7.9 Inadequate Hydro-Blasting Rate

Description:

During hydro-blasting, a high-pressure water jet impacts the concrete to be removed (FM 7.9 Exhibit 1 and FM 7.9 Exhibit 2). The water jet pressure that is used is nominally 20,000 psi (FM 7.9 Exhibit 3) although in practice it can vary somewhat (FM 7.9 Exhibit 4 and FM 7.9 Exhibit 5). Detailed discussion of the fundamentals of hydro-blasting is beyond the scope of this document, but a good reference can be found in the book by Professor David Summers, from Missouri Science & Technology University, Rolla, Missouri, in particular chapter 5, "Water jets in civil engineering applications" (FM 7.9 Exhibit 11). One parameter of interest is the movement speed of the water jet nozzles over the surface to be hydro-blasted.

The intent of hydro-demolition as applied here is to break-up and remove the concrete section of interest. This is indeed the point of using this technology in this particular application where concrete HAS to be removed. This FM is attempting to determine if and how the nozzle movement rate might cause damage beyond the application area via force or pressure build-up.

1- If the rate is too high (nozzles move fast over the concrete surface), the force may result in simply "banging" on the concrete wall without any time for the hydro-blasting process to really make a meaningful impact through the action of erosion and water pressurization within the pre-existing micro-cracks and pores in the structure;

2- If the rate is too low (nozzles move slowly over the concrete surface), the dwell time becomes higher and the depth removed per pass can become too high or the pressurized water can have time to go deeper into the structure, for example along tendon sleeves;

3- This failure mode also considers the effect of the nozzles possibly being too close to the containment wall, leading to a higher impact pressure and a deeper concrete removal per each pass (FM 7.9 Exhibit 11 Figure 5.44).

Note that issues associated with resonant frequency are analyzed separately in FM 7.2 and issues dealing directly with excessive impact force are analyzed separately in FM 7.8.

D/6/1

Data to be collected and Analyzed: 1. Determine the change in water jet force on the wall as a function of the distance of the nozzle to the containment concrete (FM 7.9 Exhibit 6, FM 7.9 Exhibit 7, and FM 7.9 Exhibit 8); 2. Examine the fundamentals of water jets technology, particularly as applied in civil engineering (FM 7.9 Exhibit 11); 3. Interview Mac & Mac employees regarding nozzle movement rates and nozzle distances used during the hydro-blasting process at CR3 (FM 7.9 Exhibit 4 and FM 7.9 Exhibit 5); 4. Summary of the Turkey Point liner issues during their containment opening (FM 7.9 Exhibit 10).
Verified Supporting Evidence: a. The force on the wall resulting from the hydro-blasting water jet increases as the distance between the nozzles and the wall decreases (FM 7.9 Exhibit 6 and FM 7.9 Exhibit 7). This makes the process sensitive to keeping a minimum distance. However, no such distance was prescribed in the work instructions (FM 7.9 Exhibit 3);
Verified Refuting Evidence: a. Both the PII calculations (FM 7.9 Exhibit 6 and FM 7.9 Exhibit 7) and the American Hydro calculation (FM 7.9 Exhibit 8) both conclude that the baseline force from the water jet to the containment wall is minimal for the prescribed distance of 1 ft; b. There are no indications that Mac & Mac operated the equipment at a higher nozzle movement rate than prescribed and expected (FM 7.9 Exhibit 3 and FM 7.9 Exhibit 4); c. There are also no indications that Mac & Mac operated the equipment at a lower nozzle movement rate than prescribed and expected (FM 7.9 Exhibit 3 and FM 7.9 Exhibit 4); d. There are also no indication that Mac & Mac operated the equipment at an inadequate distance from the concrete wall, different from what was prescribed and expected (FM 7.9 Exhibit 3 and FM 7.9 Exhibit 4);

e. The possibility of high-pressure water moving deep in the concrete along tendon sleeves and generating the delamination was suggestive. One critical observation refuting this point is that the delamination was observed at the time of the hydro-blasting mock-up operation, and chunks of concrete started falling BEFORE the tendon sleeves were apparent (FM 7.9 Exhibit 12). This would indicate that the delamination may have been present before the hydro-blasting operation started.

Discussion:

Interviews with engineers at two of the leading hydro-demolition companies, Mac & Mac and at American Hydro, demonstrated that the two systems are mostly similar. Our calculations and American Hydro calculation confirm that in both cases the force from the water jet to the concrete is not high. The force on the wall does, however, increase as the nozzles get closer to the concrete wall. American Hydro has performed eight Steam Generator Replacement (SGR) openings into post-tensioned reactor building containments (seven were performed when we started this investigation in October 2009 and one more was done since at TMI). All were successful, demonstrating that it is possible to hydro-blast the SGR opening into a post-tensioned aged concrete containment without collateral damage to surrounding concrete or structures.

Additionally, all the literature we found on comparing the various means to perform concrete removal agree that hydro-blasting is the least damaging to the underlying structure. The reference book from our reviewer Professor David Summers (FM 7.9 Exhibit 11) and discussions with the author confirmed that hydro-blasting at pressures above 15,000 psi is the favored approach to prepare a concrete surface before adding new concrete on top, through a texturing effect that favors a stronger bond. Note that a water pressure of 800 bars, as exemplified in Figure 5.46 of FM 7.9 Exhibit 11 corresponds to 12,000 psi. Therefore the hydro-blasting technique is used in nuclear containment with the "moderate pressure philosophy" as described in FM 7.9 Exhibit 11.

We found no indications that the water was just "banging" on the wall. On the contrary, an early sign that things were not right was the presence of large chunks of concrete falling from the hydro-blasted area. This is now taken as an indication that a delamination layer was present behind the hydro-blasted concrete (FM 7.9 Exhibit 9). Additionally, the water jet is rotating at 500 rpm and therefore the water is always moving very fast over the concrete surface. The main effect of the nozzle movement rate is then the depth of cut.

An important caveat to add is that although the forces generated by the water jet are not sufficient to generate the delamination, it is possible they could have been instrumental in propagating it. Once the crack started in the plane of the tendon sleeves, it is "active" because it is in an area of local tensile stresses. Therefore it can be propagating with minimal forces serving as an "activation energy"

force just pushing the local tensile stress above the tensile strength of the concrete.
Conclusion: The rate of hydro-blasting did not contribute to the delamination.

