps 1 through 5 for application of the subsequent top coat layers until a desired thickness is reached.

NOTE: In laboratory environmental conditions (71°F, 50% RH), the time between each coat layer varied between 45 and 90 minutes. The pot life for each product once mixed varied as well; however, the products were in a workable state for 30 to 60 minutes. To dispose of unused product and rollers, keep them in their respective containers until they are fully cured (several hours to harden). At this point, they are no longer considered a hazardous product. Uncured products are controlled materials and must be disposed according to their product safety data sheet recommendations and/or state regulations.

Concrete Materials and Sample Preparation

For this study, a single concrete mixture (0.45 water-to-cement ratio) was used in the preparation of all concrete samples. The concrete mixtures were prepared with #57 crushed Limestone as the coarse aggregate and natural sand for the fine aggregate. A Type-I cement manufactured in Oklahoma was used in the mixture as well. The chemical composition of the cement is given in **Table 15**. An air-entraining admixture was also added to the concrete mixture in order to mimic the type of concrete used in Ohio. Mixture proportions are presented in **Table 16**. The air content of the concrete mixtures were 6.0% ± 1%.

Table 15: Chemical composition of Portland cement

Chemical composition (% by weight)					
MgO	C_aO	SO_3	SiO_2	Al_2O_3	Fe_2O_3
1.9	62.9	3.3	19.4	5.1	3.4

Table 16: Mixture design details

Mixture	**w/c**	**Water (kg/m^3)**	**Cement (kg/m^3)**	**Coarse Aggregate (kg/m^3)**	**Fine Aggregate (kg/m^3)**	**Air Entrainment (oz.)**	**Paste (%)**
1	0.45	163.2	362.5	1088.7	709.0	16.0	29.7

Materials were batched and mixed in a temperature-controlled environment and samples were cast following the standard methods of preparing concrete samples in a laboratory environment (ASTM C 192 Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory). In order to carry out the testing regimen, approximately 65 cylinders (4 in x 8 in, 100 mm x 200 mm), 42 concrete blocks (6 in x 6 in x 6 in, 150 mm x 150 mm x 150 mm) and 69 prisms (3 in x 4 in x 12 in, 74 mm x 100 mm x 300 mm) were prepared and demolded after 24 hours. After demolding, the samples were placed into a moisture room to cure for the ASTM limit of 28 days.

After curing, the samples were placed into a controlled dry room (73°F, 23°C, 50% RH) to allow internal moisture to evaporate in order to achieve field conditions similar to what the parapets are exposed to in Ohio. Meanwhile, the surfaces of the samples were prepared as that described previously to obtain the required surface texture and physical characteristics determined prior to product application.

Pull-off Testing

To assess the bond performance of the products to the surface of concrete, pull-off testing as per ASTM D7234 (Standard Test Method for Pull-Off Adhesion Strength of Coatings on Concrete Using Portable Pull-Off Adhesion Testers) was performed. Several 6 in x 6 in x 6 in block samples were used for this test. Two surface test conditions were evaluated; a “dry” and a “wet” surface. One day (24 hours) prior to the application of the products, the blocks were either kept in a dry environment (50% RH) or placed in a wet environment (immersed in tap water) to simulate different environmental conditions encountered in the field and the influence of moisture intake. Next, the “dry” and “wet” samples were removed from their environment and allowed to dry until they reached a surface reading of 3% to 4% moisture content (concrete scale) measured with a (TRAMEX) moisture meter.

Additionally, the influence of the layer thickness of the coating material on its bond strength was also evaluated. Three thicknesses were assessed, which were prepared by applying 1, 2 and 3 coats of the product. For each specimen type, two test replicates were performed on one block (**Figure 54**).

Figure 54: Example of Pull-off Testing

Flexural Testing

Flexural testing as per ASTM C78 (Standard Test Method for Flexural Strength of Concrete Using Simple Beam with Third-Point Loading) was to determine the performance in resisting crack initiation and propagation under tensile loading (**Figure 55**). For each coating system evaluated, the sample size consisted of three beam replicates and three notched-beam replicates (3 in x 4 in x 12 in, 74 mm x 100 mm x 300 mm) in accordance with the standard. The beams were cast, conditioned, and prepared following the methodology described previously. Only one coating thickness was evaluated, the three-layer system.

Figure 55: Flexural test setup

Rapid Freeze-Thaw Testing

Rapid freeze-thaw testing was conducted to investigate the performance of the coating systems as per ASTM C666 (Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing). The beam samples were prepared and conditioned as that described previously. Three beams were prepared per coating product. Once the coating was sufficiently cured, the beam samples were vacuum saturated prior to placing in the freeze-thaw chamber. Next, the ASTM C 666 procedure was followed to determine the residual dynamic modulus of elasticity of each sample and durability factor (**Figure 56**). At the end of the test period, a visual characterization of the coating material was conducted to evaluate the condition of the coating post temperature cycling.

Figure 56: Freeze-thaw chamber with sample beams

Salt Solution Ponding Test

Sodium chloride salt solution ponding testing was conducted to investigate the performance of the coating systems in terms of resistance to coating degradation. The exposure regimen was conducted as per ASTM C1543 (Standard Test Method for Determining the Penetration of Chloride Ion into Concrete by Ponding). However, chloride penetration within the concrete was not measured as the coating layer appeared continuous at the end of the test period.

All samples' surfaces were prepared to the desired concrete surface profile and, then, surfaces were primed and coated with the respective products. Here, a worst case scenario was investigated; only one coat of product was applied to sample surfaces. After 3 months of salt solution ponding, to determine coating performance, a visual caracterisation of sample surfaces was performed along with a pull-off test to evaluate the residual bond strength of the coating products.

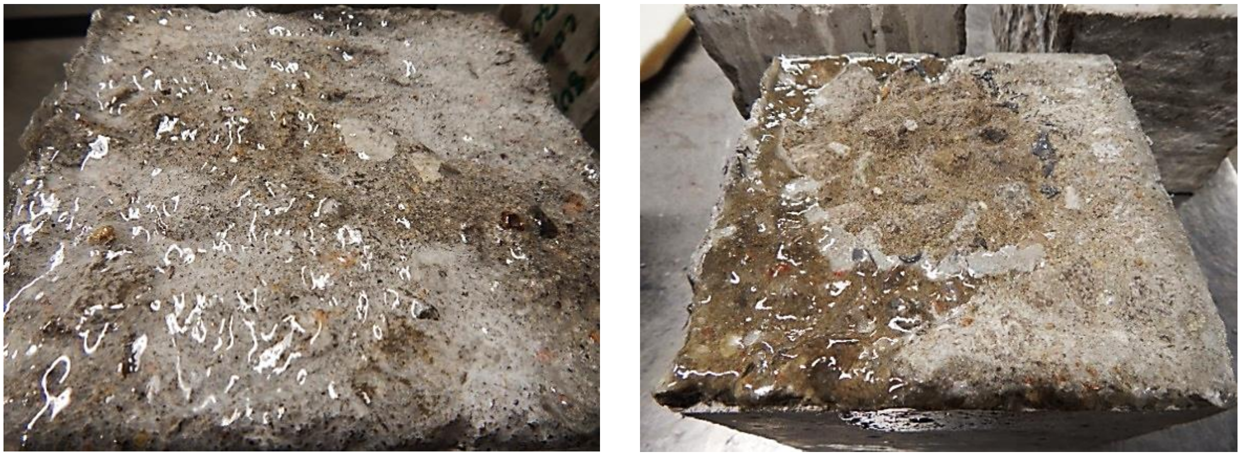
Results and Discussion

Results for Pull-off Test

The pull-off test (ASTM D7234) was performed to assess the bond performance of each of the coating systems. During this test the influence of layer thickness and moisture of the concrete at time of application on bond performance was evaluated. It has been reported that the presence of moisture within the substrate may affect the bond performance (also noted by manufacturers). The polyaspartic coatings evaluated generally do not exhibit disbonding and are generally good systems to use because of their resistance to moisture. However, they can experience poor substrate adherence if exposed to water and moisture in the air during the coating process (Tator, 2015). Primer coats are essential in order to ensure higher bond strength and reduce the risk for disbondment (Ha, 2013). Still, post-application moisture transport and vapor transport may also affect bond performance by the creation of surface blisters (Zhang, 2012) (Ha, 2013). The experimental regimen devised assessed these principles. The average results and corresponding coefficients of variation obtained for each specimen type are presented in the following tables (**Table 17** to **Table 22**) along with a bar type graph demonstrating two standard deviations (2s) from the mean to aid in the comparative analysis.

VersaFlex Aliphatic Clear Coat and Clear Seal

The following are a few observations of the test surface pre- and post-testing. The samples prepared with the Aliphatic Clear Coat did not achieve proper hardening. After an extended period of curing, the applied product was still tacky to the touch. Therefore, no thickness measurements were taken for these samples. This problem may be attributed to inaccurate measuring of each parts and mixing of product. This resulted in low bond strength and failure in the coating and bond interface. A few of the samples prepared with the Clear Seal coating system demonstrated disbondment from the concrete surface which resulted in low bond-strength and high variability in the measurements. There were signs of coating flaking for all samples post-testing after an extended period of time (**Figure 57**). Pull-out test results are presented in **Table 17**.



(a) (b)

Figure 57: (a) Rust-Oleum RG-80X disbondment prior to testing flaking and (b) VersaFlex Clear Seal flaking from surface

Table 17: Results of the pull-out test for VersaFlex products

	Concrete Moisture Conditioning	Number of Coats	Coating Thickness (mils, ± 0.4)	Average Strength (psi)	Coefficient of Variation (%)
Aliphatic Clear Coat	Dry	One	10.7	232.2	32.9
	Wet		N/A	85.9	73.3
	Dry	Two	11.9	170.1	17.2
	Wet		N/A	182.9	38.1
	Dry	Three	N/A	22.3	40.4
	Wet		N/A	17.5	12.9
Clear Seal	Dry	One	10.6	298.9	48.1
	Wet		10.6	302.1	35.7
	Dry	Two	11.5	483.4	5.6
	Wet		11.4	168.6	98.7
	Dry	Three	14.1	556.5	4.9
	Wet		11.9	338.7	57.8

Observing the results for the samples prepared with the Aliphatic Clear Coat presented in **Figure 58**, there were no observable trends in regards to failure types, as failure types varied due to improper hardening of the coating. It would seem that the application of several coats during early-age curing may have further affected the curing mechanism of the coating. As seen in **Figure 59**, failures mainly occurred within the coating material or at the bond interface between the epoxied pull-disc and the coating interface. The highest average pull-load recorded was 1.64 kips (7.3 kN) for the one-layer coating system applied on the dry sample. Fracture types for both replicates are observable in **Figure 60**. Fracture occurred at the bond interface between the concrete and coating.

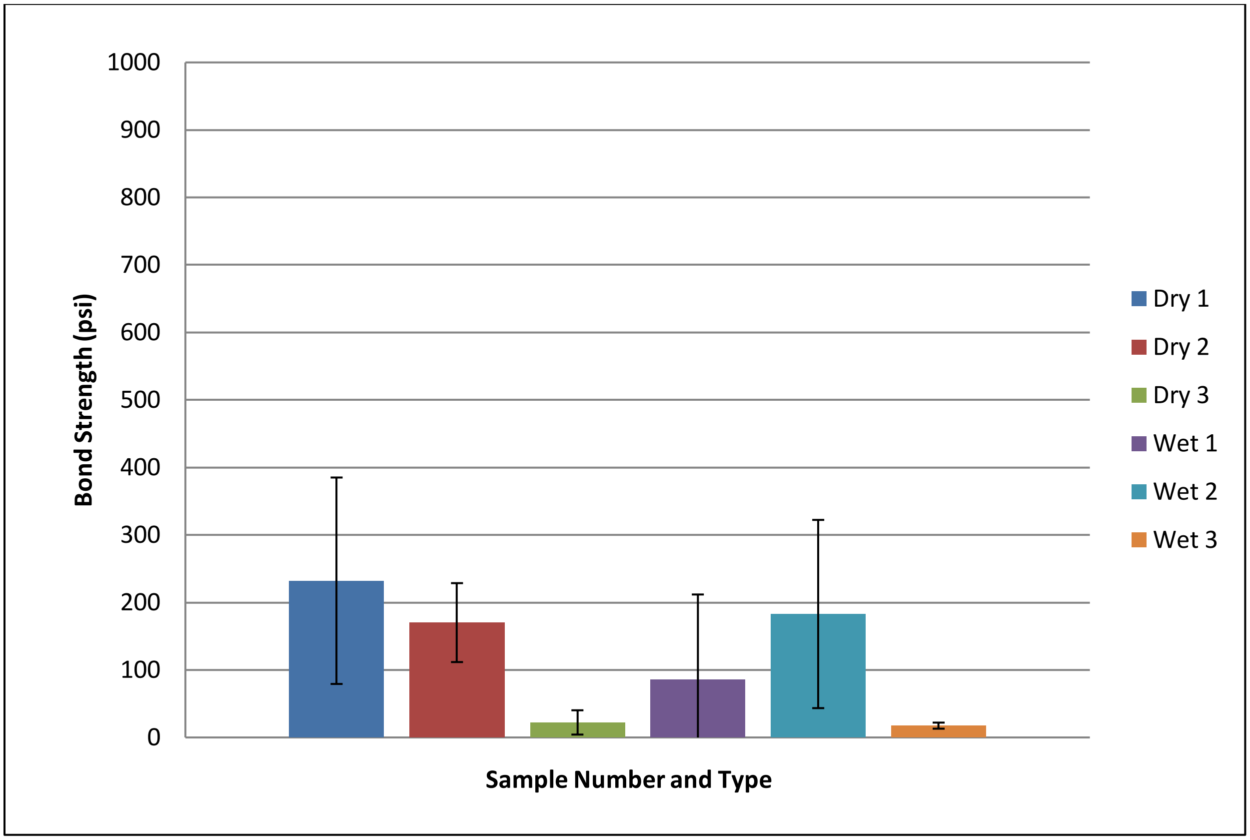


Figure 58: VersaFlex - Aliphatic Clear Coat: Pull-off test result comparison between dry and wet samples and coating thicknesses

(a) (b) (c)

Figure 59: VersaFlex Aliphatic Clear Coat failure type for wet samples with (a) one layer (b) two layers and (c) three layers of product

(a) (b)

Figure 60: VersaFlex Aliphatic Clear Coat failure type for dry samples with one layer of product: (a) replicate A and (b) replicate B

Results for the Clear Seal coating product are presented in **Figure 61**. It would seem that there is a slight gain in performance for the coatings applied on dry samples in comparison to that of the wet samples. However, the high variability in results obtained for the wet replicates cannot validate this statement. **Figure 62** illustrates fracture types for dry and wet replicates with the three-layer coating system. The dry replicates both exhibited partial failure within the concrete; however, one of the wet replicates exhibited failure in the concrete while the other failed at the bond interface. The latter resulted in a lower recorded average and high coefficient of variation. Similar fracture patterns also occurred for the one- and two-layer coating systems, which contributed to the high variability in measurements. As previously discussed, this may be caused by the observed disintegration of the coating with time combined with the influence of moisture transport post-application.

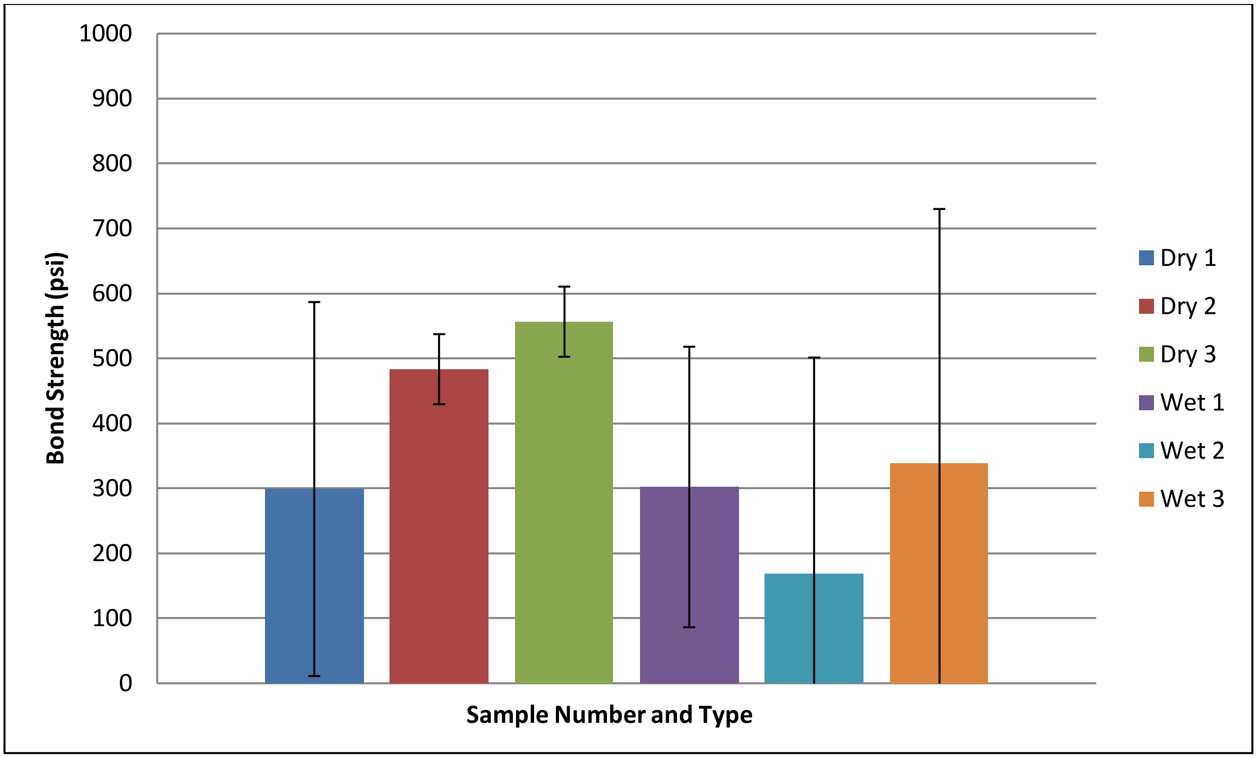


Figure 61: VersaFlex Clear Seal: Pull-off test result comparison between dry and wet samples and coating thicknesses

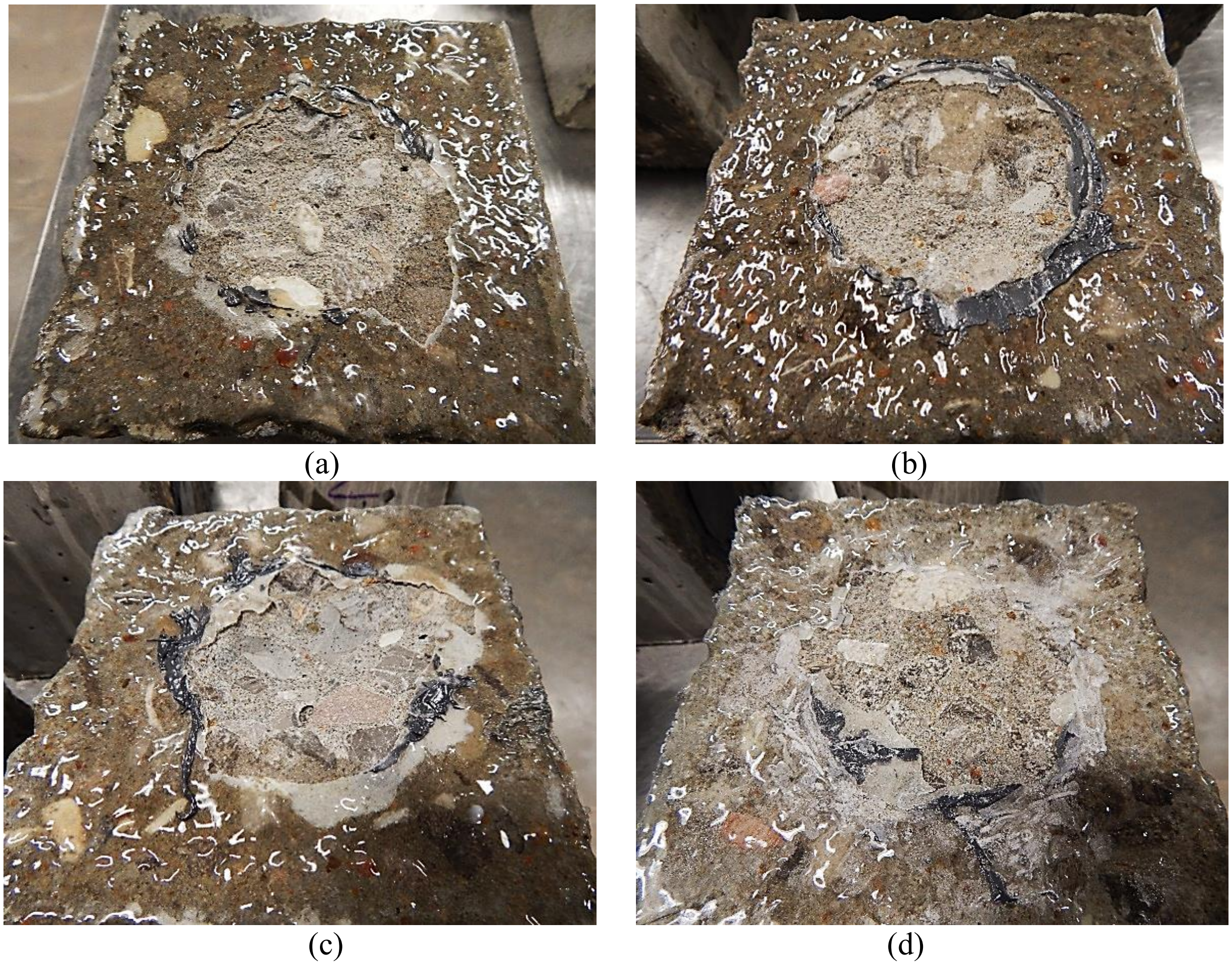


Figure 62: VersaFlex Clear Seal Coating failure type for samples with 3 layers of product: (a) & (b) dry replicates and (c) & (d) wet replicates

Rust-Oleum (Citadel) Polyurea Polyaspartic RG-80X

Overall, the bond testing for the Rust-Oleum's RG-80X product was not successful. The results displayed in **Table 18** are very low in comparison to that of the other products. As previously stated, it would seem that the coating disbonded during the cure time, which may have resulted in coating bond failures for all of the samples (**Figures 64 and 65**). There are no distinguishable trends for the effects of either moisture or layer thickness on bond strength (**Figure 63).**