TECHNICAL
GUIDELINES

Prepared by the International Concrete Repair Institute September 2004

Guide for the Preparation of Concrete Surfaces for Repair Using Hydrodemolition Methods

Guideline No. 03737

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About ICRI Guidelines

The International Concrete Repair Institute (ICRI) was founded to improve the durability of concrete repair and enhance its value for structure owners. The identification, development, and promotion of the most promising methods and materials is a primary vehicle for accelerating advances in repair technology. Working through a variety of forums, ICRI members have the opportunity to address these issues and to directly contribute to improving the practice of concrete repair.

A principal component of this effort is to make carefully selected information on important repair subjects readily accessible to decision makers. During the past several decades, much has been reported in literature on concrete repair methods and materials as they have been developed and refined. Nevertheless, it has been difficult to find critically reviewed information on the state of the art condensed into easy-to-use formats.

To that end, ICRI guidelines are prepared by sanctioned task groups and approved by the ICRI Technical Activities Committee. Each guideline is designed to address a specific area of practice recognized as essential to the achievement of durable repairs. All ICRI guideline documents are subject to continual review by the membership and may be revised as approved by the Technical Activities Committee.

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Synopsis

This guideline is intended to provide an introduction to hydrodemolition for concrete removal and surface preparation, the benefits and limitations of using hydrodemolition, and an understanding of other aspects to be addressed when incorporating hydrodemolition into a repair project. This guideline provides a description of the equipment, applications, safety procedures, and methods of water control and cleanup.

Keywords

Bond, bonding surface, bruising, chipping hammer, coating, concrete, delamination, deterioration, full depth repair, hand lance, high-pressure water, hydrodemolition, impact removal, mechanical removal, micro-fracture, post-tensioning, rebar, reinforced concrete, reinforcing steel, robot, rotomill, safety, sound concrete, surface preparation, surface profile, surface repair, tendon, vibration, wastewater, and water jet.

Purpose

This guideline is intended to provide owners, design professionals, contractors, and other interested parties with a detailed description of the hydrodemolition process; a list of the benefits and limitations of using hydrodemolition for concrete removal and surface preparation; and an understanding of other aspects to be addressed when incorporating hydrodemolition into a repair project. The guideline provides a description of the equipment, applications, safety procedures, and methods of water control and cleanup. This guideline is not intended as an operating manual for hydrodemolition equipment as that information is specific to each equipment manufacturer.

The scope of this guideline includes the use of hydrodemolition for the removal of deteriorated and sound concrete in preparation for a concrete surface repair. In addition, the use of hydrodemolition for the removal of coatings is discussed.

While the procedures outlined herein have been found to work on many projects, the requirements for each project will vary due to many different factors. Each project should be evaluated individually to ascertain the applicability and cost-effectiveness of the procedures described herein. Other methods of surface preparation are discussed in ICRI Technical Guideline No. 03732, "Selecting and Specifying Concrete Surface Preparation for Sealers, Coatings, and Polymer Overlays."

Introduction

Hydrodemolition is a concrete removal technique which utilizes high-pressure water to remove deteriorated and sound concrete. This process provides an excellent bonding surface for repair material. First developed in Europe in the 1970s, this technology has become widely accepted for concrete removal and surface preparation throughout Europe and North America.

Hydrodemolition can be used for horizontal, vertical, and overhead concrete removals and surface preparation on reinforced and non-reinforced structures. It is effective in removing concrete from around embedded metal elements such as reinforcing steel, expansion joints, anchorages, conduits, shear connectors, and shear studs. Hydrodemolition can be used for localized removals where deterioration is confined to small areas and for large area removals in preparation for a bonded overlay. This technology can also be used to remove existing coatings from concrete.

Hydrodemolition has been used on the following types of structures:

- Bridge decks and substructures
- Parking structures
- Dams and spillways
- Water treatment facilities
- Tunnels and aqueducts
- Nuclear power plants
- Piers and docks
- Stadiums
- Warehouses
- Retaining walls

The Effects of Mechanical Impact Techniques

Mechanical methods such as chipping hammers, rotomills, scabblers, and scarifiers remove concrete by impacting the surface. These procedures crush (bruise) the surface, fracture and split the coarse aggregate, and create micro-fractures in the substrate (Fig. 1 and 2). As a result, the ability of the fractured substrate to provide a durable

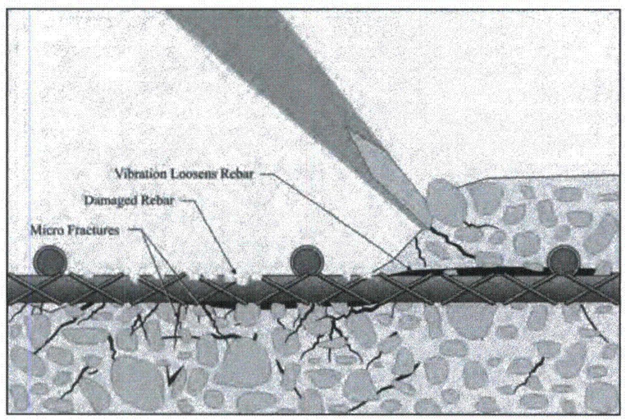

Fig. 1: Damage created by chipping hammer

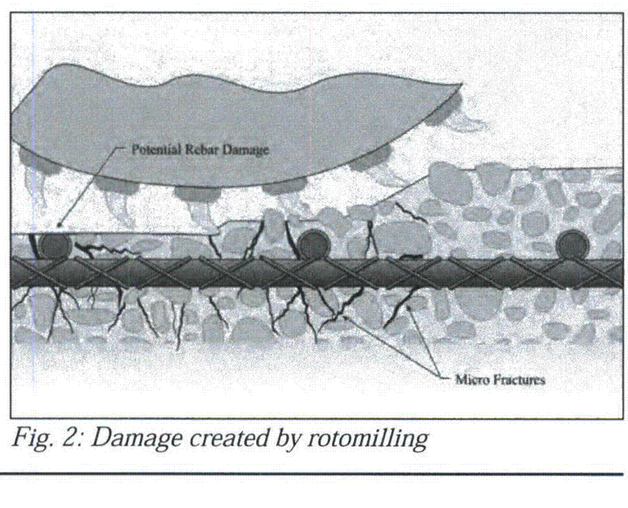

Fig. 2: Damage created by rotomilling

bond with the repair material is compromised, requiring a second step of surface preparation to remove the damaged region.

Furthermore, impact methods may damage the reinforcing steel and embedded items such as conduit, shear studs and connectors, and expansion joint hardware. Impact methods transmit vibrations through the reinforcing steel, which may cause further cracking, delamination, and loss of bond between the reinforcing steel and the existing concrete. Vibration and noise created by the mechanical impact will travel through the structure, disturbing the occupants. During repair of thin slabs and precast tees, chipping hammers may shatter the substrate resulting in unanticipated full depth repairs.

For a discussion on surface bruising and the mechanics of concrete removal by impact methods, refer to ICRI Technical Guideline No. 03732, "Selecting and Specifying Concrete Surface Preparation for Sealers, Coatings and Polymer Overlays."

Hydrodemolition Benefits and Limitations

The benefits of hydrodemolition can be placed into two groups: structural benefits that improve the quality of the repair, and environmental benefits that improve the quality of the work place. Hydrodemolition also has limitations, which need to be considered.

Structural Benefits

- A rough, irregular surface profile is created to provide an excellent mechanical bond for repair materials;
- Surface micro-fracturing (bruising) is eliminated;
- Exposed aggregates are not fractured or split;
- Lower strength and deteriorated concrete is selectively removed;
- Vibration is minimal;
- Reinforcement is cleaned, eliminating the need for a second step of surface preparation; and
- Reinforcing and other embedded metal elements are undamaged.

During concrete removal, the water jet is directed at the surface, causing high-speed erosion of the cement, sand, and aggregate. The water jet does not cut normal weight aggregate which remains intact and embedded as part of the rough, irregular surface profile (Fig. 3). The aggregate interlocks with the repair material to assist in developing a

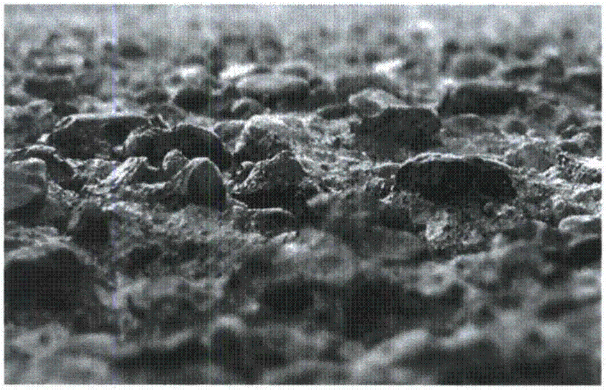

Fig. 3: Surface prepared by hydrodemolition has a rough irregular profile with protruding aggregate and is excellent for creating a mechanical bond

mechanical bond and composite action between the substrate and the repair material.

The rough, irregular surface profile provided by hydrodemolition can result in bond strengths that equal or exceed the tensile strength of the existing concrete. The concrete surface profile can exceed CSP-9 (very rough) as defined in ICRI Technical Guideline No. 03732.

Rotomills and scarifiers remove concrete to a uniform depth and may leave deteriorated concrete below the specified depth. Alternatively, the water jet moves in a consistent pattern over the surface and will remove unsound concrete even if it is below the specified depth.

Since the water jet does not create mechanical impact, vibration is not transmitted into the structure from the hydrodemolition operation. Delamination beyond the repair area caused by vibration of the reinforcing steel is greatly reduced.

During hydrodemolition, sand and cement particles mix with the water jet. The abrasive action of theses particles is usually sufficient to clean uncoated reinforcing bar and embedded metal items without damaging them. Corrosion material is removed from the reinforcing bar and metal items, allowing for easy inspection and identification of cross-sectional area loss. The reinforcing bar is cleaned without any loss of deformations. Cleaning of the entire reinforcing bar, however, will not occur if the reinforcing bar has not been completely exposed during hydrodemolition.

Environmental Benefits

- Minimizes disruptions to users of occupied space by significantly reducing transmitted sound through the structure;
- Increased speed of concrete removal can reduce construction time;
- Minimizes dust; and

- Robotic units reduce labor and minimize injuries as compared to chipping hammers.

Concrete removal by hydrodemolition can take place inside an occupied structure, such as a hotel, apartment building, office building or hospital with minimal noise disruption to the occupants.

Hydrodemolition can quickly remove concrete. As such, project duration can be reduced, minimizing the impact on the users of the structure.

During demolition, cleanup, and final wash down, the concrete debris and repair surface remain wet, minimizing dust in the work area. Since hydrodemolition cleans the reinforcing steel, the need to sandblast is eliminated unless additional concrete removal is required using chipping hammers. As such, silica dust in the work area is reduced, thereby providing a safer work environment.

The use of chipping hammers and other impact methods are labor intensive and physically demanding, which can cause injury to the employee. Robotic hydrodemolition equipment reduces the use of these tools and the possibility of injury.

Limitations

- The hydrodemolition process consumes a significant amount of water (6 to 100 gpm [25 to 380 lpm]). A potable water source must be available. The cost of the water should be considered;
- Wastewater containing sand and cement fines (slurry) must be collected, treated, and returned to the environment. Wastewater disposal may require a permit;
- Projects requiring total demolition can be done faster and more economically with crushers and similar equipment;
- Water can leak through cracks in the concrete and damage occupied space below the repair area. Hydrodemolition should not be used over occupied areas due to the risk of blow-through (unanticipated full-depth removal);
- Repair areas of varying strength will result in non-uniform removal. Areas of high strength may need to be removed using hand lances or chipping hammers;
- The water jet is blocked by reinforcing steel resulting in concrete shadows under the reinforcing bar that may need to be removed using hand lances or chipping hammers;
- Since the water jet of a robotic unit is contained in a metal shroud, some robots are unable to completely remove concrete up to a vertical surface such as a curb, wall or column. The remaining concrete may have to be removed using hand lances or chipping hammers;
- The water jet will remove the sheathing from post-tensioning tendons and may drive water into the tendon;
- The hydrodemolition robot may be too large to access small or confined areas of the structure;
- The water jet can damage coatings on reinforcing steel and other embedded items;
- The water jet can introduce water into electrical system components, especially if embedded in the concrete and already deteriorated or not properly sealed; and
- If cleanup is not properly performed in a timely manner, further surface preparation may be required.