Table 18: Results of the pull-out test for Rust-Oleum products

	Concrete Moisture Conditioning	Number of Coats	Coating Thickness (mils, ± 0.4)	Average Strength (psi)	Coefficient of Variation (%)
Polyurea Polyaspartic RG-80X	Dry	One	8.28	146.3	12.3
	Wet		8.14	81.1	2.8
	Dry	Two	8.92	68.4	49.3
	Wet		8.2	182.9	72.6
	Dry	Three	11.46	112.9	21.9
	Wet		10.68	23.9	28.3

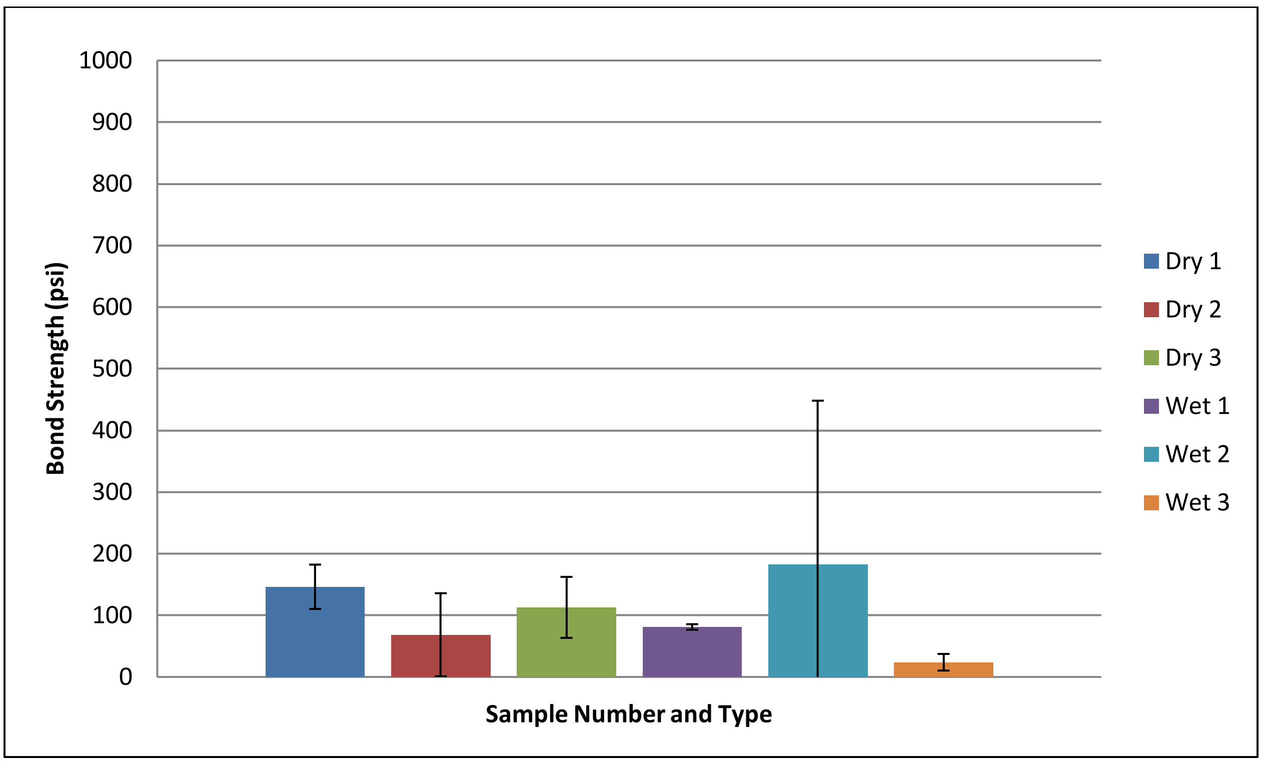
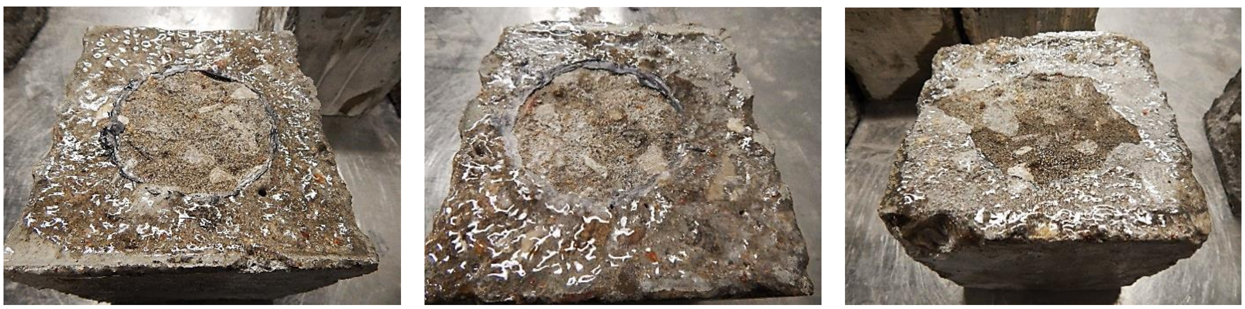


Figure 63: Polyurea Polyaspartic RG-80X Pull-off test result comparison between dry and wet samples and coating thicknesses

(a) (b) (c)

Figure 64: Rust-Oleum RG-80X failure type for dry samples with (a) one layer (b) two layers and (c) three layers of product



(a) (b) (c)

Figure 65: Rust-Oleum RG-80X failure type for wet samples with (a) one layer (b) two layers and (c) three layers of product

Mirabel Coating – Slow and Fast

The following are a few noteworthy observations about product performance during experimental investigation. Thickness readings were not obtained for either of the Mirabel products. This was due to the presence of excessive bubbles entrapped in the coating. These bubbles appeared during curing of the coating and not at time of application (**Figure 66**). The presence of such voids could diminish the effective performance of the coating; however, this was not observable while performing the bond-test. On average, the bond-strength for both the slow and fast curing products seemed adequate (**Table 19**) as the majority of the failures occurred in the concrete material. Here, consistency in fracture types resulted in a lower recorded variability in comparison to that of the other two products discussed previously.

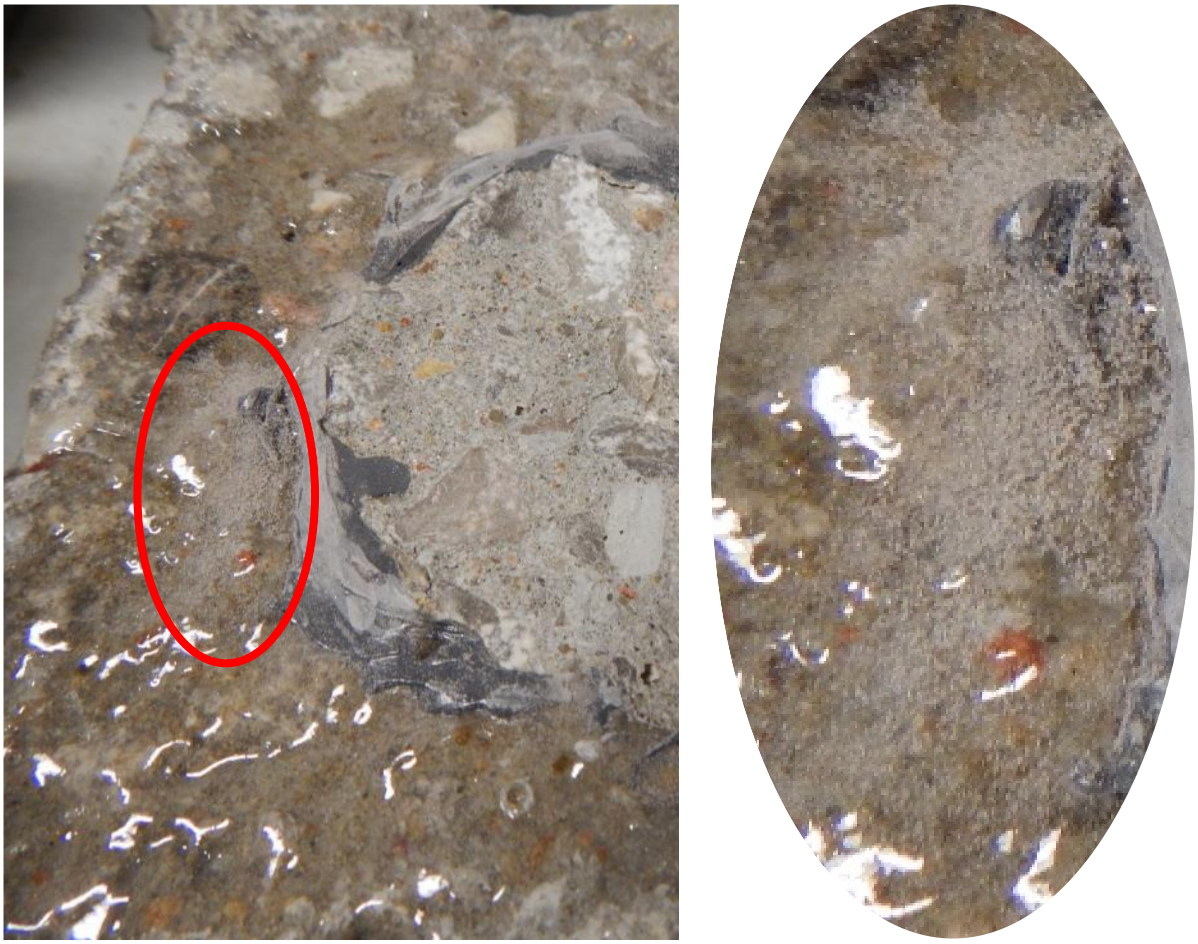


Figure 66: Excessive entrapped bubbles seen within the coating

Coefficients of variation fluctuate between 2.5% and 33.1%, yielding an average of 12.1% (**Table 18**). This may be due to the scaled uneven profile of cube surfaces which may have caused loading eccentricities. Moreover, the scaling process to remove the concrete layer may have caused micro-fissures at the surface of the concrete which weaken the bond interface as well. In general, fractures occurred within the concrete material and not at the bond interface (**Figures 67 and 68**). This demonstrates that the bond strength is superior to the tensile strength of the concrete. Similarities in measurements are due to this principle; they reflect the tensile strength properties of the concrete material at its surface.

Table 19: Results of the pull-out test for Mirabel Coating products

	Concrete Moisture Conditioning	Number of Coats	Coating Thickness (mils, ± 0.4)	Average Strength (psi)	Coefficient of Variation (%)
Mirabel Fast	Dry	One	N/A	548.6	6.6
	Wet		N/A	624.9	5.4
	Dry	Two	N/A	555.0	6.1
	Wet		N/A	553.4	12.2
	Dry	Three	N/A	534.3	2.5
	Wet		N/A	543.8	33.1
Mirabel Slow	Dry	One	N/A	721.9	16.8
	Wet		N/A	577.2	17.5
	Dry	Two	N/A	707.6	5.4
	Wet		N/A	723.5	10.3
	Dry	Three	N/A	624.9	17.6
	Wet		N/A	454.8	11.9

As seen in **Figure 67** for the Mirabel Fast curing product, there were no observables trends for values obtained for both the dry and wet samples types as well as for the number of coating layers. The results are relatively consistent for all measurements, which is attributable to the failure type (**Figure 68** and **Figure 69**). Therefore, the actual bond performance between the different sample types cannot be determined because of the concrete failure in tension.

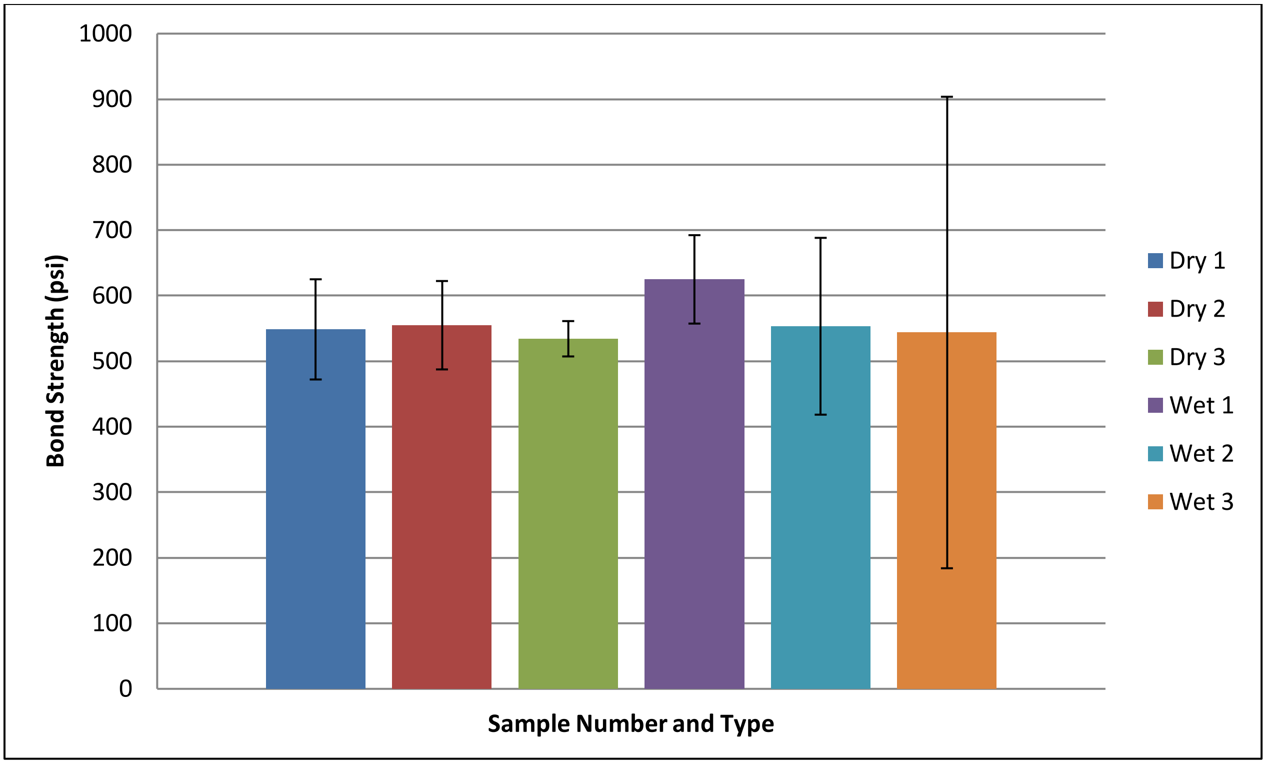


Figure 67: Mirabel Fast: Pull-off test result comparison between dry and wet samples and coating thicknesses

(a) (b) (c)

Figure 68: Mirabel Fast failure type for dry samples with (a) one layer (b) two layers and (c) three layers of product

(a) (b) (c)

Figure 69: Mirabel Fast failure type for wet samples with (a) one layer (b) two layers and (c) three layers of product

As for the results obtained for the Slow curing Mirabel product (**Figure 70**), there seemed to be a slight increase in bond-strength in comparison to that of the Fast curing product; however, the differences of 22.5%, 24.1% and 15.9% for the dry samples with 1, 2 and 3 layers respectively is not significant. On the other hand, there is a variable influence for the wet samples with percent differences of -7.9%, 18.7% and -17.8% for the 1, 2 and 3 layers respectively. As seen in **Figures 71 and 72**, failure types are similar for all samples as that seen for the Fast Mirabel product.

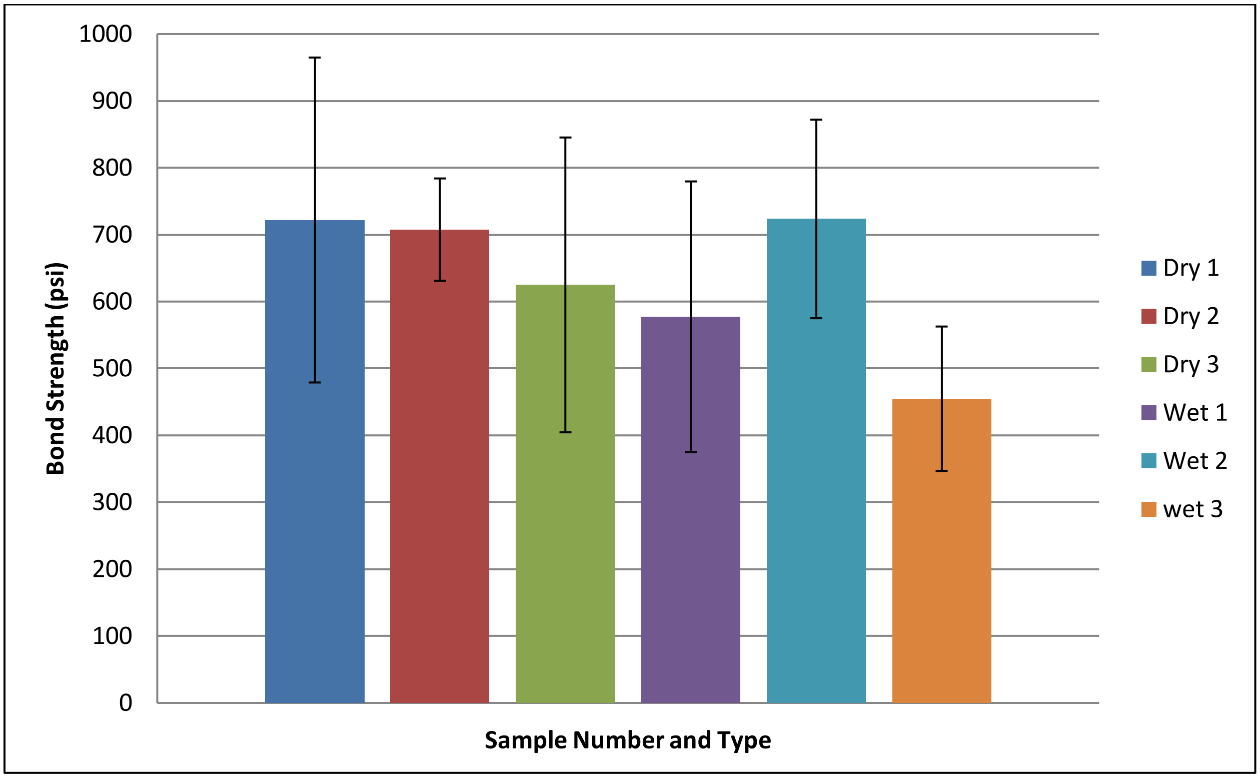


Figure 70: Mirabel Slow: Pull-off test result comparison between dry and wet samples and coating thicknesses

(a) (b) (c)

Figure 71: Mirabel Slow failure type for dry samples with (a) one layer (b) two layers and (c) three layers of product

(a) (b) (c)

Figure 72: Mirabel Slow failure type for wet samples with (a) one layer (b) two layers and (c) three layers of product

Creative Materials Technologies DYNA-PUR7416 and DYNA-PUR7416 NT6

The last product evaluated is manufactured by Creative Materials Technologies, *DYNA-PUR7416 and DYNA-PUR7416 NT6.* Neither product demonstrated any surface features of concern. Moreover, they both performed well for the pull-off testing regimens. Similarly to the Mirabel products, there weren't any significant differences in pull-off performance between the dry and wet sample types. Also, there were no noticeable trends between pull-load and layer thickness. Again, the low coefficients in variation calculated are due to the failure type being in the concrete layer. They vary between 2.9% and 46.8%, averaging 14.3% (**Table 20**).

Table 20: Results of the pull-out test for Creative Materials Technologies products

	Concrete Moisture Conditioning	Number of Coats	Coating Thickness (mils, ± 0.4)	Average Strength (psi)	Coefficient of Variation (%)
DYNA-PUR7416	Dry	One	11.74	710.8	2.9
	Wet		12.14	721.9	7.5
	Dry	Two	13.24	636.1	16.3
	Wet		12.66	526.3	28.6
	Dry	Three	14.08	707.6	4.8
	Wet		13.42	435.7	17.6
DYNA-PUR7416-NT6	Dry	One	11.88	580.4	15.1
	Wet		12.32	416.6	13.0
	Dry	Two	11.82	539.1	3.8
	Wet		14.36	408.7	46.8
	Dry	Three	14.76	610.6	3.0
	Wet		15.56	486.6	18.5

The pull-load values obtained for the regular DYNA-PUR7416 product are among the highest recorded for this study. With respect to their counterpart DYNA-PUR7416 NT6, the percent differences are 20.1%, 16.2% and 14.9% for the dry samples with 1, 2, and 3 layers respectively and 53.6%, 25.1% and -11.0% for the wet samples with 1, 2, and 3 layers respectively. Again these differences are not significant due to the inherent variability of the test method and fracture type (**Figures 73 to 78**).