The Hydrodemolition System

The hydrodemolition system consists of a support trailer or vehicle, high-pressure pump(s), a robotic unit to perform the demolition, and high-pressure hoses to connect the pump(s) to the robot. Hand lances are also available to remove concrete in areas inaccessible to the robot.

Support Trailer

Hydrodemolition units are typically transported on 40 to 50 ft trailers (Fig. 4). The robot may be transported on the same trailer or separately on a smaller trailer. The support trailer usually contains a supply of spare parts, tools, maintenance area, fuel and water storage, supply water hoses, and filters. These units are designed to be self-sufficient on the job site with adequate spare parts to perform routine maintenance and repairs.

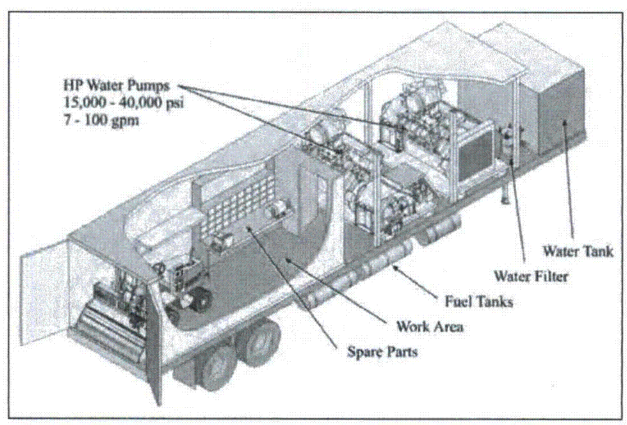

Fig. 4: Hydrodemolition support trailer. A self-contained unit transports pumps, robot, hoses, and spare parts

High Pressure Pumps

The high-pressure pumps used for hydrodemolition are capable of generating pressures from 10,000 psi to 40,000 psi (70 to 275 MPa) with flow rates from 6 to 100 gpm (25 to 380 lpm). The pumps are driven by a diesel or electric motor, typically operating between 100 and 700 horsepower. The engine size will vary based on the flow and pressure rating of the pump. The pumps operate most efficiently at their design pressure and flow. High-pressure hoses connect the pumps to the robot. The pumps may be located a significant distance (500 ft [150 m]) from the actual removal area. However, due to a drop in pressure and flow through the high-pressure hoses, the pumps should be located as close as possible to the removal area, typically within 300 ft (100 m).

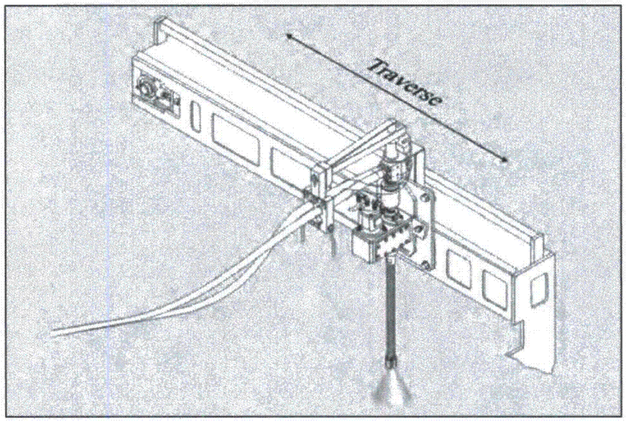

Fig. 6: Nozzle is mounted on a traverse beam

Robotic Removal Unit–Horizontal Surfaces

The force created by the high-pressure pump(s) is controlled using a robotic removal unit (Fig. 5). The robot is a diesel or electric powered, self-propelled, wheeled or tracked vehicle. It is used to uniformly move and advance the water jet over the surface during concrete removal.

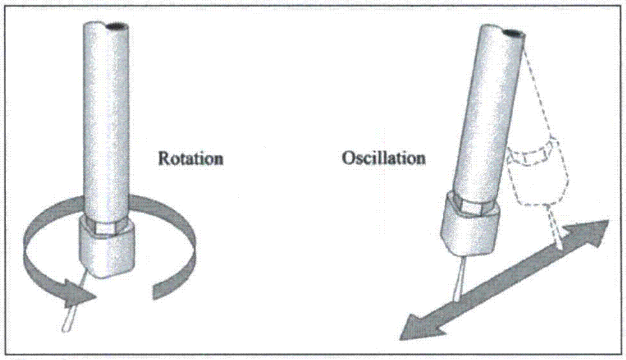

Fig. 7: Rotating or oscillating nozzles

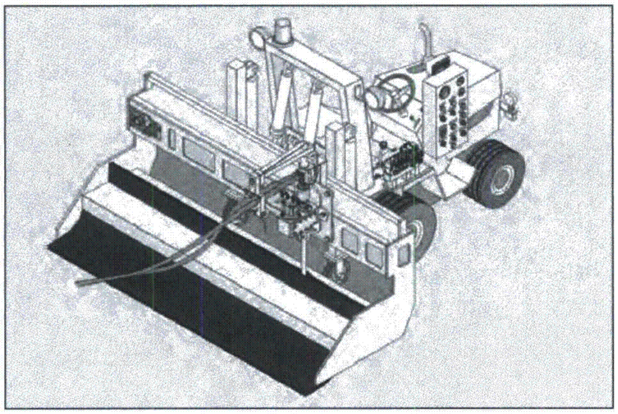

Fig. 5: Typical hydrodemolition robot

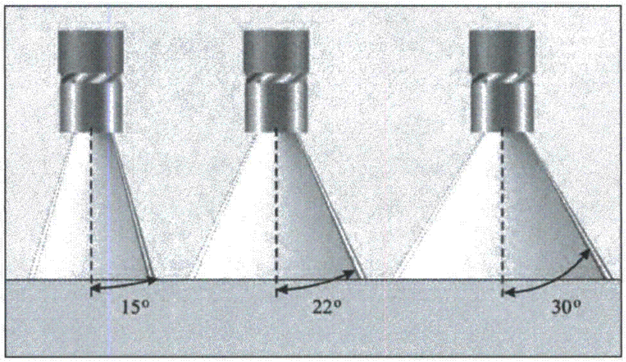

Fig. 8: Rotating nozzles are angled from center

The water jet is mounted on a trolley that traverses over the removal area along a cross feed or traverse beam (Fig. 6) perpendicular to the advance of the robot. The water-jet nozzle may either oscillate or rotate (Fig. 7). The oscillating nozzle is angled forward in the direction of the traverse. Rotating nozzles are angled from the center, creating a cone effect while rotating (Fig. 8 and 9).

The nozzle assembly is enclosed within a steel shroud with rubber seals around the perimeter to contain the debris during demolition (Fig. 10).

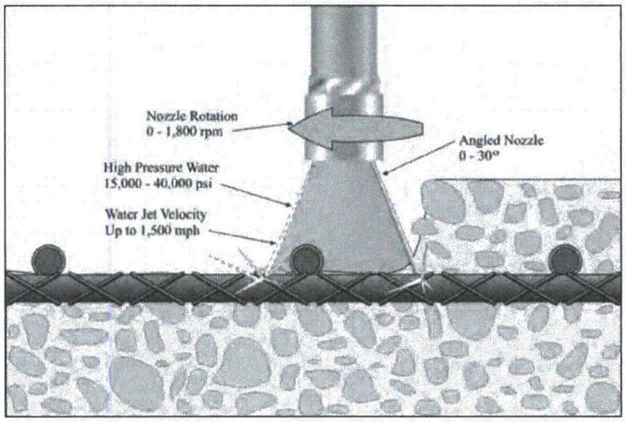

Fig. 9: Rotation of the angled nozzle creates a water cone

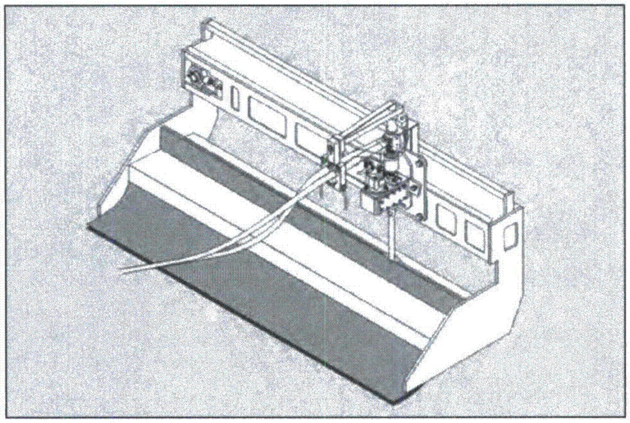

Fig. 10: Nozzle is enclosed within a steel shroud

The rotation/oscillation of the nozzle combined with the traverse and advance of the robot provide a uniform and continuous motion of the water jet over the removal area (Fig. 11). Each of these functions is fully adjustable. The depth of concrete removal is determined by the length of time the water jet is directed at the removal area.

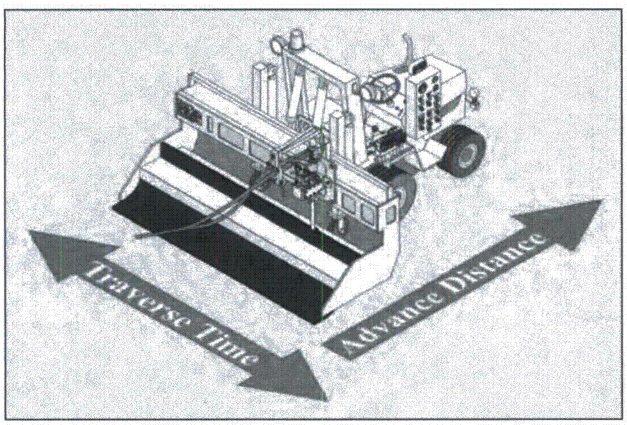

Fig. 11: The water jet traverses back and forth perpendicular to the forward advance of the robot

Adjusting the following parameters will increase or decrease the depth of removal:

a. Total traverse time (time of each traverse × number of traverses); and
b. Distance of the advance.

Once these parameters are set, the robot will reproduce the settings in a programmed sequence to provide consistent removal of the concrete. For example, during deep removal to expose the reinforcing bar 3 to 4 in. (75 to 100 mm), the traverse speed may be 8 seconds (the time required for the water jet to move from one side of the traverse beam to the other) and the water jet may traverse 3 times before the robot advances forward 1 to 2 in. (25 to 50 mm). On the other hand, for light scarification 1/4 to 1/2 in. (6 to 13 mm) or coating removal, the traverse speed may be 3 seconds and the water jet may traverse only one time before the robot advances 2 to 4 in. (50 to 100 mm).

The depth of concrete removal is controlled at the robot. Since the pumps are designed to operate at a specific pressure and flow rate, it is unusual to reduce the pressure (and subsequently the flow rate) to adjust the depth of removal.

Narrow areas may be removed by adjusting sensors that limit the movement of the water jet along the traverse beam. The traverse and advance functions limit the removal to a rectangular area along the advance path of the robot. Because the water jet is contained within a steel shroud, most robots are unable to remove concrete within 3 to 6 in. (75 to 150 mm) of vertical surfaces.

Specialized Robotic Equipment—Vertical and Overhead Surfaces

Various types of robotic equipment are available to perform removals on walls, soffits, substructures, beams, columns, and tunnels. These robots are often built on wheeled or tracked vehicles and have the ability to lift the traverse beam into the vertical or overhead position. The primary functions of traverse and advance are utilized in order to provide uniform concrete removal during vertical and overhead repairs.

As an alternative to the robot, the water jet may also be attached to a frame that allows the jet to move in a two dimensional "X-Y" plane. The X-Y movement of traverse and advance are present in these units to provide uniform concrete removal. The X-Y frames can be lifted and positioned over the removal area using a crane, backhoe, all-terrain forklift or other similar equipment.

Hand Lance

Hand lances operate at pressures of 10,000 to 40,000 psi (70 to 275 MPa) while delivering approximately 2 to 12 gpm (8 to 45 lpm) of water. Hand lances are not as fast or as precise for concrete removal as a programmed robot and are slower than chipping hammers. Hand lances are effective in performing light scarification and coating removals. It should be noted that the water jets on hand lances may not be shrouded, increasing the risk of debris becoming airborne. Hand lances can be used for removal of:

- Concrete shadows below reinforcing bar;
- Concrete adjacent to walls, columns, curbs, and in tight and confined areas not accessible to the robotic equipment; and
- Coatings.