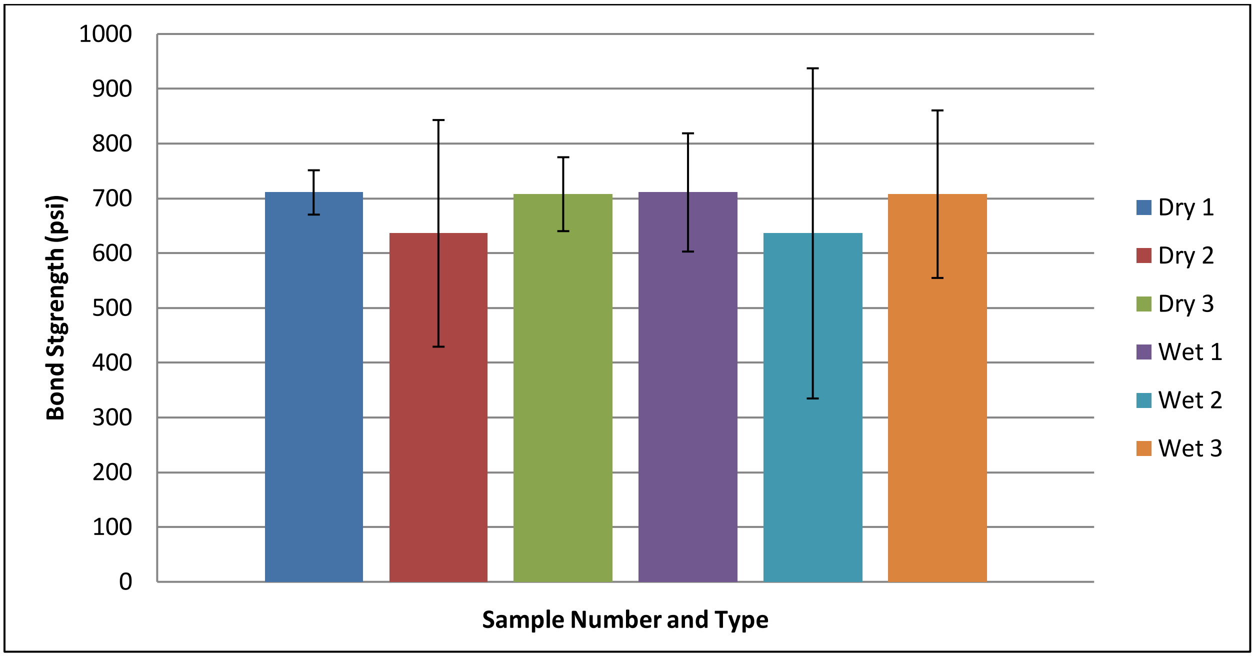


Figure 73: DYNA-PUR7416: Pull-off test result comparison between dry and wet samples and coating thicknesses

(a) (b) (c)

Figure 74: DYNA-PUR7416 failure type for dry samples with (a) one layer, (b) two layers and (c) three layers of product

(a) (b) (c)

Figure 75: DYNA-PUR7416 failure type for wet samples with (a) one layer, (b) two layers and (c) three layers of product

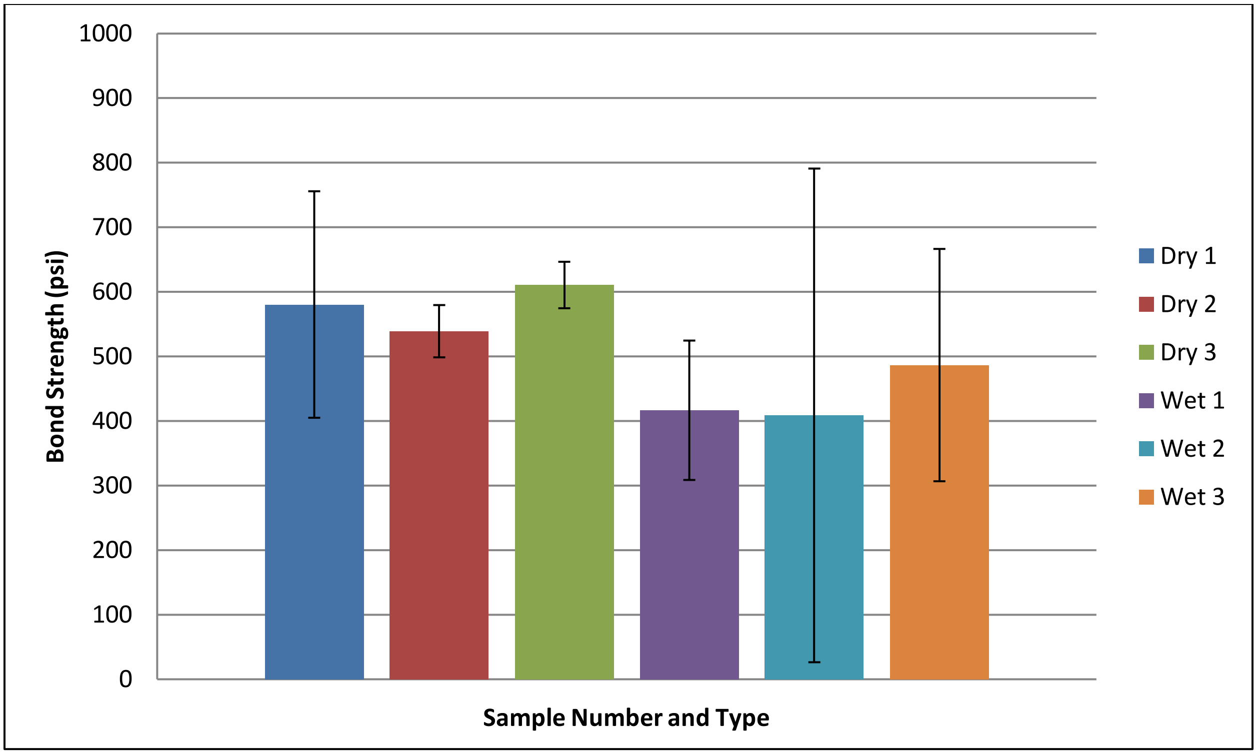


Figure 76: DYNA-PUR7416 NT6: Pull-off test result comparison between dry and wet samples and coating thicknesses

(a) (b) (c)

Figure 77: DYNA-PUR7416 NT6 failure type for dry samples with (a) one layer (b) two layers and (c) three layers of product

(a) **(b)** **(c)**

Figure 78: DYNA-PUR7416 NT6 failure type for wet samples with (a) one layer (b) two layers and (c) three layers of product

Overall Pull-Off Test Performance

As seen in **Figure 79**, the materials with the highest bond strength are the Mirabel Slow and the DYNA-PUR7416 (REG) followed by DYNA-PUR7416 NT6 and the Mirabel Fast. The latter had the lowest recorded coefficients of variation. The variability in the fracture types and coating condition resulted in lower pull-loads for the VersaFlex Clear Seal and Aliphatic Clear Coat. The lowest results recorded are for the Rust-Oleum Polyurea Polyaspartic RG-80X. However, RG-80X was not eliminated and its performance was still evaluated for the other test regimens. As an outcome of this first experimental task, the noticed potential in disbonding and flaking arising in time lead to an increase in the time period between coating and testing. A period of at least three weeks was planned for the other test regimens to allow sufficient hardening of the coating system and to provide a sufficient amount of time for problems to occur if they were to occur. Also, quality control on the preparation of the products was increased. Better care was taken in the precision of the measuring and mixing time of Parts A and B to ensure reproducibility of the coatings. The latter helped eliminate some of the noticed problems for the Rust-Oleum RG-80X and the VersaFlex Aliphatic Clear Coat.

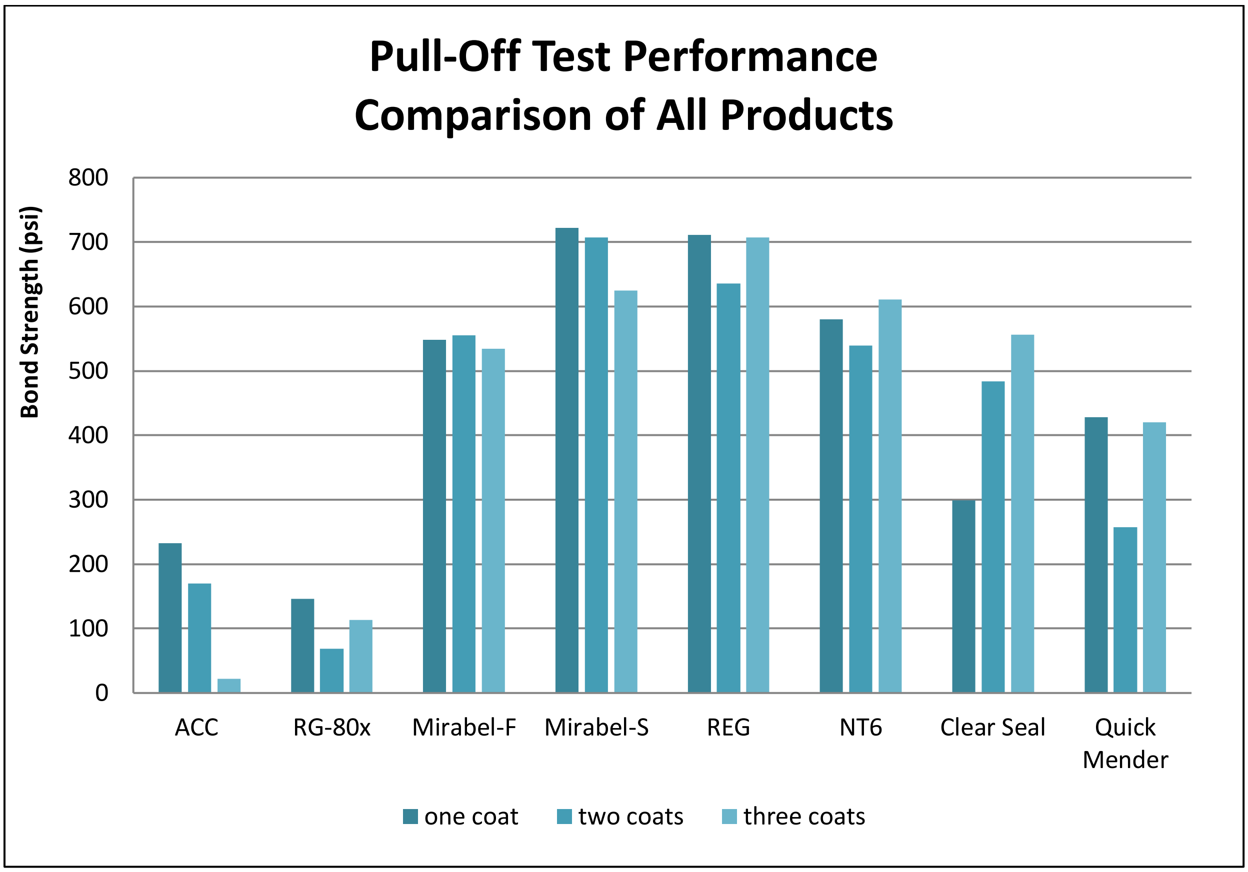


Figure 79: Pull-off test results comparison for all products, dry samples

Results for Flexural Testing

A series of tests were carried out on standard beam and notched beam specimens coated on a single face. The coated surfaces were prepared in the same manner as the pull off specimens, by roughening the surface to expose aggregate. The beams were tested in such a manner that the coated face would be under tensile stress while loading. Therefore, an increase in modulus of Rupture could be due to the composite effect of both the coating and concrete materials' properties. A summary of the results obtained for the flexural test regimen are presented in the following sections. **Table 21** and **Table 22** provide the average coating thicknesses, average Modulus of ruptures, coefficients of variation along with the results of an ANOVA hypothesis test; followed by a comparative graph depicting the average values obtained for each sample type with two standard deviations from the average (**Figures 80** to **83**).

Standard Beams – All Products

As seen in **Table 22** and **Figure 80**, all beam samples outperformed the control sample except for the samples prepared with the VersaFlex Aliphatic Clear Coat and the Mirabel Fast curing product. Two of the products demonstrated superior properties, Creative Material Technologies DYNA-PUR7416 and Polyurea Polyaspartic RG-80X. Although disbondment was noticeable for the Aliphatic Clear Coat and RG-80X cube samples, the beam samples did not show any signs of disbondment. The increase in modulus of rupture could be due to the composite effect of the coating providing additional resistance to tensile crack initiation.

However, the results of an ANOVA test, where the null hypothesis is that the mean modulus of rupture for all groups is the same, demonstrate that the null hypothesis is supported, meaning the results are statistically insignificant. The returned p-value (0.22) is superior to a generally accepted confidence level of 0.05 for concrete testing. Moreover, looking at the potential range in mean values represented by the 95% confidence range (2s) for all products with respect to that of the control value, it can be seen that the results are similar (**Figure 80**). However, the slightly higher (but still acceptable) coefficients of variation obtained for the coated samples may have influenced this hypothesis outcome.

As previously mentioned in the experimental procedure section, the uneven scaled surface of the test face may have contributed to the variance in results. Since the uneven surface may have been a potential source of error, a new test regimen without scaled surfaces was carried out for four of the evaluated products. The results of the comparative analysis are shown in **Figure 81**. This sample set has a higher standard deviation but, it also has a relative higher modulus of rupture compared to that of the scaled samples. The Mirabel Fast product recorded the highest strength; although, the Fast product specimen recorded the second lowest strength for its scaled counterpart. Looking at the trend, there are no discernable differences between coating products as that seen for the scaled standard beams.

Table 21: Results of flexural testing for scaled standard beams, all products

Name	**Coating Thickness (mils, ± 0.4)**	**Modulus of Rupture (psi)**	**COV (%)**
Control	N/A	556.0	5.1
VersaFlex			
Aliphatic Clear Coat	15.8	513.5	2.5
Clear Seal	12.3	572.1	12.7
Rust-Oleum (Citadel)			
Polyurea Polyaspartic RG-80X	11.5	670.9	11.2
Mirabel			
Fast	N/A	525.6	16.5
Slow	N/A	592.0	1.5
Creative Material Technologies			
DYNA-PUR7416	12.3	630.9	9.2
DYNA-PUR7416-NT6	13.6	613.1	8.2
ANOVA TEST for Modulus of Rupture			
F value	1.5	p-value	0.22

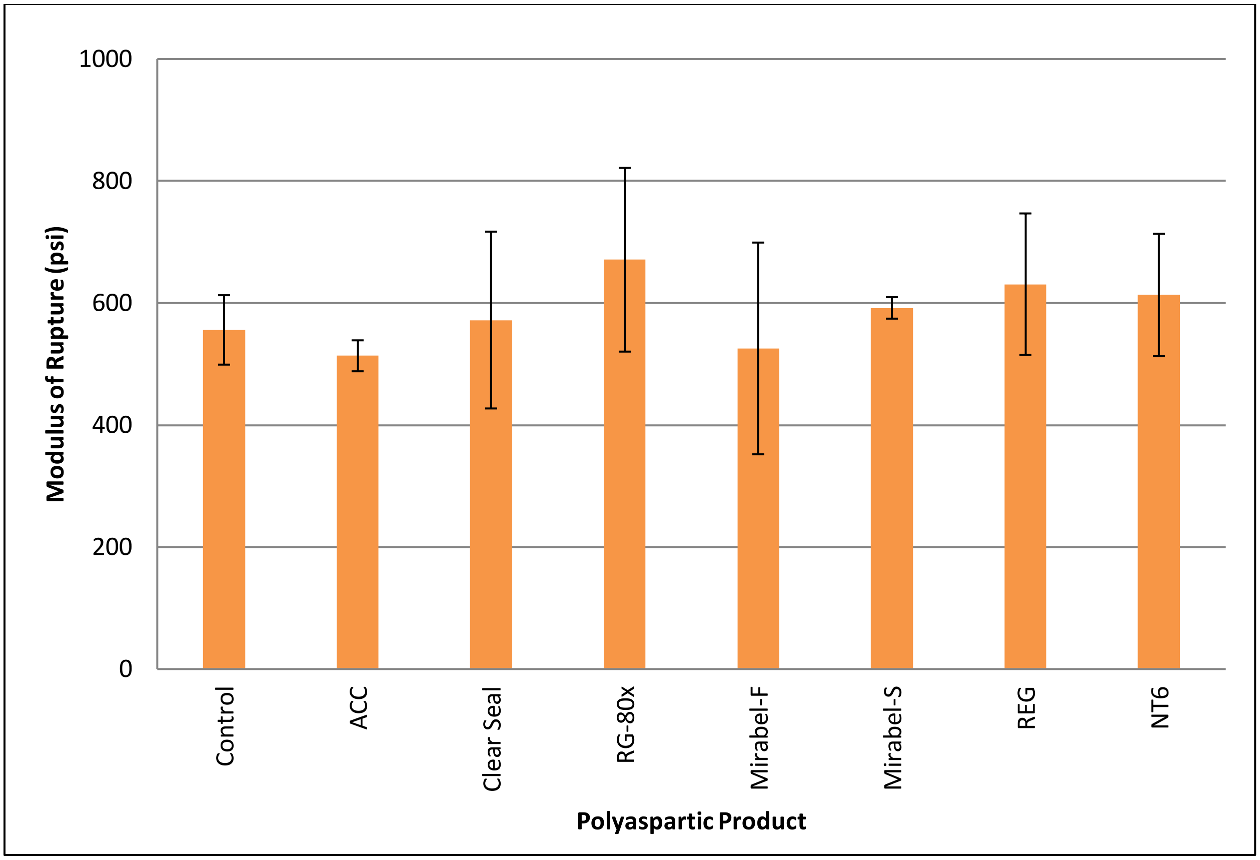


Figure 80: Flexural test results comparison (modulus of rupture) for scaled standard beams, all products

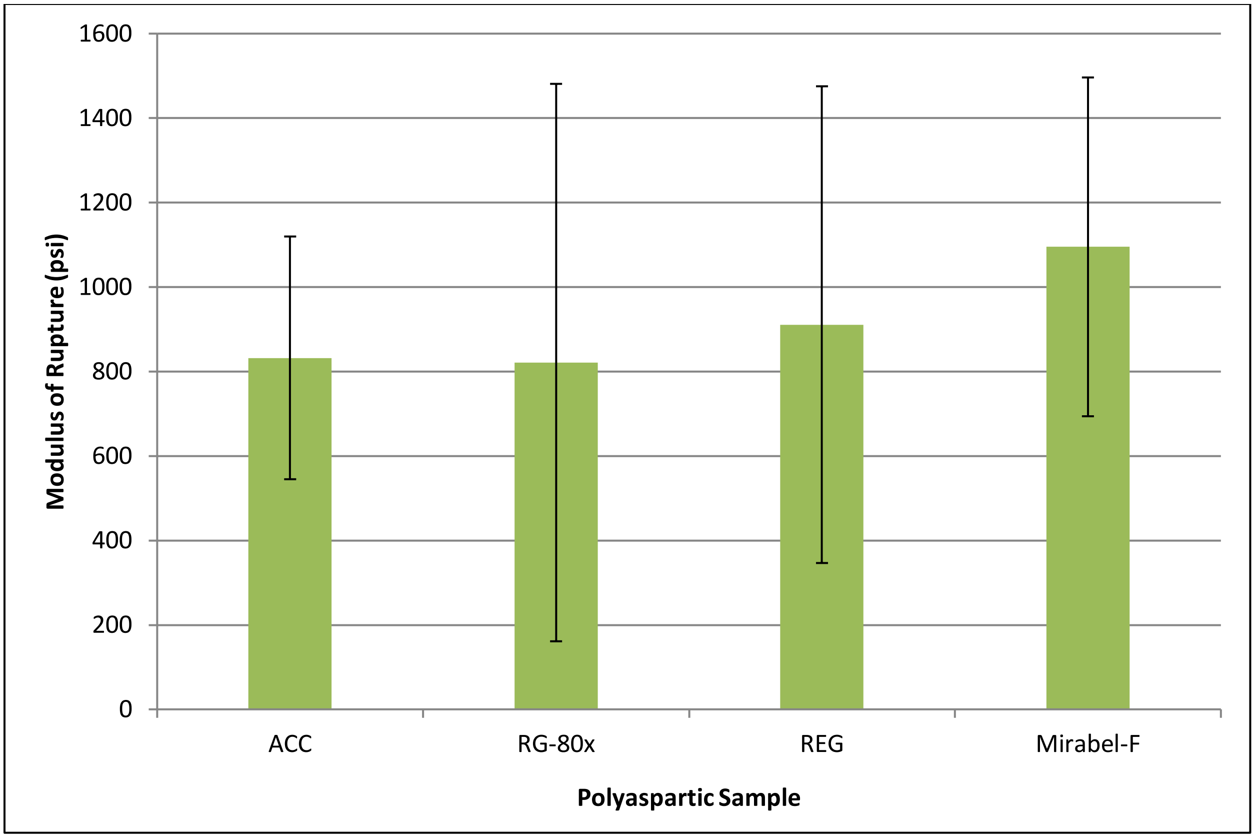


Figure 81: Flexural test results (modulus of rupture) comparison for standard beams, all products

Notched Beams – All Products

First, it needs to be mentioned that the results presented in **Table 22** and **Figure 82** are a second trial. The results for the first set of beams were unusually low with higher than acceptable coefficients of variation. As such the test regimen was restarted. The second set of data was more acceptable; but, high variability and low results were still obtained for the Aliphatic Clear Coat and Mirabel Fast curing products respectively. On average, all but the Mirabel products surpassed the control value. As previously stated, the increase in modulus of rupture could be due attributed to the composite effect of the coating.

For this sample set, the null hypothesis (the mean modulus of Rupture for all groups are the same) is rejected. The returned p-value (1.9 E-4) is inferior to the confidence level of 0.05. However, the high F value demonstrates high variance for the data set. Thus, a subsequent analysis was conducted removing the results obtained for the samples coated with the Mirabel products. In this case the returned F and p-value are 0.78 and 0.58 respectively. In this case, the null hypothesis would be supported with an acceptable variance. This can be seen in **Figure 82** where the mean values within the range in standard deviations (2s) are all within that of the control and each other except for the Mirabel Products.

Again, the uneven scaled surface of the test face may have contributed to the variance in results. Since the uneven surface may have been a potential source of error, a new test regimen was completed by testing notched beams without scaling them. The results are shown in **Figure 83**. The results demonstrate that although the average values are slightly lower than that reported for the scaled notched-beams, there are still within the 95% confidence interval. Again, the statistical variance implies that the average means recorded are similar for all products.