Safety

Hydrodemolition involves the use of potentially dangerous specialized equipment. At all times, the manufacturer's instructions for the safe operation of the equipment and personal protective equipment should be followed, as well as all local, state, and federal regulations. Hydrodemolition units should be supervised and operated by qualified personnel certified by the equipment manufacturer.

Hydrodemolition employs high-velocity water jets to demolish concrete and perform surface preparation. Even though the water jet is shrouded on robotic units, debris can be propelled from beneath the shroud with sufficient velocity to cause serious injury. Serious injury or death can also occur if struck by the water jet. Hand lances are typically not shrouded and care must be exercised to avoid injury when using these tools.

Workers, equipment operators, and any individuals entering the work area are required to wear hard hats, safety glasses, hearing protection, safety shoes, gloves, long pants and long-sleeve shirts, and must be trained in the proper use of personal protective equipment. When using a hand lance, the operator should wear a full-face shield, rain suit, and metatarsal and shin guards. Additional protective clothing may also be required for use with hand lances. Everyone involved with the hydrodemolition operation should receive specific training outlining the dangers associated with the use of high-pressure water.

Prior to starting demolition, an inspection of the area should be performed including the area under the work area. All barricades, partitions, shielding, and shoring must be installed and warning signs posted to prevent unauthorized entry into the work area. The area below the work area must be closed off and clearly marked "Danger— Do Not Enter." Electrical conduits or other electrical equipment in the work area should be deenergized to avoid electrical shock.

Special precautions are required for post-tensioned structures as referred to in the section "Considerations for Hydrodemolition Use."

Hydrodemolition Applications

Scarification

Scarification is performed to remove the surface concrete and provide a rough profile (Fig. 12 and 13). Scarification is often used in preparation for a concrete overlay. If the surface was previously rotomilled, the minimum removal depth using hydrodemolition should equal the size of the coarse aggregate to remove all concrete micro fractures and damaged or crushed aggregate.

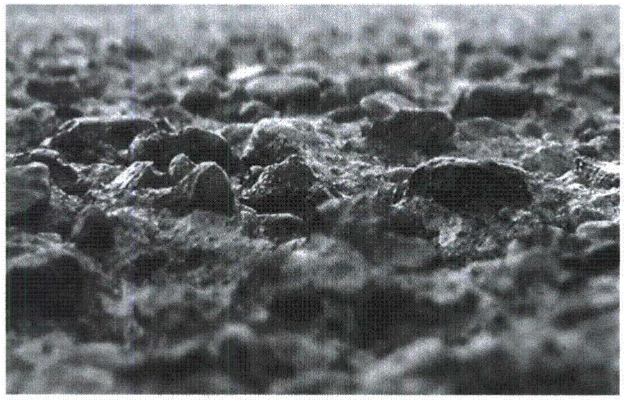

Fig. 12: Scarified surface with 1 in. aggregate

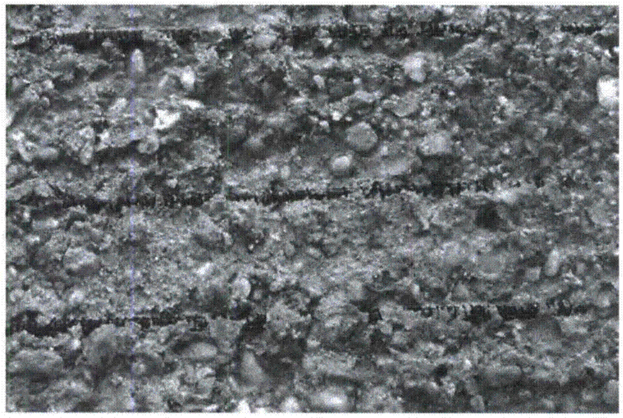

Fig. 13: Scarified surface with 3/4 in. aggregate

Scarification may not remove all unsound concrete due to the rapid rate at which the water jet moves over the surface. It may be necessary to resurvey the scarified surface and identify delaminated or deteriorated areas for further removal.

Partial Depth Removal

Partial depth removal is commonly required if chloride contamination has reached the top mat of reinforcing steel or deterioration, delamination or spalling occurs within the top mat of reinforcing steel. Partial depth concrete removal can expose the top mat of reinforcing steel and provide clearance, typically a minimum of 3/4 in. (19 mm), below the bottom reinforcing bar of the top mat (Fig. 14 and 15). Determining the reinforcing bar size and concrete cover are critical to determine the required removal depth.

Concrete removal using hand lances or chipping hammers may be required to remove shadows under the reinforcing bar, previously repaired areas

Fig. 14: Partial depth removal

Fig. 15: Partial depth removal on a retaining wall

or high areas resulting from variations in the strength of the concrete. In addition, concrete removal may be necessary adjacent to vertical surfaces such as curbs, walls and columns. Saw cutting of the perimeter of the repair area, if required, should be performed after hydrodemolition to prevent damage to the saw cut. This will require additional concrete removal along the repair perimeter with hand lances or chipping hammers. If the saw cut is made first, the area outside the saw cut should be protected using a steel plate. The steel plate will allow the water jet to slightly over run the saw cut without damaging the surface outside the saw cut while completely removing the concrete within the repair area.

Full Depth Removal

Hydrodemolition can be used for full depth removal where delamination has occurred in the lower mat of reinforcing or chloride contamination exists throughout the entire thickness of the slab. Full depth removal can be performed along expansion joints and other areas where there is a high concentration of reinforcing steel that may be damaged if conventional removal methods are used. Other structural elements such as shear connectors, shear studs, and steel beam flanges can be exposed without damage.

During full depth removal, the removal rate slows as the depth increases because the water jet stream dissipates as it moves away from the nozzle and the water jet must push more water and debris from its path prior to contacting the surface to be removed.

Full depth removal is often necessary on waffle or pan joist slab systems (Fig. 16).

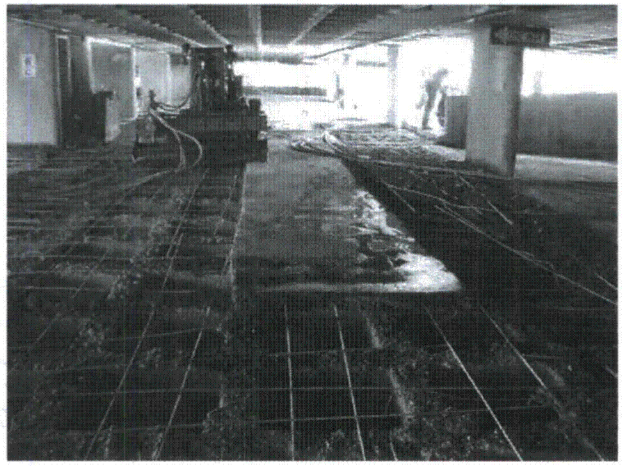

Fig. 16: Full depth removal—waffle slab

Coating Removal

Hydrodemolition can be used for the removal of epoxy, urethane, hot applied membrane, and other coatings from concrete surfaces (Fig. 17). When performing coating removal, a multiple jet nozzle is used. The multiple jets allow the water to penetrate the coating without damaging the concrete. However, if the concrete below the coating is deteriorated, it may be removed along with the coating.

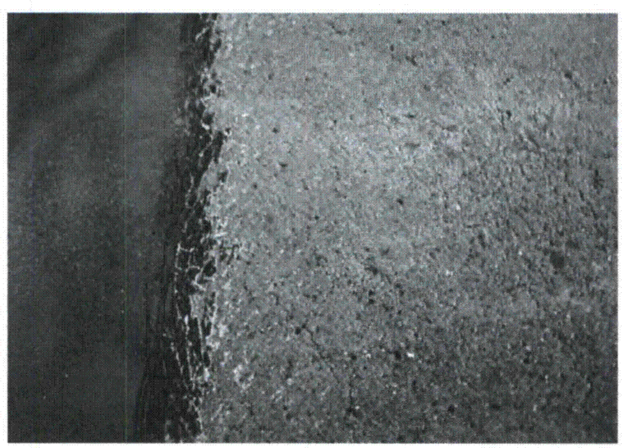

Fig. 17: Coating removal using a spinning, multi-nozzle spray head

The Hydrodemolition Process

Concrete removal by hydrodemolition is impacted by the following factors:

- Size and density of the aggregate;
- Concrete strength;
- Uniformity of concrete strength;
- Extent of cracking;
- Deterioration and delamination;
- Surface hardeners;
- Previous repairs with dissimilar strength material; and
- Size and spacing of reinforcing steel or other embedded items.

In sound concrete, the variation in the depth of removal will generally equal the size of the coarse aggregate (Fig. 18). For example, if the coarse aggregate is 1 in. (25 mm), $D = 1$ in. (25 mm) and the specified depth of removal is 2 in. (50 mm), the range of removal will be 2 in. (50mm) $\pm D/2$ (1/2 in. or 13 mm), or 1-1/2 in. (38 mm) to 2-1/2 in. (63 mm).

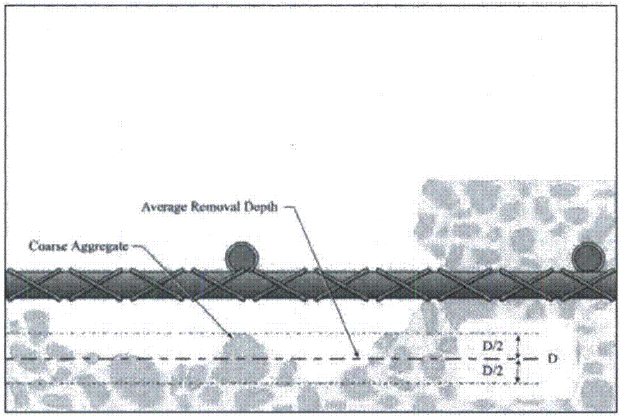

Fig. 18: The depth of removal depends on the size of the course aggregate

During hydrodemolition, a high-pressure water jet is uniformly moved over the surface and, provided the concrete is sound and the strength does not change significantly, the removal depth will remain consistent. Depth variations occur when the concrete strength changes, cracking or delamination is present, the concrete is deteriorated or the surface has been previously repaired using a different type and strength of material. In comparison, rotomilling or dry-milling equipment can be set to a specific depth and the milling drum will mill the surface to that depth regardless of any variations in the concrete strength, quality or level of deterioration.

If the strength of the concrete increases or a high-strength repair area is encountered during hydrodemolition, the removal depth will decrease (Fig. 19). The decrease in depth may not be immediately detected by the operator, resulting in an area of shallow removal (Fig. 20). To obtain the required depth in higher strength concrete, the total traverse time is increased and the advance of the robot is decreased. If the high-strength repair area is large enough, it may be possible to set up the hydrodemolition robot over the area and remove to the specified depth. This