Table 22: Results of flexural testing for scaled notched beams, all products

Name	Coating Thickness (mils, ± 0.4)	Modulus of Rupture (psi)	COV (%)
Control	N/A	438.1	4.9
VersaFlex			
Aliphatic Clear Coat	15.83	527.5	22.7
Clear Seal	12.33	511.8	5.5
Rust-Oleum (Citadel)			
Polyurea Polyaspartic RG-80X	11.53	503.8	10.3
Mirabel			
Fast	N/A	564.8	11.6
Slow	N/A	325.0	11.5
Creative Material Technologies			
DYNA-PUR7416	11.89	489.7	10.0
DYNA-PUR7416-NT6	13.57	486.8	6.4
ANOVA TEST for Modulus of Rupture			
F value	4.3	p-value	0.007

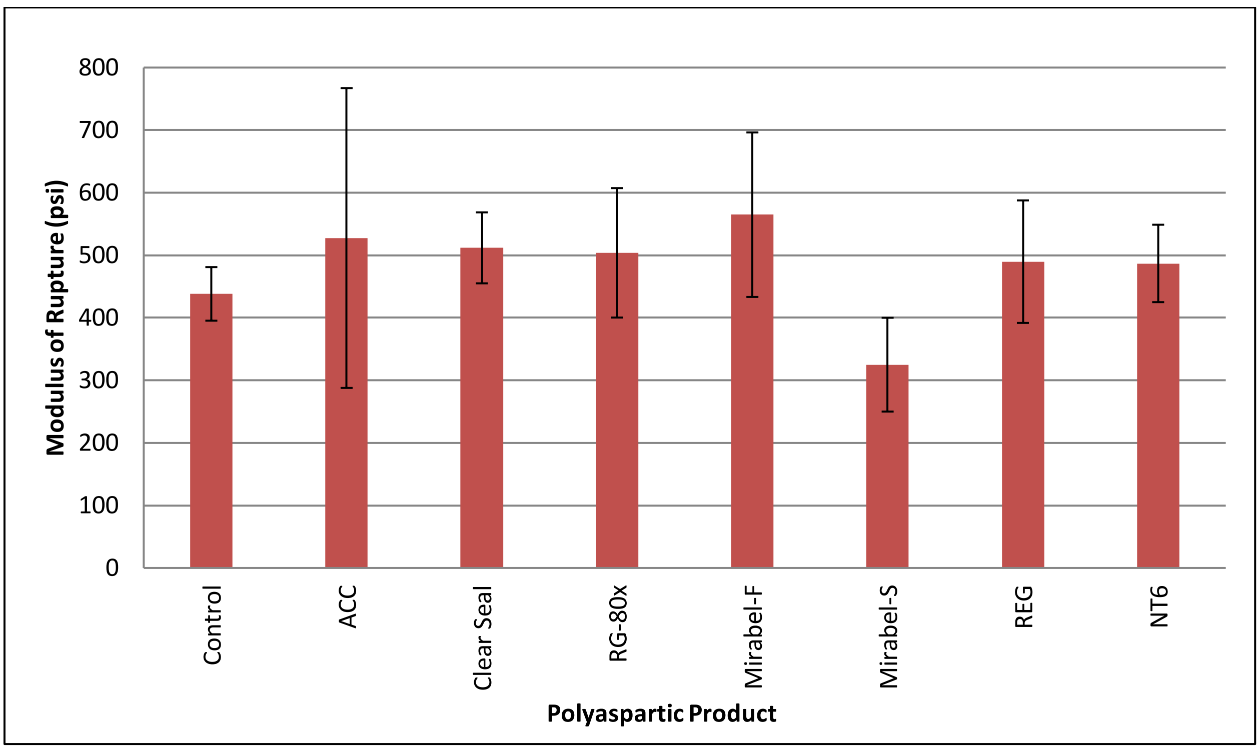


Figure 82: Flexural test results (modulus of rupture) comparison for scaled notched beams, all products

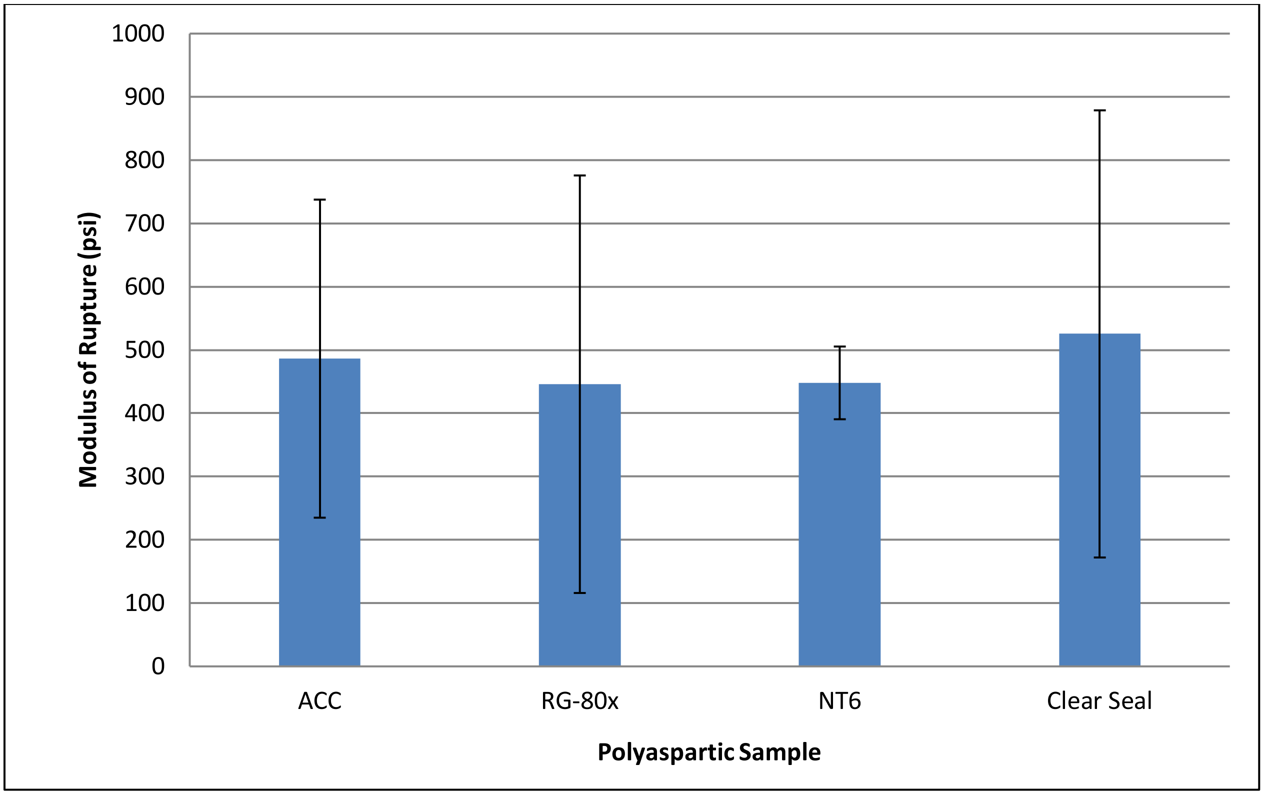


Figure 83: Flexural test results (modulus of rupture) comparison for standard notched beam samples

Results for Compression and Modulus of Elasticity Test

A series of tests were performed on cylindrical samples coated with the products investigated. Prior to coating, the sample surfaces were scaled exposing the coarse aggregate as described for the previous sample types. After a prolonged curing time of the coating systems, the static modulus of elasticity test (ASTM C469) and the compressive strength test (ASTM C39) were performed to assess the ability of the coatings to aid the composite material in resisting deformation under load and contain fractured concrete. Here, the influence of layer thickness was evaluated. The average results and corresponding coefficients of variation obtained for each specimen type are presented in **Tables 23**. In addition to this, **Figure 84** shows the compressive test results and **Figures 85-90** depict the failures types obtained for one representative cylinder for each coating thickness and product type.

First, the application of a polyaspartic polyuria coating on the concrete samples seems to have a beneficial effect on increasing the compressive strength of the cylindrical concrete sample. On average, there is a noticeable increase of approximately 10%. The coating may have provided a confining type effect to the cylinder under compression load by providing transverse resistance to the developed tensile stress. This can be seen by the failure types demonstrated in **Figures 85 to 90**. For all products and number of coatings, the coating material held the fractured concrete sample together. Although small fissures propagated through the surface of the coating, no concrete fragments were loss and the cylinder shape was still somewhat intact. Therefore, the coatings were able to contain the concrete fragments from scaling and/or spalling in comparison to the uncoated samples.

However, signs of coating disbondment were visually noticeable post-testing. All samples except for the Creative Material Technologies' products exhibited coating disbondment. For these samples, the measured compressive strengths were slightly lower which may be attributed to the lost in composite effect during loading. This may also explain the slightly higher coefficients of variation obtained for samples showing disbonded coating. This behavior was independent of coating thickness.

The effects of coating thickness were evaluated within product type. An analysis of variance was conducted to determine whether increasing the number of coats would increase the compressive strength of the concrete composite. In **Table 23**, the results of the ANOVA demonstrate that there is no statistical difference between the compressive strengths obtained. Therefore, the small differences in strength seen among coating thicknesses are negligible. However, there is a noticeable trend where the single coat systems outperformed their counterparts, except for the RG-80X and Clear Seal products.

Table 23: Results of the compression test for all products

	Number of Coats	Coating Thickness (mils, ± 0.4)	Average Strength (psi)	Coefficient of Variation (%)	ANOVA F-Value/ p-value
Control	N/A	N/A	3329		N/A
VersaFlex					
Aliphatic Clear Coat	One	10.8	3729	7.5	6.410/0.083
	Two	11.5	3668	8.1	
	Three	13.0	3611	7.6	
Clear Seal	One	8.4	3881	4.6	0.138/0.879
	Two	9.7	3460	5.8	
	Three	10.7	4056	7.0	
Rust-Oleum					
RG-80X	One	9.2	3252		0.483/0.658
	Two	10.0	3526		
	Three	11.4	3509		
Mirabel					
Fast	One	N/A	2887	9.0	55.115/0.018
	Two	N/A	3685	3.9	
	Three	N/A	3844	4.1	
Creative Materials					
DYNA-PUR7416	One	7.4	3983	3.8	3.978/0.201
	Two	9.8	3878	5.6	
	Three	11.9	3936	3.1	
DYNA-PUR7416-NT6	One	12.2	4113	6.7	0.483/0.658
	Two	12.9	1741	6.5	
	Three	14.2	3979	6.1	

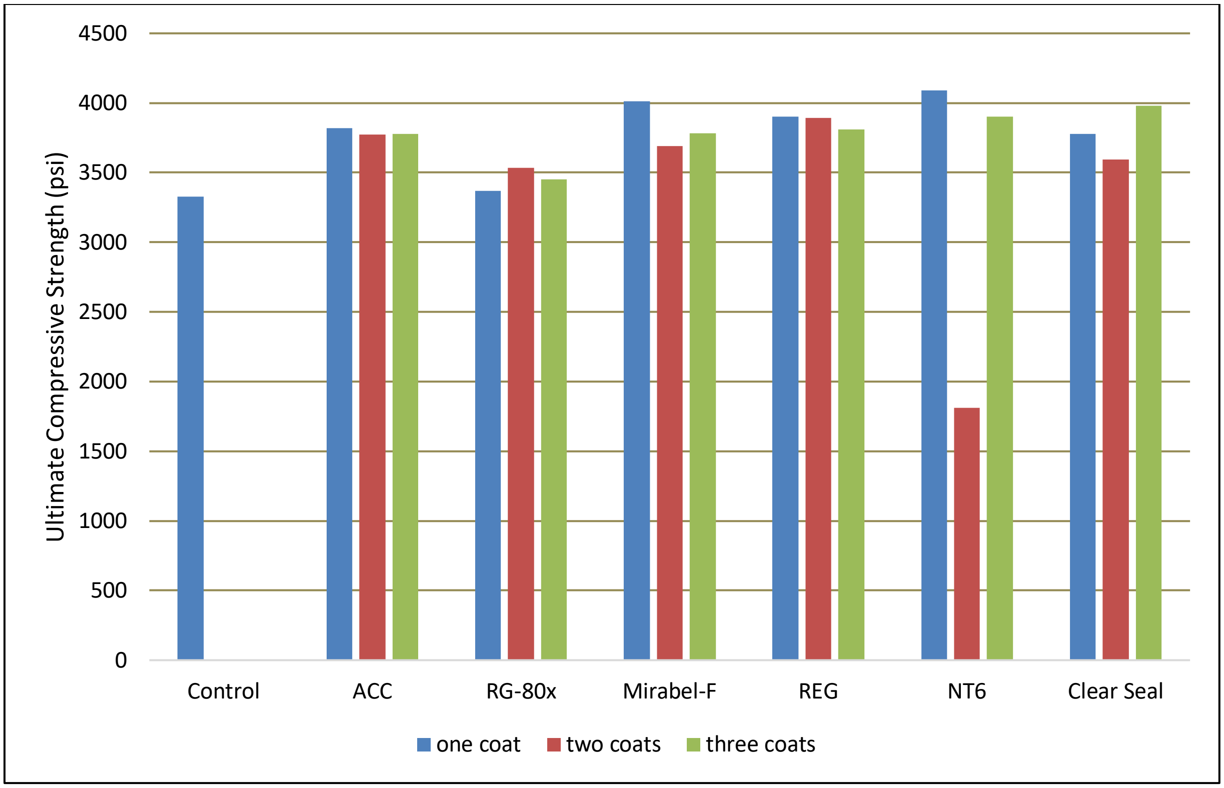
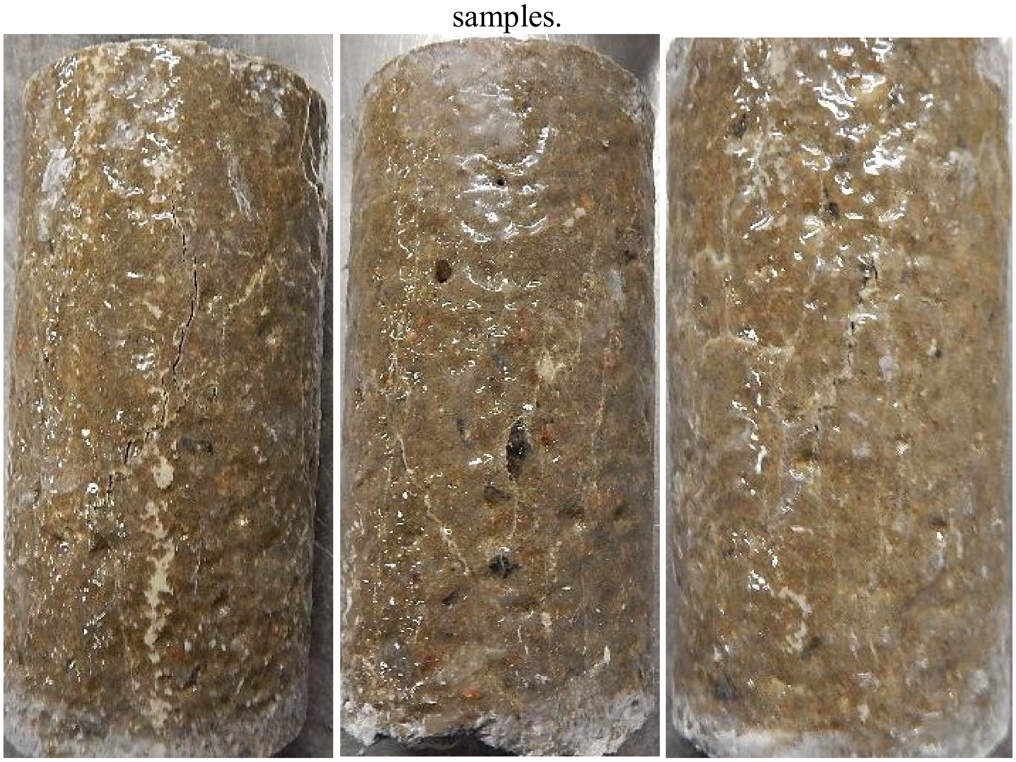


Figure 84: Compression test results comparison for all products: one, two and three coats samples.

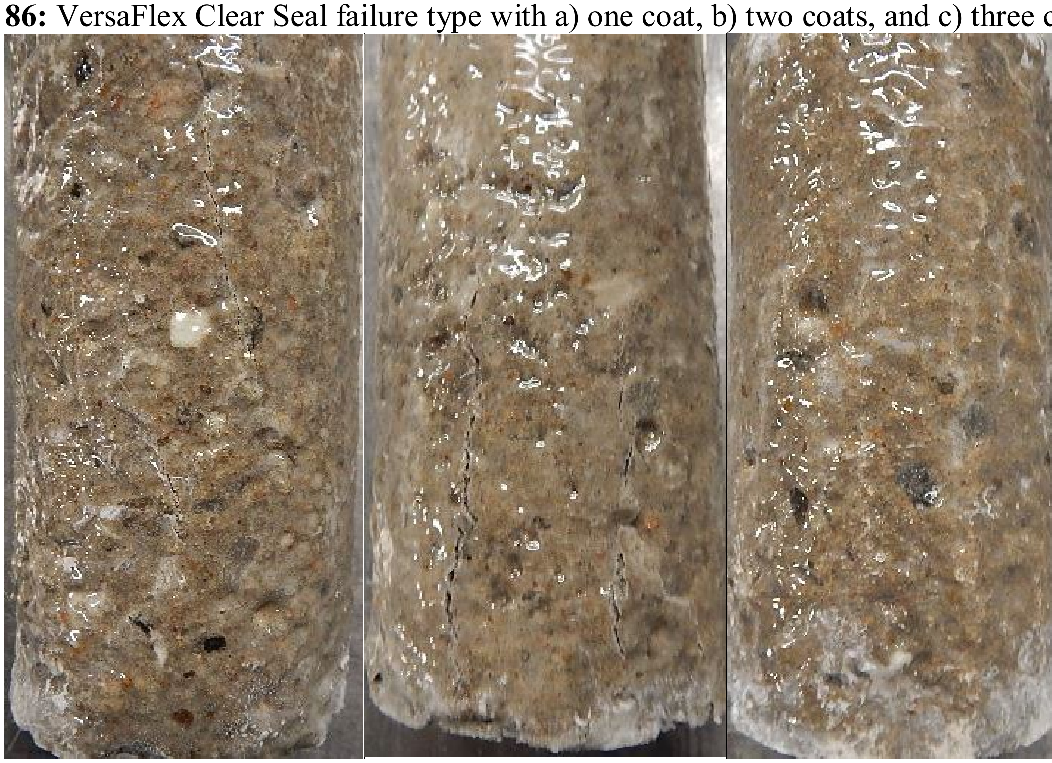


a) b) c)

Figure 85: VersaFlex Aliphatic Clear Coat failure type with a) one coat, b) two coats, and c) three coats

a) b) c)

Figure 86: VersaFlex Clear Seal failure type with a) one coat, b) two coats, and c) three coats



a) b) c)

Figure 87: Polyurea Polyaspartic RG-80X failure type with a) one coat, b) two coats, and c) three coats

a) b) c)

Figure 88: Mirabel Fast failure type with a) one coat, b) two coats, and c) three coats

a) b) c)

Figure 89: DYNA-PUR7416 (REG) failure type with a) one coat, b) two coats, and c) three coats

a) b) c)

Figure 90: DYNA-PUR7416 NT6 failure type with a) one coat, b) two coats, and c) three coats

The stress-strain behavior for each sample type was recorded while conducting the load test. The calculated chord modulus of Elasticity, following the procedure stated in ASTM C469, is shown in **Table 24**. For a few samples, due to equipment failure, it was not possible to record the strain response for both sample replicates. In the case of the Aliphatic Clear Coat and DYNA-PUR7416-NT6 products, no strain results were obtained for both sample replicates. With available results, there is no statistical difference between the product types based on the returned p-value from an ANOVA test. Results obtained for the 1, 2 and 3 coats systems were statistically insignificant where an analysis of Variance was possible to conduct. However, results demonstrate an increase in stiffness properties of the composite system in comparison to that of the control sample. There is an average percent increase in modulus of Elasticity of 61% for coated samples.

Table 24: Results of modulus of Elasticity testing, all products

Name	Modulus One Coat (ksi)	Modulus Two Coats (ksi)	Modulus Three Coats (ksi)
Control		1665.26	
VersaFlex			
Aliphatic Clear Coat	-	2663.18	2675.33
Clear Seal	3071.93	3937.88	1881.36
Rustoleum (Citadel)			
RG-80X	2663.22	2237.60	2567.65
Mirabel			
Mirabel Fast	2746.06	2596.17	2617.61
Creative Material Technologies			
DYNA-PUR7416	2734.04	2590.66	2582.18
DYNA-PUR7416-NT6		2680.59	2565.78
ANOVA, one coat			
F-value	0.530	p-value	0.749
ANOVA, two coats			
F-value	0.604	p-value	0.706
ANOVA, three coats			
F-value	0.762	p-value	0.614

In the context of field exposure and resistance to durability mechanisms such as freezing and thawing of concrete, an increase in mechanical properties of the concrete cover, due to the composite effect provided by the coating, may give additional resistance to stress-strain related surface damage. In this case, the small increase in measured coating thicknesses between 1, 2 and 3 coats are not sufficient to significantly change the results. But it is recommended to apply more than one coat to ensure adequate and even coverage of the entire area and prevent small areas susceptible to water infiltration (Tator, 2015). Also, the product types evaluated have been reported to be sensitive to erosion-abrasion type deterioration (Tator, 2015) so a slight increase in the initial thickness could increase the service life of the coating. This principle is of interest in the rapid freeze-thaw durability test conducted on prismatic samples.

Rapid Freeze-Thaw Cycling Test

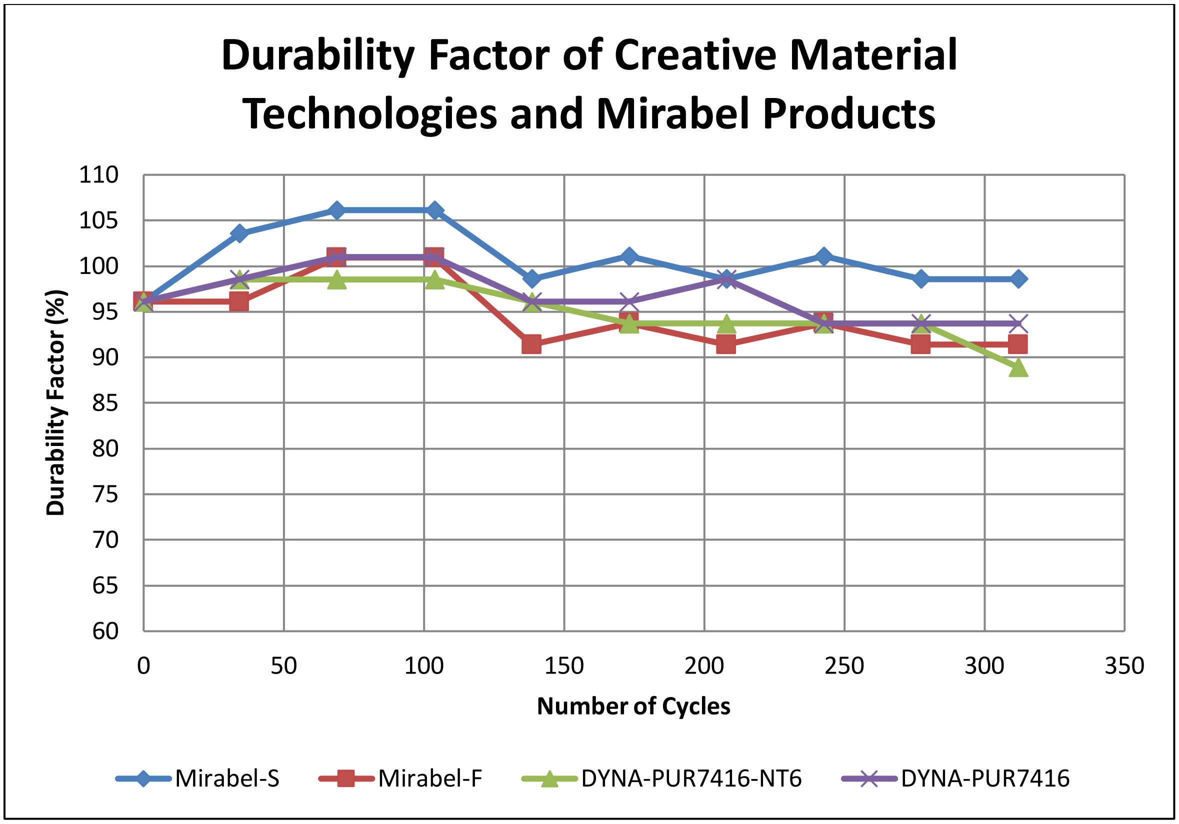
A series of rapid freeze-thaw cycling was performed to determine the performance of the coating on a scaled surface. The test regimen was performed as per ASTM C666 except for sample conditioning as mentioned in the experimental procedure section. As per ASTM C666 criteria, all coated concrete products performed well and are considered acceptable (**Figure 91**). The Durability Factor maintained above 90% for the duration of the test. This is as expected since the concrete mixture is the same for all products and air entrainment provided acceptable resistance to damage. However, a visual characterization of the samples' surfaces demonstrated signs of deterioration due to freeze-thaw exposure.

Pictures of distress features seen for specimens coated with Creative Material Technologies and Mirabel products are provided in **Figures 92** to **96**. The main visible surface features seen for all sample types are:

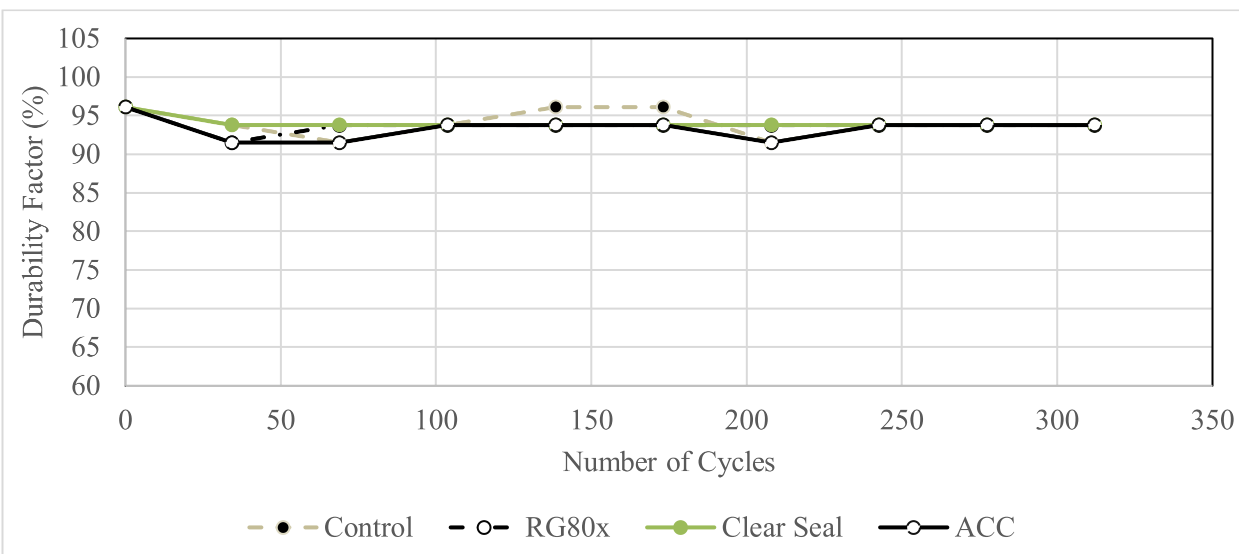
- mortar flaking,
- edge deterioration and scaling,
- aggregate exposure from loss of coating,
- erosion of coating across sample surface.

Surface disintegration is noticeable for uncoated concrete surfaces and at its edges. In some instances, the coating prevented the loss in material as seen in **Figure 96** where a scaled piece was retained by the coating. However, loss in coating was noticeable across the sample surfaces. At various degrees, all samples exhibited erosion of the coating. Tator (2015) reported that one of the biggest drawbacks of a polyaspartic coating is its low abrasion resistance. Here the repeated action of ice nucleation at the sample surface led to abrasion-erosion type damage. This should be considered when evaluating appropriate coating thicknesses as they may degrade with time. Still, the coating was considered performant in inhibiting surface deterioration of the concrete itself assuming good bond performance in time.

The bond performance of the coating was assessed by carrying-out the V-notched test on sample surfaces. An example of the surface test for each sample type can be seen on **Figures 97 to 99**. For both Mirabel products, the coating remained intact. However, both products from Creative Material Technologies exhibited areas of poor bond performance. When performing the V-notched test, the coatings easily peeled off the surface.



a)



b)

c)

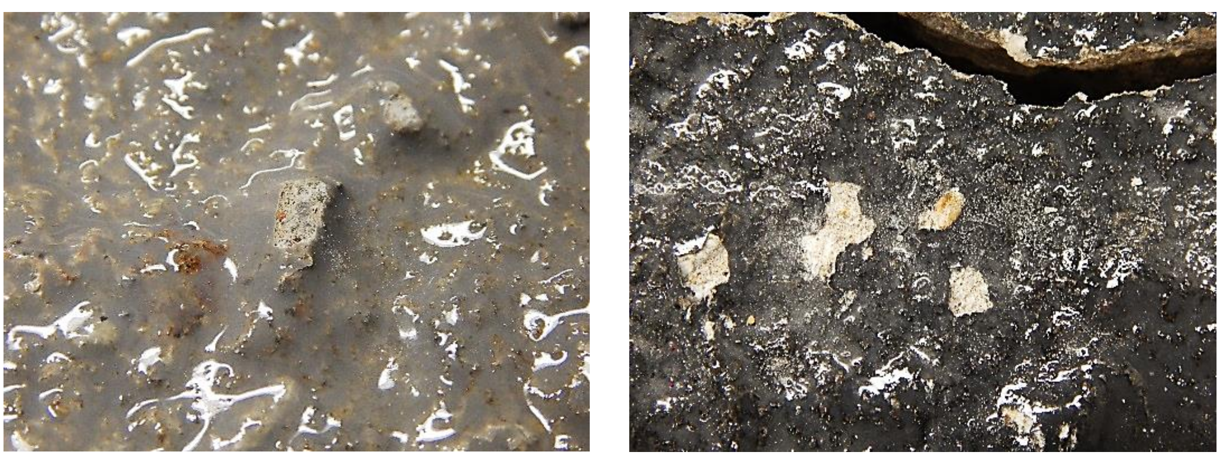
Figure 91: Cyclic freeze-thaw test result comparison between product types: a) Creative Material Technologies and Mirabel products b) Rust-Oleum and VersaFlex products

a) b)

Figure 92: Freeze-thaw distress features: concrete surface deterioration and mortar flaking a) Mirabel Fast and b) Mirabel Slow products

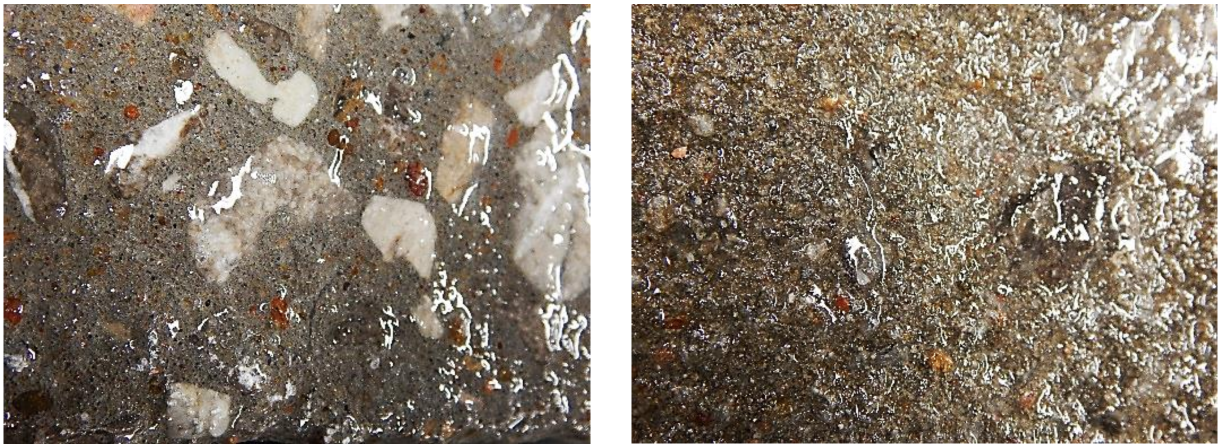
a) b) c)

Figure 93: Freeze-thaw distress features: edge deterioration and scaling retained by coating, a) DYNA-PUR7416, b) DYNA-PUR7416 NT6 and c) Mirabel Fast products



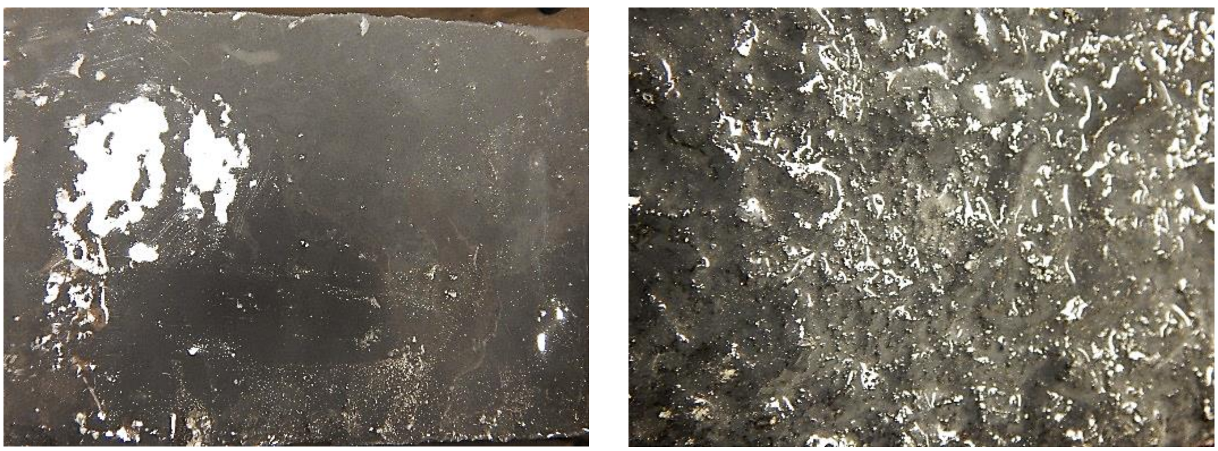
a) b)

Figure 94: Freeze-thaw distress features: loss in surface coating: a) DYNA-PUR7416, b) DYNA-PUR7416 NT6



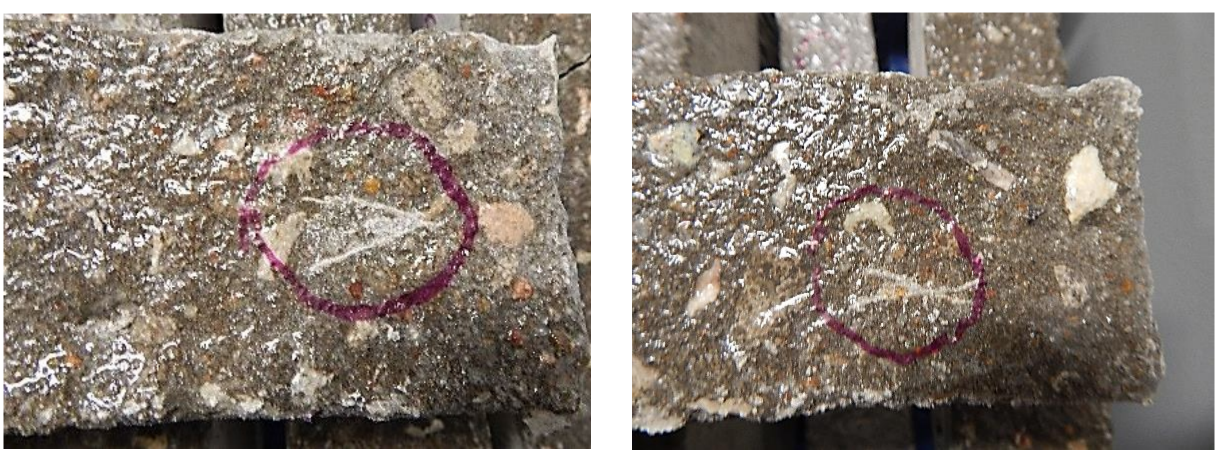
a) b)

Figure 95: Freeze-thaw distress features: loss in surface coating: a) before freeze-thaw exposure, b) after exposure for Mirabel Fast



a) b)

Figure 96: Freeze-thaw distress features: loss in surface coating: a) before freeze-thaw exposure, b) after exposure for DYNA-PUR7416 NT6



a) b)

Figure 97: Example of V-notched test result: a) Clear Seal and b) Aliphatic Clear Coat products

Figure 98: Example of V-notched test result: Rust-Oleum RG-80X product

a) b)

Figure 99: Example of V-notched test result: a) DYNA-PUR7416 and b) DYNA-PUR7416 NT6 products

Table 25: Overall summary of test results of polyaspartic polyurea products

Product	VersaFlex		Rust-Oleum	Creative Material Technologies		Mirabel	
	Clear Seal	Aliphatic Clear Coat	RG-80X	DYNA-PUR 7416	DYNA-PUR 7416 NT6	Polyaspartic Slow	Polyaspartic Fast
	1a	1b	2	3	4	5a	5b
Laboratory Performance							
Pull-Off Strength	Variable bond strength. Fracture at bond interface and substrate Disbondment post-test.	Variable bond strength. Did not achieve proper hardening. Failure at bond interface	Low bond strength. Disbondment pre-test. Failure at bond interface.	Good bond strength. Failure at concrete substrate	Good bond strength. Failure at concrete substrate	Good bond strength. Failure at concrete substrate	Good bond strength. Failure at concrete substrate
Mod. of Rupture Standard beam	MOR ≈ control MOR ≈ other products	MOR ≈ control ≈ other products	MOR ≈ control ≈ other products Recorded highest MOR	MOR ≈ control ≈ other products	MOR ≈ control ≈ other products	MOR ≈ control ≈ other products	MOR ≈ control ≈ other products
Mod. of Rupture Notched beam	MOR ≥ control MOR ≈ other products	MOR ≥ control MOR ≈ other products Recorded highest MOR	MOR ≥ control MOR ≈ other products	MOR ≥ control MOR ≈ other products	MOR ≥ control MOR ≈ other products	MOR < control	MOR ≥ control MOR ≈ other products Recorded highest MOR
Compressive Strength	$\sigma_c \geq$ control $\sigma_c \approx$ other products	$\sigma_c \geq$ control $\sigma_c \approx$ other products	$\sigma_c \approx$ control $\sigma_c \leq$ other products	$\sigma_c \geq$ control $\sigma_c \approx$ other products	$\sigma_c \geq$ control $\sigma_c \approx$ other products Recorded highest σ_c problem with 2-coat system.	$\sigma_c \geq$ control $\sigma_c \approx$ other products	$\sigma_c \geq$ control $\sigma_c \approx$ other products
Modulus of Elasticity	E > control E ≈ other products	E > control E ≈ other products	E > control E ≈ other products	E > control E ≈ other products	E > control E ≈ other products	E > control E ≈ other products	E > control E ≈ other products
Rapid Freeze/Thaw	DF > 90 Coating erosion	DF > 90 Coating erosion	DF > 90 Coating erosion	DF > 90 Coating erosion Scaling Disbondmen	DF > 90 Coating erosion Scaling Disbondmen	DF > 90 Coating erosion	DF > 90 Coating erosion
Performance of Field Application							
Visual Survey	Not Evaluated	Slight Scaling. Disbondment in some areas	Slight Scaling	Slight Scaling	Slight Scaling	Coating did not adhere to the concrete surface.	Not Evaluated
V-Notch		Lower Bond Strength	Good bond strength Substrate failure	Good bond strength Substrate failure	Good bond strength Substrate failure	No bond Strength Coating peeled off	
Overall Product Performance							
	Good mechanical but variable performance	Good mechanical but variable performance	Good mechanical but variable performance	Most consistent product overall. Superior mechanical performance	Superior mechanical performance	Good mechanical but variable performance	Superior mechanical performance

Salt Solution Ponding Test

In order to evaluate the resistance of the coating to degradation in the presence of a chloride salt solution, a modified ASTM C1543 procedure was carried out on slab samples with a surface prepared as that previously described in the Experimental Procedure section. Although it was not possible to measure the loss in coating thickness, visual assessment of all coatings indicates signs of degradtion **(Figure 100)**. There was no evidence of coating peeling at the end of the test period. This was validated through the pull-off test. All samples mainly exhibited a combination of failure in the concrete substrate with areas of bond surface failure. This resulted in variable bond strength results between sample replicates. Still, results are comparable to that previously seen.

Looking at the results of the bond test, illustrated in **Figure 101**, the bond strength after salt solution exposure compares to that of cube specimens not exposed to the aggressive solution. First, due to the high coefficient of variability, there is no clear distinction between results obtained. All coating recorded bond-strengths within the overall variability of the investigated samples. However, similar trends in performance, as that previously reported, can be seen. Again, the Mirabel and the DYNA-PUR7416 (REG) products recorded the highest bond strengths although slightly lower in comparison to their cube conterparts. There is a slight decrease in bond strength for the DYNA-PUR7416 (NT6) while VersaFlex Clear Seal is performing at the same level as that previously recorded. As for the VersaFlex Alipahtic Clear Coat and the Rust-Oleum Polyurea Polyaspartic RG-80X products, they both performed better than their cube conterparts. Disbondment issues previously seen on the cubes were not exhibited here. As a result, both products performed well and comparable to other products evaluated.

Hence, based on tests conducted, coating deterioration was not sufficient to significantly alter the bond properties. None-the-less, it should be of concern if the product is applied in areas exposed to aggressive deicing salt solutions. This may be addressed via an increase in coating thickness, but, this was not evaluated.

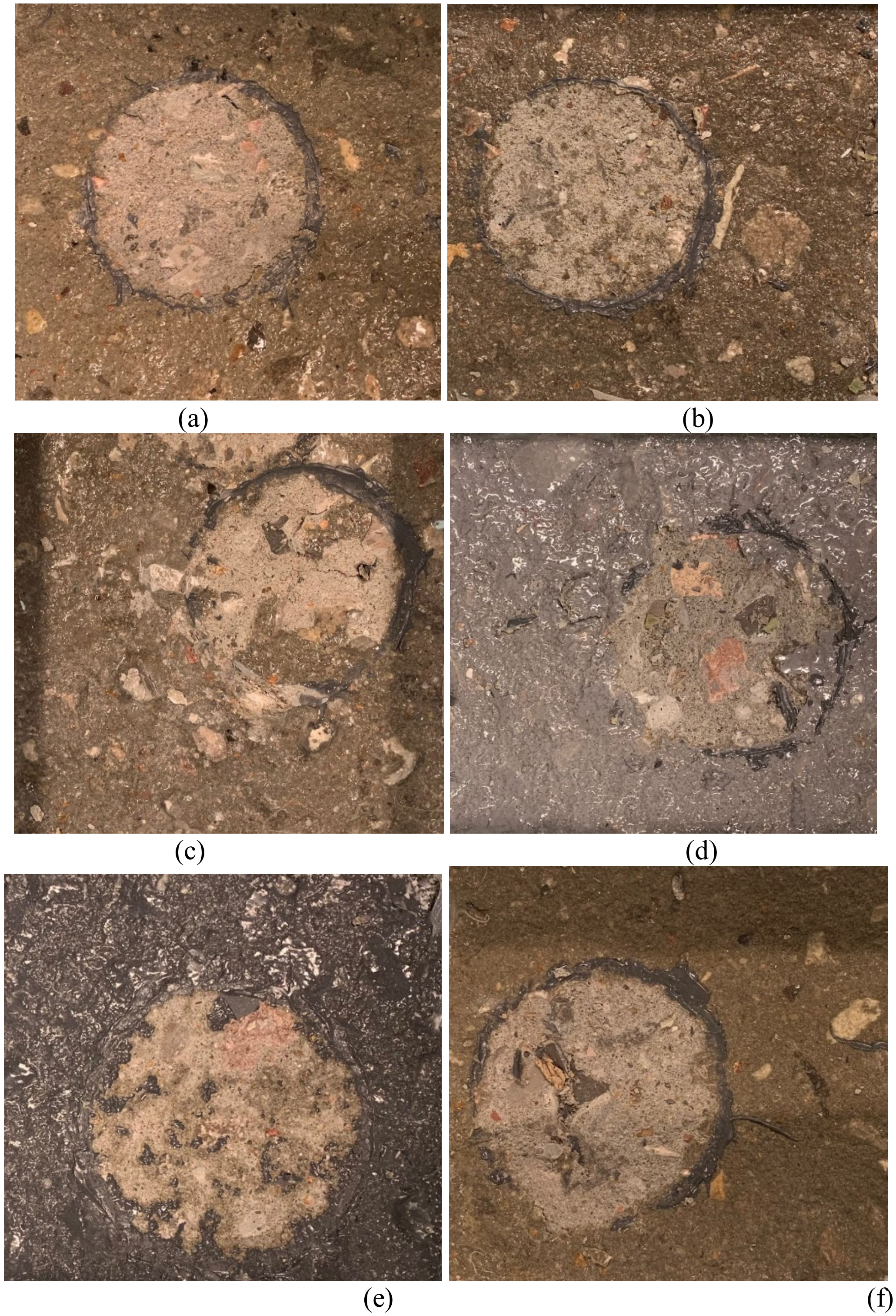


Figure 100: Coating disintegration and pull-off test failure surfaces for salt solution ponding samples with one layer of product: (a) VersaFlex Aliphatic Clear Coat, (b) Rust-Oleum Polyurea Polyaspartic RG-80X, (c) Mirabel Fast, (d) DYNA-PUR7416 (REG), (e) DYNA-PUR7416 (NT6) and (f) VersaFlex Clear Seal.

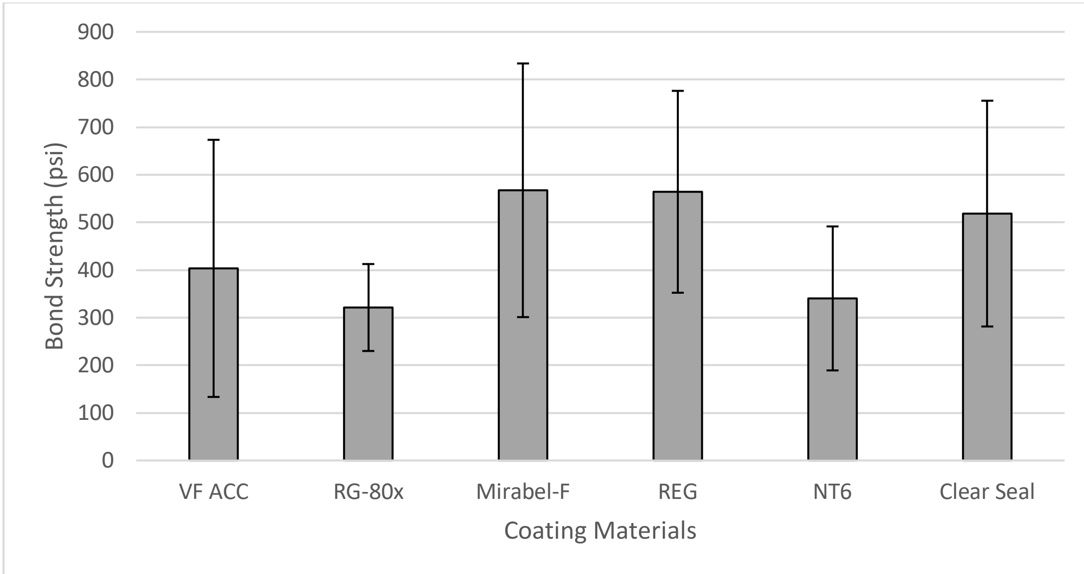


Figure 101: Pull-off test results comparison for all products, salt solution ponding samples

HYDRODEMOLITION AND POLYASPARTIC CONCLUSIONS

Hydrodemolition

The spalling of parapet walls presents danger to the traveling public as pieces of deteriorated concrete may fall onto the road below. The current repair method involves chipping off the weakened concrete using pneumatic hammers. While this process removes damaged concrete, it has the potential to damage sound concrete. Additionally, it has negative implications for health and safety of construction workers involved in removing the concrete. The main two concerns include exposure to silica dust and long-term musculoskeletal damage to the worker using the chipping hammer.

In this research, the main objective was to evaluate the feasibility of using a Hydrodemolition robot for removal of unsound concrete from parapet walls. The sub-objectives included:

a) Evaluating the logistics of transporting and setting up the robot and the support equipment to complete Hydrodemolition within one shift.
b) Assessing the effectiveness of the Hydrodemolition robot in removing unsound concrete.
c) Analyzing the economic effectiveness of replacing the current system with one that uses Hydrodemolition robots.

These objectives were achieved through an initial field testing using a CONJET 327 Hydrodemolition robot on the parapet walls of the bridge on I-270 over Gantz Road in Grove City. During the field testing, we evaluated the technical and economical feasibility of using the robot to repair spalled parapet walls.

We observed that Hydrodemolition offers the following advantages over traditional repair methods:

1. **Worker Safety and Health:** Pneumatic tools used for concrete demolition can expose the workers to harmful effects of crystalline silica and increase the risk of hand-arm vibration syndrome. Hydrodemolition eliminates these hazards. Since the robot is remote controlled, workers can operate it from a safe distance. In addition, the water used in the process contains the concrete dust so none is airborne.
2. **Public Safety:** Hydrodemolition removes all unsound concrete, so it mitigates the possibility of loose pieces falling on the traveling public.
3. **Quality:** Hydrodemolition does not cause microfractures in sound concrete. The machine also cleans, but does not damage, the rebar. It has the capability of removing existing epoxy coatings on parapets, so that deteriorated coatings can be replaced.
4. **Time & Efficiency:** The Hydrodemolition process will increase safety and reduce inconvenience to traveling public. The speed of the machine will significantly reduce the duration of lane closures.
5. **Multipurpose Application:** The CONJET robot will not only have the capability of removing unsound concrete from vertical surfaces (parapet walls), but can also be utilized for removal of unsound concrete from bridge decks, abutments, piers and other elements. The boom lift, a very versatile equipment, can be sued for a wide variety of applications.

6. **Proactive vs. Reactive Maintenance:** Current ODOT maintenance practices are 100% reactive. The hydrodemolition equipment can enable ODOT to be proactive and perform preventative maintenance on bridges.

The price to use the Hydrodemolition CONJET Robot to rehabilitate bridge parapets is estimated to be approximately $2,170 less per bridge than the price to continue with ODOT's current practice of using pneumatic chipping hammers. This does not account for potential reduction in life cycle cost of the bridge if the time to the next parapet replacement can be extended due to a better repair. Hydrodemolition can potentially increase productivity, decreases the time it takes to remove spalled concrete, and increases safety for the maintenance workers and the traveling public. An additional benefit is that the unit can be used for other maintenance purposes.

Based on the analysis, A CONJET 557 robot, a Hammelman 303 high pressure pump, and a JLG 60S boom lift were purchased. A manufacturer's representative visited ODOT District 6 garage for three days to provide comprehensive classroom and field training to ODOT District 6 and District 11 maintenance personnel who will use this equipment on a regular basis. Subsequently, ODOT personnel mobilized the equipment and performed deck repairs on their own. In order to achieve the productivity and economic gains projected in this research:

1. ODOT personnel will need to become proficient in operating the CONJET and the pump. It may take a season for ODOT employees to achieve the projected productivity.
2. Experience will also help ODOT personnel to accurately estimate the amount of water required and number of vacuum trucks required to haul off the water generated from Hydrodemolition. The amount of water used for hydrodemolition depends on the type of nozzle used and the water pressure for operations. It will vary with each application. However, we believe that ODOT engineers will become proficient in estimating these quantities within one season.
3. The location of the robot, pump, water tanker, and vacuum truck at the site are critical to success of the operations. Pre-planning on the day before the work is scheduled to be done will ensure smooth operations.
4. Lastly, we would like to stress the importance of safety measures in these operations. This point was strongly emphasized by the CONJET trainer. We strongly recommend that:
   a. ODOT maintenance personnel follow a rigorous maintenance schedule as recommended by the manufacturer.
   b. The high pressure water hose and the interconnects be inspected daily before the beginning of the work to make sure that no damage is present.
   c. We strongly recommend that, during the operations, ODOT establishes a Controlled Access Zone around the equipment to minimize the exposure of workers to hazards. Only operators should be allowed in this area. Additionally, we also recommend that traffic control should be set up in such a way that motorists' exposure to operations in limited. Performing work at off peak hours and at night time is also recommended.

Polyaspartic Coatings

The purpose of the investigation was to identify several acceptable manufacturers of polyaspartic polyuria coating materials that could be used on a scaled concrete surface to inhibit further surface disintegration. In order to achieve the latter, an adequate bond-strength between the coating and the substrate must be achieved. As such, this was evaluated by performing the pull-off test and the V-notched test. Results demonstrated that bond performance was acceptable but variable throughout the study for all. Here, adequate surface preparation (dry, clean and free of loose debris) along with adequate product batching, mixing and application will favor bond performance.

Both Creative Material Technologies' and Mirabel's products performed adequately in the laboratory. However, it was observed in the laboratory and field testing that the bond performance may be affected by freeze-thaw cycling. Here, Creative Material Technologies and Mirabel products demonstrated signs of bond degradation. However, the products failing the bond-test (Rust-Oleum and VersaFlex) performed adequately for all other tests including freeze-thaw testing. In the case of the Rust-Oleum RG-80X, the disbondment issue initially seen was not observed for the remainder of the study.

As for mechanical performance of the products, the presence of a thin coat of product did not significantly add to the performance of the concrete samples under flexural or compression loading. The performance of the products is considered to be similar for all. There are no additional benefits in terms of mechanical performance to adding 2 or 3 coats of product. However, due to the uneven surface profile of scaled concrete, it is still recommended to apply more than one coat to ensure adequate coverage of all affected area. Water infiltration through discontinuous areas could lead to loss in bond performance.

Moreover, susceptibility of the polyaspartic polyurea products to erosion-abrasion resistance may factor into selecting the number of desired coats. At the end of laboratory cyclic freeze-thaw testing, all products showed visible signs of surface degradation, leading to disbondment in the case of the Creative Material Technologies products. Further testing would be required to determine the actual time-to-deterioration of the product. However, 300 cycles were sufficient to visually reduce the surface layer and expose small areas to water infiltration. To a lesser extent, similar distress features are also noticeable for field samples.

In the end, all products met the study objective of containing failed concrete fragments. For the compression test in accordance with ASTM C39, the applied products aided in restraining the failed concrete cylinder also giving a slight increase in strength and stiffness properties. The field impact test also supports laboratory findings.

Therefore, based on findings of this study, it is concluded that all products evaluated are acceptable for the purpose of sealing the surface and restraining small concrete fragments from falling off the surface. Although all products presented some degree of variable performance between subjected tests, it was found that Creative Material Technologies' products were the least variable in terms of mechanical performance. However, it showed the most signs of coating degradation after freeze-thaw testing. Next, Mirabel products also exhibited good to superior properties in the laboratory study including freeze-thaw performance but, it failed the field test. Thus, it is recommended to revisit field performance for this product. VersaFlex and Rust-Oleum both performed well in the field study. For the laboratory study, they demonstrated acceptable but variable results in terms of bond performance.

APPLICATION OF RESEARCH RESULTS AND BENEFITS

ODOT District 6 spends considerable amount of time, money, and manpower performing bridge parapet maintenance repairs. The benefit received from doing this research would be seen in prolonging parapet life. This will be achieved through developing a SOP supported by data driven techniques and processes while providing cost savings. The current method of chipping deteriorated concrete and leaving it unsealed is not effective at solving the issue of falling parapet pieces. Chipping is time consuming and damages substrate concrete and reinforcing bars, often resulting in the maintenance crews having to return to the same area in time frames as short as one year.

This research relates to ODOT's mission of "Take care of what we have." It directly addresses the Strategic Focus Research Area of Transportation Asset Management. This represents an example of "Developing methods to better utilize resources and integrate advances in science, technology, and construction techniques." It will also enhance Transportation Safety, because deteriorated parapet material represents a risk to the traveling public. Hydrodemolition may be effective in removing deteriorated concrete without damaging the substrate or reinforcing bars. This lessens the chance of further deterioration making the parapet safer and eliminating the need to return to the same area. Polyaspartic coatings may provide a long lasting protective layer to deteriorated areas and may be effective at retaining loose concrete, thus improving safety.

The research is expected to benefit ODOT and Ohio through extended service life, and reduction in maintenance repair costs. Longer lasting repairs will extend the life of infrastructure and reduce disruption to the traveling public.

If successful, this research will benefit ODOT by providing a method for determining the most cost effective way to repair the spalling of bridge parapets. The research will create a decision matrix that will help determine:

1. Appropriate methods of concrete removal
2. The material and processes to be followed for parapet repairs
3. Provide ODOT with recommended materials, processes, and training requirements for application of the protective materials
4. Which repair methods provide a more aesthetically pleasing repair
5. What preventive measures should be used prior to concrete deterioration

The main users are expected to be maintenance personnel in ODOT districts. Other potential users would be other DOTs. ODOT may apply the results of the research through the SOP developed during this project.

NEED FOR FUTURE RESEARCH

It is recommended that the field sites be revisited after several years of exposure to investigate long term performance of the materials. For example, the degree of resistance to abrasion caused by snow and grit thrown up by snowplows may not be determined for several years. Also, it is not known how well these materials will age, and if they will become more brittle or lose adhesion over time. There is also a need to develop and validate a lab test that can be used to predict poor adhesion. In the current testing, the Mirabel product adhered well in the laboratory but peel off of the parapet during field testing.

REFERENCES

1. ASTM C469/C469M-14 Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression, ASTM International, West Conshohocken, PA, 2014, https://doi.org/10.1520/C0469_C0469M
2. ASTM C666/C666M-15 Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing, ASTM International, West Conshohocken, PA, 2015, https://doi.org/10.1520/C0666_C0666M-15
3. ASTM C78/C78M-18 Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading), ASTM International, West Conshohocken, PA, 2018, https://doi.org/10.1520/C0078_C0078M-18
4. ASTM D6677-07(2012) Standard Test Method for Evaluating Adhesion by Knife, ASTM International, West Conshohocken, PA, 2012, https://doi.org/10.1520/D6677-07R12
5. ASTM D7234-12 Standard Test Method for Pull-Off Adhesion Strength of Coatings on Concrete Using Portable Pull-Off Adhesion Testers, ASTM International, West Conshohocken, PA, 2012, https://doi.org/10.1520/D7234-12
6. *Hand and Power Tools* (OSHA 3080, ISBN 0-16-049865-1). (2002). Retrieved from https://www.osha.gov/Publications/osha3080.pdf
7. *Hydrodemolition.* Retrieved from http://conjet.com/method/hydrodemolition/
8. ICRI Guideline No. 310.2-1997- Selecting and Specifying Concrete Surface Preparation for Sealers, Coatings, and Polymer Overlays.
9. Lux, Tom. (2014). *Why Does My Epoxy Floor Have Bubbles?* Retrieved from http://www.florock.net/2014/06/epoxy-floor-bubbles/
10. Nasvik, Joe. (2016). "POLYASPARTIC POLYUREA COATINGS." *Concrete Construction.* Retrieved from http://www.concreteconstruction.net/products/decorative-concrete-surfaces/polyaspartic-polyurea-coatings_o
11. *ODOT's Snow & Ice Program*. Retrieved from https://www.dot.state.oh.us/Divisions/Operations/Maintenance/SnowandIce/Pages/Snow_Ice.aspx
12. *OSHA.* United States Department of Labor. Retrieved from https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=STANDARDS&p_id=1270
13. *OSHA's Respirable Crystalline Silica Standard for Construction.* (2017, December). Retrieved from https://www.osha.gov/Publications/OSHA3681.pdf
14. *PADS - Hand-Arm Vibration.* (n.d.). Retrieved from http://labor.alaska.gov/lss/pads/hand-arm.htm
15. von Fay, K. F. (2015). *Guide to Concrete Repair, Second Edition.* Denver: U.S. Department of the Interior, Bureau of Reclamation, Technical Service Center.
16. Tator, Kenneth B.. (2015). ASM Handbook, Volume 05B - Protective Organic Coatings - 41.1 Variability within a Properly Applied Coating Layer. ASM International.

APPENDIX A: ECONOMIC ANALYSIS

Current ODOT District 6 Practice

Table A.1 below displays the current Ohio Department of Transportation (ODOT), District 6 costs incurred for bridge parapet rehabilitation along with a projected average cost calculated from costs accrued over the past three years. These prices were supplied by ODOT.

Table A.1: Current ODOT bridge parapet rehabilitation costs

Description	**Year**			**Average**	**Cost**
	2015	2016	2017		
Number of Bridges	56	38	57	50	N/A
Sum of total labor hours	7,200	5,568	6,036	6,268	N/A
Direct Labor cost	$125,400	$114,300	$122,000	$120,567	$120,567
Labor with overhead	$225,720	$205,740	$219,600	$217,020	$217,020
Equipment hours	425	488	536	483	$8,211
Equipment miles	30,173	30,188	23,658	28,006	$70,015
				Total	**$295,246**

<u>Analysis</u>:

- Labor Cost = $\frac{\$217{,}020}{50\ bridges}$ = $ 4,340.40 per bridge
- Equipment Cost = $\frac{\$8{,}211+\$70{,}015}{50\ bridges}$ = $ 1,564.52 per bridge
- Total Cost = **$ 5,904.92 per bridge**
- Effect on Traffic =

  $$\frac{50\ bridges}{year} \times \frac{4\ days}{bridge} \times \frac{8\ hours}{day} \times 2\ lanes\ closed\ at\ a\ time = 3200\ lane\ hours\ per\ year$$

  If it is assumed that, on an average, each lane carries 350 vehicles per hour, **lane closures affect 1.12 million vehicles annually**.
- Potential Silica Exposure = **125 Labor hours per bridge**

<u>Calculation Assumptions</u>:

Values utilized in calculations were determined by taking the average values (i.e. labor with overhead costs) supplied by ODOT over the past three years.

For determination of the total cost to operate equipment for parapet equipment, it was assumed that running the equipment costs $17.00 / hour (totaling $8,211.00).

For determination of the total cost of equipment miles for parapet rehabilitation, it was assumed that it costs $2.50 per mile (totaling $70,015.00).

Proposed Practice with CONJET Hydrodemolition Equipment

The current practice of repairing spalled concrete off of parapet walls can be replaced by the use of hydrodemolition equipment. The initial capital investment for this alternative will be as follows:

CONJET 557 Hydrodemolition Robot	$197,768
High Pressure (Hammelmann HDP 303) Pump	$232,668
Boom Lift JLG 600S	$99,718
Trailer for Transportation	$10,000
Total:	$540,154

This capital investment is higher than the amount estimated in the research proposal as a result of the following factors:

1. The original proposal was based on the use of CONJET 327 (smaller) hydrodemolition robot, which costs less. During field tests during research, it was observed that the reach required to perform repair work at the bottom of the outer face of the parapet wall could not be achieved using the CONJET 327. Additionally, the manufacturer believes that additional extensions (to achieve the required reach) to the demolition arm of CONJET 327 would cause the robot to become unstable and unsafe. The CONJET 557 costs more than CONJET 327, because it is larger than the CONJET 327. The CONJET 557 has a longer (wider) cutting span and has the capability to reach over the side of the parapet to the bottom of the wall.

2. After field research, the research team believes that a Boom Lift (positioned under the deck) is necessary for catching the water from hydrodemolition. The cost of purchasing the lift was not included in the original proposal. A long term rental of the lift is not economically efficient; consequently, the research team is recommending purchasing the lift.

3. The numbers quoted above displays the most recent and accurate costs for shipping the units to District 6.

NOTE: See **Table A.5** of Delta Costs at the end of this document for a comparison between the equipment estimate in the original proposal and the recommended equipment purchase.

Cost Breakdown:

Table A.2 below displays the cost breakdown of bridge parapet repairs using the CONJET robot and equipment. Each case displays costs based on the usage of the CONJET robot on bridge parapet wall repairs and other repairs that D-6 decides to use the equipment for.

Table A.2: Annual cost for bridge parapet repairs based on varying CONJET usage

	Description	Annual Cost for Parapet Repairs For Cases Described Below			
		Case 1	Case 2	Case 3	Case 4
1	CONJET 557 Ownership Cost	$19,777	$9,889	$6,526	$4,944
2	Pump Ownership Cost	$23,267	$11,634	$7,678	$5,817
3	CONJET and Pump Operating Cost	$19,000	$19,000	$19,000	$19,000
4	Boom Lift Ownership Cost	$11,648	$5,824	$3,844	$2,912
6	Water Tanker (50 days / year)	$4,900	$4,900	$4,900	$4,900
7	Vacuum Truck (50 days / year)	$34,775	$34,775	$34,775	$34,775
8	CONJET / Pump Operator ($34/hr for 50 days)	$13,600	$13,600	$13,600	$13,600
9	Flaggers (2 Flaggers, $21.6 /hr for 50 days)	$17,280	$17,280	$17,280	$17,280
10	Boom Lift Operator ($34/hr for 50 days)	$13,600	$13,600	$13,600	$13,600
11	Mobilization and Demobilization for CONJET and Pump	$21,100	$21,100	$21,100	$21,100
Equipment Total		$134,467	$107,122	$97,823	$93,448
Labor Total		$44,480	$44,480	$44,480	$44,480
Overall Total		$178,947	$151,602	$142,303	$137,928

* The average number of bridges on which parapet wall repairs were performed in the last three years is equal to a total of 50 bridges.

NOTE: With proper planning and traffic control, using CONJET, damaged concrete on a bridge can potentially be repaired in 1 day. Thus, CONJET will be used 50 days a year to perform the repair tasks that D-6 performs annually. For rest of the period (150 days annually), the CONJET can possibly be used for other D-6 concrete repair needs. The boom lift is extremely versatile. D-6 crews can use it on a number of different maintenance tasks.

CASE 1: CONJET used for Parapet Wall Repair Only
[50 days, 25% utilization]

- Labor Cost = $\frac{\$44{,}480}{50\ bridges}$ = \$ 889.60 per bridge

- Equipment Cost = $\frac{\$134{,}467}{50\ bridges}$ = \$ 2,689.34 per bridge

- Total Cost = **\$ 3,578.94 per bridge**

- Effect on Traffic = $\frac{50\ bridges}{year} \times \frac{1\ days}{bridge} \times \frac{8\ hours}{day} \times 2\ lanes\ closed\ at\ a\ time = 800\ lane\ hours\ per\ year$

  If we assume that, on an average, each lane carries 350 vehicles per hour, the **lane closure affects 280,000 vehicles annually**.

- Potential Silica Exposure = **Eliminated**.
  The water used for hydrodemolition will act as a control measure and eliminate all silica dust.

Current annual cost of parapet wall repair = \$ 295,246.00

Annual Cost of repair using hydrodemolition = \$ 178,947.00

Annual Savings = \$295,246.00 – \$ 178,947.00 = **\$ 116,299.00**

Percent Savings = $\frac{\$116{,}299}{\$\ 295{,}246}$ = **39.4%**

Time to recover initial capital investment = $\frac{\$540{,}154}{\$\ 116{,}299.00\ per\ year}$ = **4.6 years**

Anticipated Service Life of the Equipment = 10 years

CASE 2: CONJET used for Parapet Wall Repair
+
50 days on other concrete demolition tasks
[100 days, 50% utilization]

- Labor Cost = $\frac{\$44{,}480}{50\ bridges}$ = \$ 889.60 per bridge

- Equipment Cost = $\frac{\$107{,}122}{50\ bridges}$ = \$ 2,142.44 per bridge

- Total Cost = **\$ 3,032.04 per bridge**

- Effect on Traffic = $\frac{50\ bridges}{year} \times \frac{1\ days}{bridge} \times \frac{8\ hours}{day} \times 2\ lanes\ closed\ at\ a\ time =$
  $800\ lane\ hours\ per\ year$

- If we assume that, on an average, each lane carries 350 vehicles per hour, the **lane closure affects 280,000 vehicles annually**.

- Potential Silica Exposure = **Eliminated**.
  The water used for hydrodemolition will act as a control measure and eliminate all silica dust.

Current annual cost of parapet wall repair = \$ 295,246.00

Annual Cost of repair using hydrodemolition = \$ 151,601

Annual Savings = \$295,246.00 – \$ 151,601.00 = **\$ 143,645.00**

Percent Savings = $\frac{\$143{,}645}{\$\ 295{,}246}$ = **48.7%**

Time to recover initial capital investment = $\frac{\$540{,}154}{\$\ 143{,}645\ per\ year}$ = **3.8 years**

Anticipated Service Life of the Equipment = 10 years

CASE 3: CONJET used for parapet wall repair
+
100 days on other concrete demolition tasks
[150 days, 75% utilization]

- Labor Cost = $\frac{\$44{,}480}{50\ bridges}$ = \$ 889.60 per bridge

- Equipment Cost = $\frac{\$97{,}823}{50\ bridges}$ = \$ 1,956.46 per bridge

- Total Cost = **\$ 2,846.06 per bridge**

- Effect on Traffic = $\frac{50\ bridges}{year} \times \frac{1\ days}{bridge} \times \frac{8\ hours}{day} \times 2\ lanes\ closed\ at\ a\ time =$ $800\ lane\ hours\ per\ year$

- If we assume that, on an average, each lane carries 350 vehicles per hour, the **lane closure affects 280,000 vehicles annually**.

- Potential Silica Exposure = **Eliminated**.
  The water used for hydrodemolition will act as a control measure and eliminate all silica dust.

Current annual cost of parapet wall repair = \$ 295,246.00

Annual Cost of repair using hydrodemolition: \$ 142,303.00

Annual Savings = \$295,246.00 – \$ 142,303.00 = **\$ 152,943.00**

Percent Savings = $\frac{\$152{,}943}{\$\ 295{,}246}$ = **51.8%**

Time to recover initial capital investment = $\frac{\$540{,}154}{\$\ 152{,}943\ per\ year}$ = **3.5 years**

Anticipated Service Life of the Equipment = 10 years

CASE 4: CONJET used for parapet wall repair
+
150 days on other concrete demolition tasks
[200 days, 100% utilization]

- Labor Cost = $\frac{\$44,480}{50\ bridges}$ = $ 889.60 per bridge
- Equipment Cost = $\frac{\$93,448}{50\ bridges}$ = $ 1,868.96 per bridge
- Total Cost = **$ 2,758.56 per bridge**
- Effect on Traffic = $\frac{50\ bridges}{year} \times \frac{1\ days}{bridge} \times \frac{8\ hours}{day} \times 2\ lanes\ closed\ at\ a\ time = 800\ lane\ hours\ per\ year$

  If we assume that, on an average, each lane carries 350 vehicles per hour, the **lane closure affects 280,000 vehicles annually**.
- Potential Silica Exposure = **Eliminated**.
  The water used for hydrodemolition will act as a control measure and eliminate all silica dust.

Current annual cost of parapet wall repair = $ 295,246.00

Annual Cost of repair using hydrodemolition: $ 137,928.00

Annual Savings = $295,246.00 – $ 137,928.00 = **$ 157,318.00**

Percent Savings = $\frac{\$157,318}{\$\ 295,246}$ = **53.3%**

Time to recover initial capital investment = $\frac{\$540,154}{\$\ 157,318\ per\ year}$ = **3.4 years**

Anticipated Service Life of the Equipment = 10 years

Summary:

Table A.3: Overall summary of the costs and hazard mitigations that hydrodemolition provides

	Current D-6 Practice	CONJET only for Parapet Wall Repairs (50 days of Annual Use)	CONJET for Parapet Wall Repairs + 50 days use for other concrete demolition	CONJET for Parapet Wall Repairs + 100 days use for other concrete demolition	CONJET for Parapet Wall Repairs + 150 days use for other concrete demolition
Labor Cost with Overhead (per bridge)	$4,340.40	$889.60	$889.60	$889.60	$889.60
Equipment Cost (per bridge)	$1,564.50	$2,689.34	$2,142.44	$1,956.47	$1,868.96
Total Cost (per bridge)	$5,904.90	$3,578.94	$3,032.04	$2,846.07	$2,758.56
Cost Savings	**N/A**	**39.4%**	**48.7%**	**51.8%**	**53.3%**
Time to recover the initial investment	**N/A**	**4.6 years**	**3.8 years**	**3.5 years**	**3.4 years**
Time Required	200 days	50 days	50 days for work currently done + 50 days for additional bridge repair	50 days for work currently done + 100 days for additional bridge repair	50 days for work currently done + 150 days for additional bridge repair
Time Saving (Extra Work)	**N/A**	**75%**	**75% time saving (on current work) + 50 extra days to perform other work**	**75% time saving (on current work) + 100 extra days to perform other work**	**75% time saving (on current work) + 150 extra days to perform other work**
Unintended Damage	**May require additional maintenance due to Damage to reinforcing steel and Micro cracking in concrete**	**Does not cause micro-cracking and damage to reinforcement and creates a long term repair eliminating the need to return to the same structure multiple times for additional repairs.**			
Silica Exposure[1] (per bridge)	125 Labor Hours	**Silica Exposure is eliminated**			
Elimination of Safety Hazard	**N/A**	**100%**	**100%**	**100%**	**100%**
Adverse Health Effects	**Jack hammers may cause adverse health effects[2] on workers**	**Adverse effects on worker's health are eliminated**			
Traffic Affected (Annual) (Estimated[2])	1,120,000 vehicles	280,000 vehicles	280,000 vehicles + Traffic affected due to work on additional bridges. Due to high efficiency of the CONJET, traffic impact will be significantly reduced.		
Reduction in Traffic impact (per bridge)	**N/A**	**75%**	**75% reduction on the number of vehicles currently impacted + reduction in impact on traffic on any additional bridges repaired**		

[1]As per OSHA, breathing in very small ("respirable") crystalline silica particles, causes multiple diseases, including silicosis, an incurable lung disease that leads to disability and death (“OSHA's Respirable Crystalline Silica Standard for Construction”). Respirable crystalline silica also causes lung cancer, chronic obstructive pulmonary disease (COPD), and kidney disease. Exposure to respirable crystalline silica is related to the development of autoimmune disorders and cardiovascular impairment. OSHA's Respirable Crystalline Silica standard for construction requires employers to limit worker exposures to respirable crystalline silica and to take other steps to protect workers. All construction employers covered by the standard are required to:

- Establish and implement a written exposure control plan that identifies tasks that involve exposure and methods used to protect workers, including procedures to restrict access to work areas where high exposures may occur.
- Designate a competent person to implement the written exposure control plan.
- Restrict housekeeping practices that expose workers to silica where feasible alternatives are available.
- Offer medical exams-including chest X-rays and lung function tests-every three years for workers who are required by the standard to wear a respirator for 30 or more days per year.
- Train workers on work operations that result in silica exposure and ways to limit exposure.
- Keep records of exposure measurements, objective data, and medical exams.

[2]Assumption: 2 lanes closed at a time, AADT = 8,400 (350 vehicles / hour)

Back-Up Data:

Table A.4: Back-up data regarding cost calculations of CONJET usage per equipment type

	Description	25% CONJET Utilization	50% CONJET Utilization (25% time for Parapet Wall Maintenance + 25% time Other Concrete Demolition Activities)	75% CONJET Utilization (25% time for Parapet Wall Maintenance + 50% time Other Concrete Demolition Activities)	100% CONJET Utilization (25% time for Parapet Wall Maintenance + 75% time Other Concrete Demolition Activities)
		Annual Cost for Parapet Repairs	Annual Cost for Parapet Repairs	Annual Cost for Parapet Repairs	Annual Cost for Parapet Repairs
1	CONJET 557 Ownership Cost	$19,777	$9,888	$6,592	$4,944
2	Pump Ownership Cost	$22,707	$11,354	$7,569	$5,676.75
3	CONJET and Pump Operating Cost	$19,000	$19,000	$19,000	$19,000
4	Boom Lift Ownership Cost	$11,648	$5,824	$3,883	$2,912.00
6	Water Tanker (50 days / year)	$4,900	$4,900	$4,900	$4,900
7	Vacuum Truck (50 days / year)	$34,775	$34,775	$34,775	$34,775
8	CONJET / Pump Operator ($34/hr for 50 days)	$13,600	$13,600	$13,600	$13,600
9	Flaggers (2 Flaggers, $21.6 /hr for 50 days)	$17,280	$17,280	$17,280	$17,280
10	Boom Lift Operator ($34/hr for 50 days)	$13,600	$13,600	$13,600	$13,600
11	Mobilization and Demobilization for CONJET and Pump	$21,100	$21,100	$21,100	$21,100
	Total	$178,387	$151,321	$142,299	$137,788

<u>Delta Cost Analysis</u>:
Table A.5: Comparison between the original and proposed equipment estimates

Item Type	Original Item	Cost in Proposal	Recommended Item	New Cost	Delta Cost
High Pressure Pump	Not Specified	$225000	Model 303	$222,400*	-$2,600
CONJET Robot	Model 327	$115000	Model 527	$193,648*	+$78,648
Spare Parts (as recommended by manufacturer)		$4500		$4120	-$380
High Pressure Hose (300 feet)		$10500		$10,268	-$232
Manlift	Not in original proposal	$0	GLJ 600S	$99,718	+$99,718
Transport Trailer	Not in original proposal	$0	TBD	$10,000	$10,000
Total		$355,000		$540,154	+$185,154

(*) Cost includes shipping and customs.

APPENDIX B: ADDENDUM

Hydrodemolition Equipment

In the field, a CONJET 327 was used to remove spalled concrete on bridge parapets. During testing, it was observed that the machine would require modification (addition) of a custom built beam in order for the robot to reach the bottom of the outer face of the parapet wall. The typical parapet design provided by ODOT was shared with a regional distributor, and they recommended a different machine for this particular work, CONJET 557. The longer reach of this machine will ensure that the application requirements for parapet wall rehabilitation are met (See the figure to the right provided by CONJET). The initial capital cost of purchasing the CONJET, pump, trailer, and boom lift will be approximately $ **618,482** total.

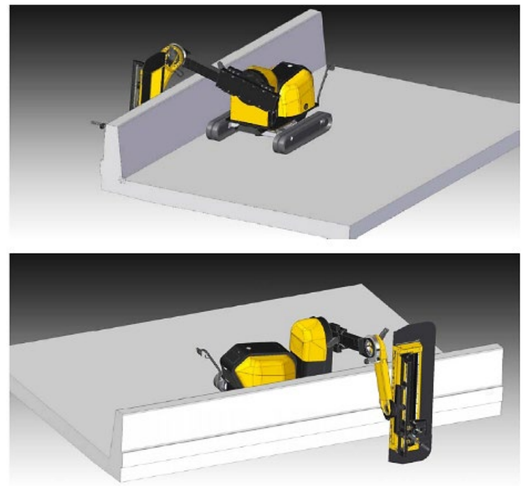


Figure B.1 – CONJET Robot

Annual Ownership Cost of CONJET:

Per the quote received from National Hydro (CONJET Distributor), the cost to purchase the CONJET will be $ 197,767.34

Table B.1: Hydrodemolition equipment quote from National Hydro (CONJET Distributor)

Qty	Description	Parts No.	Unit price in USD	Total price in USD
1	**Robot 557 Diesel Standard**	3312 2540 90	179,290.00	179,290.00
1	Spare Part Kit 557	3312 1406 19	4,120.00	4,120.00
1	Wireless Com. Kit Robot-Pump	3312 2527 18	5,349.00	5,349.00
4	Control cables	3312 2462 60	598	2,392.00
1	HP Connection kit / pump	3312 2545 28	850	850
	Total			**192,001.00**
	Conjet 557 customs and freight			5,766.34
	Total delivered			**197,767.34**

Source: Quote from the manufacturer (see **Appendix A: Economic Analysis**)

Service Life of CONJET Robot = 10 years (Source: Equipment Manufacturer's representative (National Hydro), Penn Hydro (Hydrodemolition Contractor for the project)

$$\text{Annual Cost of Ownership} = \frac{\$197{,}767.34}{10\ years} = \$\ 19{,}776.73 \text{ per year*}$$

*Depreciation or interest costs have not been accounted for in this calculation.

The research team recommends purchasing the CONJET robot, because the CONJET robot eliminates silica exposure, hand-arm vibration, micro-fractures, and the robot quickly removes unsound concrete.

Annual Ownership Cost of the Pump:

The CONJET representative recommended a Hammelmann HDP 503 high pressure pump (Specs in Appendix) to serve the CONJET robot. Based on ODOT request, we have included analysis for HDP 303. The manufacturer's representative claims a service life of 20 years (10,000 hrs. for the engine). For analysis purposes, we believe that it is reasonable to assume a service life of 10 years, the same as the CONJET because the pump is specified for this particular CONJET. The options are as follows:

1. New Pump (HDP 303) : $227,068

$$\text{Annual Cost of Ownership} = \frac{\$227{,}068}{10\ years} = \$\ 22{,}707 \text{ per year*}$$

CONJET and Pump Operating Cost:

The manufacturer's representative reported that the operating cost of the equipment is approximately $10-$12/hr (assuming 10,000 hours use over 10 years), the contractor (Penn Hydro) reported that their operating cost was $40/hr. Keeping in mind the inherent biases of the providers of these numbers, an average operating cost of $20/hr was used in calculations. Additionally, the pump and CONJET will consume 25 gallons of diesel per hour ($75 /hr, assuming a cost of $ 3/gallon). Total cost of operation is $95/hr.

The estimated annual usage of the CONJET over a year will be 200 hours (4 hours per bridge).

Estimated Annual Operating Cost for the Pump and CONJET = $19,000 / year

Water Supply and Disposal Equipment

Boom Lift:

The boom lift will primarily be used for holding up the water catching mechanism. In order to hold sufficient amount of water for smooth operation of CONJET, the research team recommends that a boom lift of at least 1,000 lb capacity shall be used. A JLG 600s boom lift will meet these requirements. Per current ODOT contract with CAT rental agreement the rental costs are as follows:

1. Monthly Rental: $ 4,450

   Annual Cost = $\frac{\$4{,}450}{Month} \times 5\ Months$ = $ 22,250 per year.

The purchase price for a JLG 600s was quoted at $99,718

2. Ownership Cost: $ 99,718

   Annual Cost = $\frac{\$99{,}718}{10\ years}$ = $ 9,972 per year.

   Operating Cost = $\$1{,}195 + \$475$ = $ 1,670 per year.

The research team recommends the second option, because for not much more money ODOT will be able to use the boom lift all year round for various tasks not related to hydrodemolition.

Water Tanker and Vactor:

As per the 2017 ODOT Equipment Standard Rates:
(http://www.dot.state.oh.us/Divisions/Facilities/EquipMgt/EMS/Documents/2017%20Equipment%20Standard%20Rates.pdf)

a. Water Tanker = $\frac{\$98}{day} \times \frac{50\ days}{year}$ = $4,900

b. Vacuum Truck = $\frac{\$695.50}{day} \times \frac{50\ days}{year} = \$34{,}775$

Labor

CONJET / Pump Operator: ($34 /hr for 80 days) = $\frac{\$34}{hr} \times \frac{8\ hrs}{day} \times \frac{50\ days}{year}$ = $13,600 (including O/H)

Flaggers: (2 Flaggers, $21.6 /hr for 80 days) = $\frac{\$21.6}{hr} \times \frac{8\ hrs}{day} \times \frac{50\ days}{year} \times 2$ = $17,280 (including O/H)

Boom Lift Operator: ($34 /hr for 80 days) = $\frac{\$34}{hr} \times \frac{8\ hrs}{day} \times \frac{50\ days}{year}$ = $13,600 (including O/H)

Equipment Transportation

Trailer for CONJET:

$$\text{Annual Cost of Ownership} = \frac{\$10{,}000}{10\ years} = \$\ 1{,}000 \text{ per year}$$

It was assumed that the average round trip to a bridge in District 6 will be 50 miles (Assuming that the equipment is stored in Delaware, OH).

Transportation for CONJET (1 ton pick –up):

$$\text{Annual Cost} = \frac{\$208}{day} \times \frac{50\ days}{year} = \$10{,}400$$

Stake Truck for Pump (1 ton Standard):

$$\text{Annual Cost} = \frac{\$194}{day} \times \frac{50\ days}{year} = \$9{,}700$$

Total Cost = $1,000 + $10,400 + $9,700 = **$21,100**

APPENDIX C: HAMMELMANN PUMP AND GENERATOR SPECS

HAMMELMANN High Pressure Pump Type HDP-503

WB3714604 3-plunger design

1 HAMMELMANN High Pressure Pump Type HDP-503

Special features:

- Forged crankshaft, made of heat treated steel. Supported by heavy duty roller bearings.
- Forced lubrication system, consisting of oil pump, oil cooler, oil filter and oil pressure gauge serving shell bearings through the crankshaft.
- Stainless steel pump head, not subjected to alternating stress and therefore eliminating fracture, valves spring loaded and guided, interchangeable valve seat rings.
- Hydrodynamic Seal (no high pressure packing) with solid ceramic pistons

Performance data:

Output: 43 gpm
Max. operating pressure: 23,000 psi
Motor rating required: 757 HP
Piston diameter: 40 mm
Motor speed: 1800 rpm
Completely mounted on a welded base frame. Pump driven through highly flexible coupling with protection cover, batteries and installation works for diesel engine.

1 - PRESSURE REGULATING AND BYPASS VALVE
directly controlled.
Infinite adjustment of the operating pressure and unloading by means of air operated cylinder, incl. air pressure adjusting valve, high pressure water gauge, overflow connection and G 1/2" thread for rupture disc.

1 - OVERFLOW LINE
to discharge overflow water and cooling water to the buffer tank.

1 - CONTROL LINE
for the pneumatic pressure regulating valve with air pressure adjusting valve and gauge. Additionally, equipped with electrically actuated 3/2-way valve (24 V) to load/unload the pneumatic pressure regulating valve by electric signal.

1 - PNEUMATIC SYSTEM
incl. air tank for control of PRV valve.

1 - RUPTURE DISC ASSEMBLY
for 200 bar and above compulsory with 2 extra rupture discs.

1 - DISCHARGE FITTING

1 - VOLVO DIESEL
diesel engine type TAD 1643 VE, 757 HP at 1800 min-1, EU-Tier II (EPA Tier 2)

1 - AUTOMATIC MONITORING UNIT (ES2 COMPUTER)
with automatic motor cut out and optical indication of failures. Control functions diesel engine: speed of engine, temperature, oil pressure, generator and work hour control. Control functions high pressure pump: water boost pressure, oil pressure, oil temperature, water temperature, differential pressure of the water filter and operating pressure of the pump. The ES2 computer will be mounted to holder on frame.

1 - ELECTRONIC REGULATOR
for diesel engines to regulate the flow of the high pressure pump by adjusting the speed of the diesel engine. Range of adjustment from idle speed to maximum speed. When the consumer is closed, the engine rpm automatically drops to idle speed.

The advantages of this system are:

- Optimum fuel consumption (fuel savings up to 45 %).
- Longer engine life as there is no permanent operation under full load.
- Considerably less wear and tear on the pressure regulating system because working with overflow water is largely eliminated.

The electronic regulator can only be utilized in conjunction with a pneumatically controlled pressure regulating valve and an electrically operated pistol or foot switch or key switch.

1 - INLET BOOST PUMP
To provide positive inlet pressure for HP pump.

1 - SET OF PUMP SAFETY CUT OFF SWITCHES for above.

1 - BAG FILTER
suitable for HDP-500 series pump at a filter fineness of 10 Micron. The filter housing is stainless steel. The filter element can be easily replaced. A vent valve and drain cock are fitted.

1 - BYPASS KEY SWITCH

1 - EXHAUST SILENCER INSTALLATION

1 - TANDEM AXLE GALVANIZED TRAILER
Mounting of above to tandem axle trailer complete with: Dual jack, Spare tire, lockable tool box
400 gallon inlet water tank with plumbed connections to and from pump.
200 gallon DOT fuel tank

Price for new unit as described above: $249,950.00 NET Purchase price

High Pressure Pump Series HDP 500

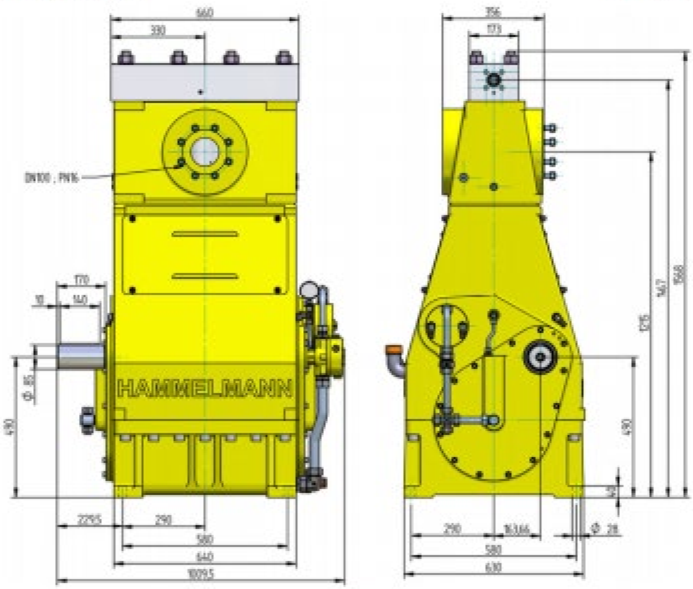
Design criteria

Hammelmann high pressure pumps are built to operate at the continuous maximum duty stated in the performance parameters. Just compare the crankshaft speed, average plunger speed, plunger diameter and power rating.

Energy efficient

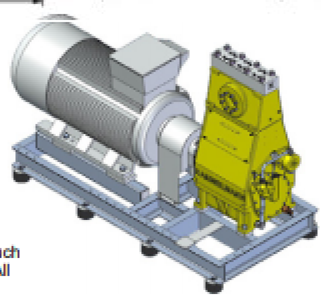
High pressure pump

Weight: 1960 kg



Stationary unit with electric motor

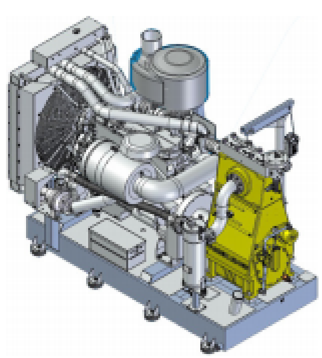
Length:	2896 mm
Width:	1330 mm
Height:	1910 mm
Weight:	approx. 5600 kg at 400 kW



Main dimensions without accessories such as suction line, pressure regulator etc. All shown as right side drive.
Detailed dimensional drawings and weights available on request.

Stationary unit with diesel engine

Length:	3140 mm
Width:	1690 mm
Height:	2410 mm
Weight:	approx. 6700 kg at 522 kW with full fuel tank



Features

- Power ratings up to 500 kW
- Vertical 3 cylinder design
- Wide variety of complementary ancillaries

Quality and reliability

- Stainless steel pump head free of alternating stress
- Cross head piston bellows seal
- Choice of 'application specific' seal assemblies
- Solid ceramic or tungsten carbide plungers
- Choice of bronze or stainless steel suction chamber
- Crank section calculation by 'Finite element method' ensures long working life under continuous load
- Crankshaft supported by 2 bearings and incorporating twin helical speed reducing gears
- Pressurised oil lubrication system with oil cooler/filter

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HDP 500 series, technical data

Performance parameters (Standard design)

HDP	Q [l/min]	Required power rating [kW] 300	350	400	450	500	D	r. p. m. n 1	n 2
		Operating pressure [bar]							
504	52*	3000*						1500	315
	63*	2550*	3000*				28	1500/1800	380
	77*	2100*	2450*	2750*	3000*			1800	465
	68*	2250*	2600*					1500	315
	85 / 82*	1870	2180*	2500*	2600*		32	1500/1800	380
	104 / 100*	1530	1780	2050*	2300*	2550*		1800	465
	85 / 83*	1850	2200*					1500	315
	102 / 100*	1550	1800	2100*	2200*		35	1500/1800	380
	125 / 122*	1250	1450	1700	1900	2200*		1800	465
		*Ultra high pressure							
503	113	1430	1670					1500	315
	136	1170	1370	1570	1670		40	1500/1800	380
	166	980	1140	1300	1470	1630		1800	465
	143	1130	1320					1500	315
	173	930	1080	1240	1320		45	1500/1800	380
	212	770	900	1030	1160	1290		1800	465
502	178	920	1070					1500	315
	214	750	880	1000	1070		50	1500/1800	380
	262	620	730	830	940	1040		1800	465
	214	760	880					1500	315
	257	620	720	830	880		55	1500/1800	380
	313	520	600	690	770	860		1800	465
	258 /	640	740					1500	315
	309	520	610	690	740		60	1500/1800	380
	377	430	510	580	650	720		1800	465
	306	540	630					1500	315
	367	440	520	590	630		65	1500/1800	380
	447	370	430	490	550	620		1800	465
	354	470	540					1500	315
	425	380	450	510	540		70	1500/1800	380
	518	320	370	420	480	530		1800	465
	407	410	470					1500	315
	488	330	390	440	470		75	1500/1800	380
	595	200	320	370	420	460		1800	465
	449	360	410					1500	315
	538	290	340	390	410		80	1500/1800	380
	656	240	280	320	370	410		1800	465
501 High flow	449	360	410					1500	315
	538	290	340	390	410		80	1500/1800	380
	656	240	280	320	370	410		1800	465
	507	320	370					1500	315
	608	260	310	350	370		85	1500/1800	380
	741	220	250	290	320	360		1800	465
	574	280	330					1500	315
	689	230	270	310	330		90	1500/1800	380
	839	190	220	260	290	320		1800	465
	709	230	260					1500	315
	850	190	220	250	260		100	1500/1800	380
	1036	150	180	210	230	260		1800	465
	875	190	220					1500	315
	1050	150	180	200	220		110	1500/1800	380
	1280	130	150	170	190	210		1800	465

Note: Actual flow rates for water as pumped medium (volumetric efficiency has already been taken into

- Rod force: 210 kN
- Stroke:100 mm
- Mean piston speed at n_2
  315 r.p.m. = 1,06 m/sec
  380 r.p.m. = 1,27 m/sec
  465 r.p.m. = 1,54 m/sec

Typical high pressure pump units

- Stationary unit with diesel motor

- Stationary unit with electric motor

Energy efficient

Hammelmann plunger pumps convert 93 to 98 % of the shaft power to hydraulic energy.

Conversion table		
Rating	1 kW	= 1.34 HP
Op. pressure	bar	= 14.5 psi
Flow rate	1 l	= 0.264 US gallon
	1 l	= 0.22 Imp. gallon

HDP	Seal**	Sealing system
504	Dynamic D 28	Tungsten carbide plunger & bushing
	Dynamic D 35	Tungsten carbide plunger / bronze bushing
503	Dynamic	Ceramic plunger / bronze bushing
	Packing	Ceramic plunger / packing
502	Dynamic D 50 -75	Ceramic plunger / bronze bushing
	Packing D 50 - 80	Ceramik plunger / packing
501	Packing	Ceramik plunger / packing

D = Piston/Plunger dia. [mm]
n1 = Motor/Engine r.p.m. [1/min]
n2 = Crankshaft r.p.m. [1/min]

** The dynamic high pressure sealing extends the advantages of the labyrinth design with further increased efficiency.

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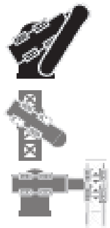
APPENDIX D: CONJET ROBOT 557 DATA SHEET

Distributor/Agent

ROBOT 557 DATA SHEET

Configurations

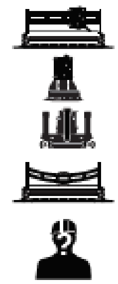
ARMS



Multi Purpose Arm (Standard)

Future developments

TOOLS



Standard

Rotor

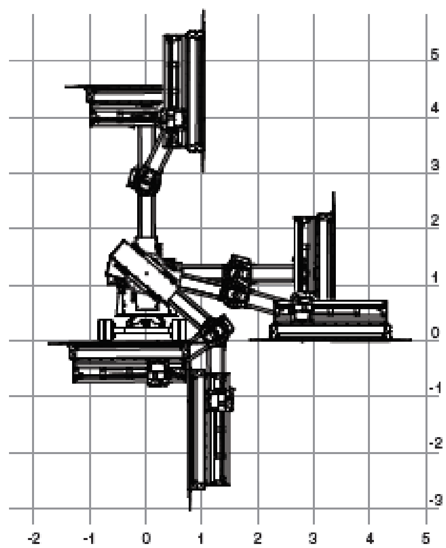
Ship cleaning / Surface preparation

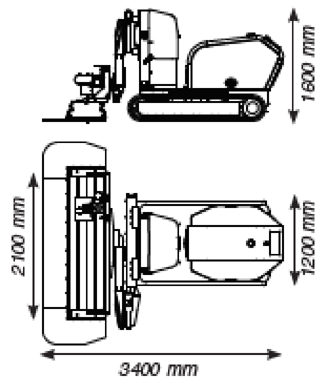
Radius

Custom

Cover chart

-standard configuration





Suggested powerpacks:

Do not forget the powerpack supplying the robot with high pressure water! Suitable powerpacks for Robot 557 range in power from 380 kW to 800 kW, depending on the application. Further information concerning powerpacks can be found in the powerpack brochure or product overview brochure.

Technical Data

-standard configuration

Weight	2500 kg (5500 lb)
Length	3400 mm (11ft 2in)
Width / with extended tracks	1200 / 1900 mm (3 ft 11 in / 6 ft 3 in)
Width, feed beam	2100 mm (6 ft 11 in)
Height, minimum (tool / body)	1600 / 1250 mm (5 ft 3 in / 4 ft 1 in)
Cutting height vertical	5000 mm (16 ft 5 in)
Cutting height overhead	4200 mm (13 ft 9 in)
Cutting below track level	2200 mm (7 ft 2 in)
Cutting width	2100 mm (6 ft 11 in)
Maximum reaction force	3000 N
Power supply	Diesel engine, Yanmar

CE, EMC certified

Pictures are illustrative only and do not necessarily show the configuration of the products on the market at the given point in time.
These products must be used in conformity with safe practice and applicable statues, regulations, codes and ordinances.
Subject to change without prior notice.

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APPENDIX E: HAMMELMAN HDP 303 DATA SHEET

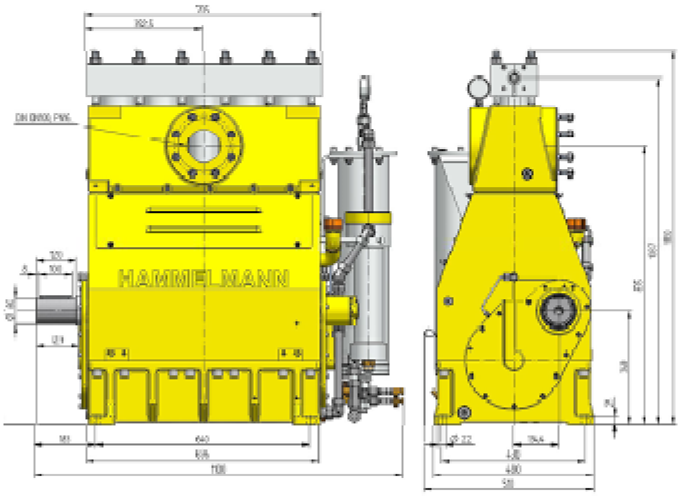
HDP 300 High Pressure Pump series

Design criteria

Hammelmann high pressure pumps are built to operate at the continuous maximum duty stated in the performance parameters. Just compare the crankshaft speed, average plunger speed, plunger diameter and power rating.

High pressure pump

Weight: approx. 1070 kg



Features

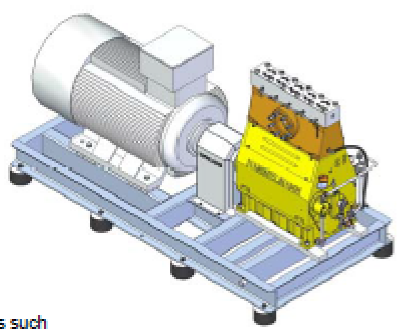
- Power ratings up to 300 kW
- Vertical 5 cylinder design
- Wide variety of complementary ancillaries

Quality and reliability

- Crank section calculation by 'Finite element method' ensures long working life under continuous load
- Stainless steel pump head free of alternating stress
- Integral speed reduction gear
- Pressurised oil lubrication system with oil cooler/filter
- Bellows form hermetic seal between the suction chamber and crank section
- Solid ceramic or tungsten carbide plungers
- Choice of application specific seal assemblies
- Choice of bronze (standard) or stainless steel suction chamber

Stationary unit with electric motor

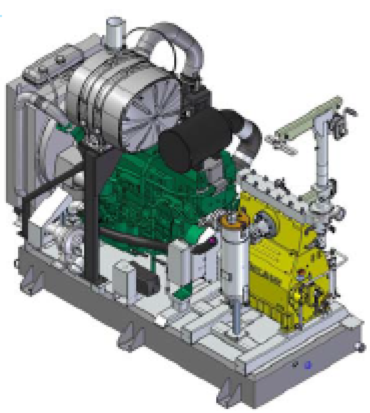
Length: 2570 mm
Width: 1290 mm
Height: 1440 mm
Weight: approx. 3200 kg at 250 kW



Main dimensions without accessories such as suction line, pressure regulator etc. All shown as right side drive. Detailed dimensional drawings and weights available on request.

Stationary unit with diesel engine

Length: 3060 mm
Width: 1570 mm
Height: 2600 mm
Weight: approx. 4500 kg at 315 kW with full fuel tank



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Technical data, series HDP 300

Performance parameters (Standard design)

Note: Actual flow rates for water as pumped medium (volumetric efficiency has already been taken into account).

HDP	Q [l/min]	Required power rating [kW]						D	r. p. m.	
		110	132	160	200	250	300		n 1	n 2
		Operating pressure [bar]								
304	35/33*	1650	1950	2500*	3200*				1500	411
	42/39*	1350	1650	1950	2500*	3200*		17,5	1500/1800	493
	51/47*	1150	1350	1650	2300*	2600*	3200*		1800/2150	591
	46/42*	1250	1500	1850	2500*	2800*			1500	411
	55/51*	1050	1250	1500	1900	2400*	2800*	20	1500/1800	493
	66/62*	900	1050	1300	1600	2000*	2600*		1800/2150	591
303	70	810	970	1170	1470	1800			1500	411
	86	670	800	970	1220	1520	1800	25	1500/1800	493
	101	560	670	810	1020	1270	1600		1800/2150	591
	88	640	770	930	1170	1430			1500	411
	107	530	640	780	970	1210	1430	28	1500/1800	493
	126	450	540	650	810	1020	1300		1800/2150	591
302	101	560	670	810	1020	1240			1500	411
	122	460	560	670	840	1050	1240	30	1500/1800	493
	145	390	470	570	710	890	1100		1800/2150	591
	126	480	560	690	870	1030			1500	411
	152	390	470	570	720	900	1030	33	1500/1800	493
	182	330	390	480	600	750	900		1800/2150	591
	139	410	490	600	750	910			1500	411
	167	340	410	500	620	780	910	35	1500/1800	493
	200	290	340	420	520	650	800		1800/2150	591
	185	310	380	460	570	700			1500	411
	221	260	310	380	470	590	700	40	1500/1800	493
	264	220	260	320	400	500	620		1800/2150	591
	237	250	300	360	450	550			1500	411
	282	210	250	300	380	470	550	45	1500/1800	493
	337	170	210	250	310	390	480		1800/2150	591
	295	200	240	290	360	450			1500	411
	352	170	200	240	300	380	450	50	1500/1800	493
	421	140	170	200	250	320	380		1800/2150	591
	357	170	200	240	300	370			1500	411
	426	140	170	200	250	310	370	55	1500/1800	493
	509	120	140	170	210	260	320		1800/2150	591
	418	140	170	200	250	310			1500	411
	502	120	140	170	210	260	310	60	1500/1800	493
	600	100	120	140	180	220	270		1800/2150	591
	491	120	140	170	220	270			1500	411
	589	100	120	140	180	220	260	65	1500/1800	493
	704	80	100	120	150	190	230		1800/2150	591
	569	100	120	150	190	230			1500	411
	683	90	100	120	160	190	230	70	1500/1800	493
	818	70	90	100	130	160	200		1800/2150	591
	744	80	95	115	145	170			1500	411
	892	65	80	95	120	150	170	80	1500/1800	493
	1069	55	65	80	100	125	150		1800/2150	591

* Ultra high pressure

** The dynamic high pressure sealing extends the advantages of the labyrinth design with further increased efficiency.
*** Special ceramic plungers up to max. 3200 bar.

D = Piston/Plunger dia. [mm]
n1 = Motor/Engine r.p.m.
n2 = Crankshaft

- Rod force: 88 kN
- Stroke: 75 mm
- Mean piston speed at n_2
  411r.p.m. = 1,02 m/sec
  493 r.p.m. = 1,23 m/sec
  591 r.p.m. = 1,48 m/sec

Typical high pressure pump units

- Stationary diesel unit in BDF-Container with workshop

- Stationary electric unit

- Electric unit in container

Energy efficient

Hammelmann plunger pumps convert 93 to 98 % of the shaft power to hydraulic energy.

Conversion table

Rating	1 kW = 1,34 HP
Op. Pressure	1 bar = 14,5 psi
Flow rate	1 l = 0,264 US gallon
	1 l = 0,22 Imp. gallon

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HAMMELMANN®

APPENDIX F: JLG 600S Specs and Data Sheet

Performance

Platform Height		
600S	59 ft 8 in.	18.18 m
660SJ	65 ft 8 in.	20.02 m
Horizontal Outreach		
600S	50 ft 2 in.	15.29 m
660SJ	57 ft 1 in.	17.40 m
Swing	360° Continuous	
Platform Capacity		
600S Restricted/Unrestricted	1,000 lb/600 lb	454 kg/272 kg
660SJ Restricted/Unrestricted	750 lb/550 lb	340 kg/249 kg
Platform Rotator		
600S	160° Hydraulic	
660SJ	180° Hydraulic	
Weight[1]		
600S	21,461 lb	9,735 kg
660SJ	25,341 lb	11,494 kg
Max. Ground Bearing Pressure		
600S	77.7 psi	5.46 kg/cm²
660SJ	85 psi	5.97 kg/cm²
Drive Speed 4WD	3.8 mph	6.1 km/hr
Gradeability 4WD	45%	
Axle Oscillation	8 in.	0.2 m
Turning Radius, Inside/Outside		
2WS	9 ft 7in./19 ft 4 in.	2.92 m/5.89 m
4WS	5 ft 3 in./12 ft 8 in.	1.61 m/3.87 m

1. Certain options or country standards increase weight

Standard Specifications

Power Source

Dual Fuel Engine		
Ford MSG425-DF	84 hp	62 kW
Diesel Engine		
Deutz D2.9L4 Tier 4 Final	48.8 hp	36.4 kW
Fuel Tank Capacity	31 gal	117 L

Hydraulic System

Capacity	34 gal	129 L
Auxiliary Power	12V DC	

Tires

Standard	355/55D625 Pneumatic
Optional	Foam-Filled

Standard Features

- Oscillating Axle
- Hydraulic Platform Rotator
- 110V AC Receptacle in the Platform
- 5 Degree Tilt Alarm/Indicator Light
- Swing-Out Engine Tray
- 12V DC Auxiliary Power
- Hourmeter
- SkyGuard®
- Control ADE® System
- All Motion Alarm
- Proportional Controls
- Gull-Wing Hoods
- Platform Console Machine Status
- Light Panel*
- Engine Distress Warning/Shutdown—
- Selectable via JLG Analyzer
- Lifting/Tie Down Lugs

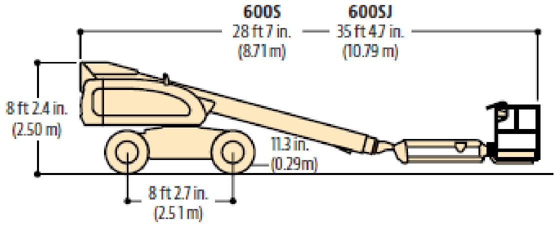
*Provides indicator lights at platform control console for system distress, fuel level, low fuel, 5 degree tilt light and foot switch status.

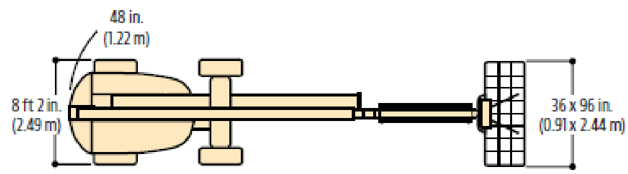
Accessories & Options

- 36 x 72 in. (0.91 x 1.83 m) Platform
- Fall Arrest Platform
- Inward Swinging Gate
- Mesh to Top Rail Bolt-on Aluminum 6 ft
- Mesh to Top Rail Bolt-on Aluminum 8 ft
- Soft Touch System
- Operators Tool Tray
- Tow Package
- 43.5 lb (19.7 kg) Propane Tank
- Cold Weather Start Kit (Ford)
- Cold Weather Start Kit (Deutz)
- Hostile Environment Kit
- Light Package
- Platform Worklights
- Flashing Amber Beacon
- Arctic Package
- Accessory Packages:
  - SkyWelder®
  - SkyGlazier®
  - Nite Bright®
  - SkyCutter®
  - Pipe Rack
  - SkyPower®

Dimensions

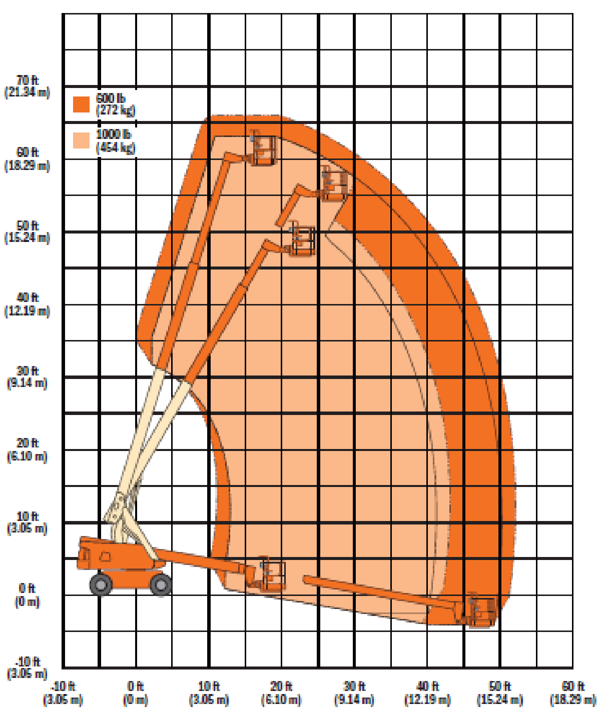
All dimensions are approximate.



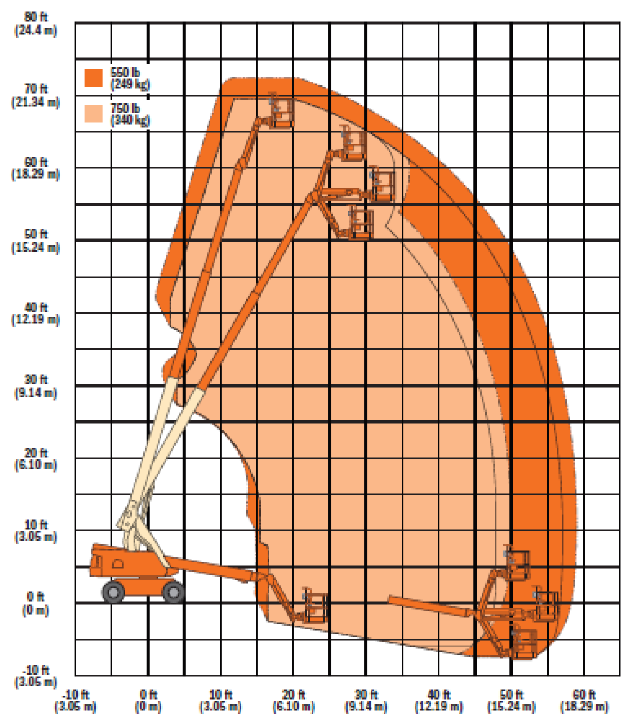


Reach Dimensions

600S



660SJ



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