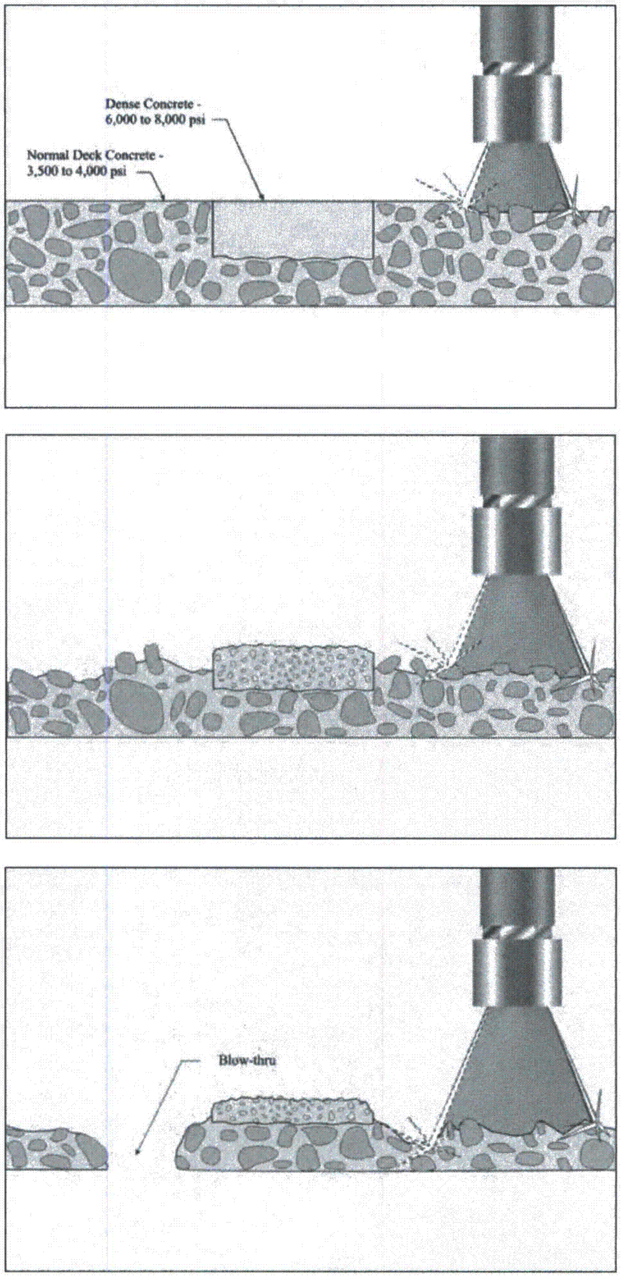

Fig. 19: High-strength concrete is removed at a slower rate than normal concrete, which can result in a non-uniform removal

Fig. 20: High-strength repair area within the hydro-demolition area

procedure can be problematic for two reasons. First, if the water jet overruns the high-strength repair area, it may result in a blow-through or full depth removal at the perimeter of the high-strength repair area. Second, since the water jet must be slowed significantly, it may cause excessive removal below the high-strength area once it is removed and the softer base concrete is exposed. For these reasons, it is often preferable to use chipping hammers in high-strength repair areas.

The opposite effect is encountered if the concrete strength decreases or there is cracking, deterioration or delaminations (Fig. 21). Concrete that is deteriorated, low strength or delaminated is removed faster than the surrounding sound concrete by the water jet. For example, if the average removal depth is 2 in. (50 mm) and there is a delamination that is 2 in. (50 mm) deep, the actual removal within the delaminated area could be 3 to 4 in. (75 to 100 mm) deep. For this reason, removal in an area that is seriously deteriorated and delaminated may not be consistent.

This effect is often described as "selective removal of deteriorated concrete." While the water jet is traversing and advancing uniformly over the surface, it is removing unsound, delaminated, deteriorated, cracked, and low strength concrete selectively below the specified removal depth.

Selective removal is not without limitations. For example, if the robot is traversing and advancing rapidly as during scarification, it may not remove deeper delaminations.

Size and spacing of the reinforcing steel will also influence the removal depth. The reinforcing steel blocks the water jet and shields the concrete below, creating concrete "shadows" (Fig. 22 and 23). Removal of concrete shadows becomes more difficult as the reinforcing bar size increases and

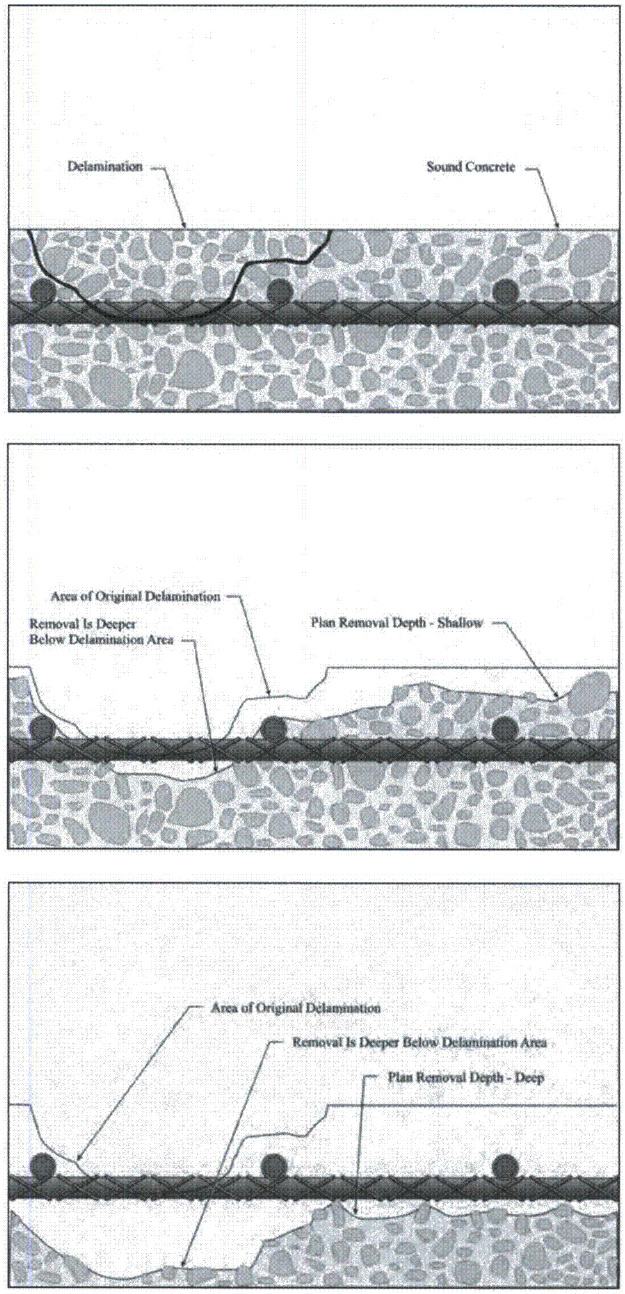

Fig. 21: Delaminated or deteriorated concrete is removed at a faster rate leading to non-uniform removal

is most difficult at reinforcing bar intersections. Increasing the specified depth of removal will minimize the amount of shadowing.

Pointing the water jet under the reinforcing bar can reduce concrete shadows. This can be accomplished by using a rotating or oscillating nozzle (refer to Fig. 7-9). Rotating nozzles are typically angled 10° and 30° from center. The nozzle rotates between 100 and 1800 rpm, creating a demolition cone that will undercut both the transverse and parallel reinforcing bar provided the specified removal depth is greater than the

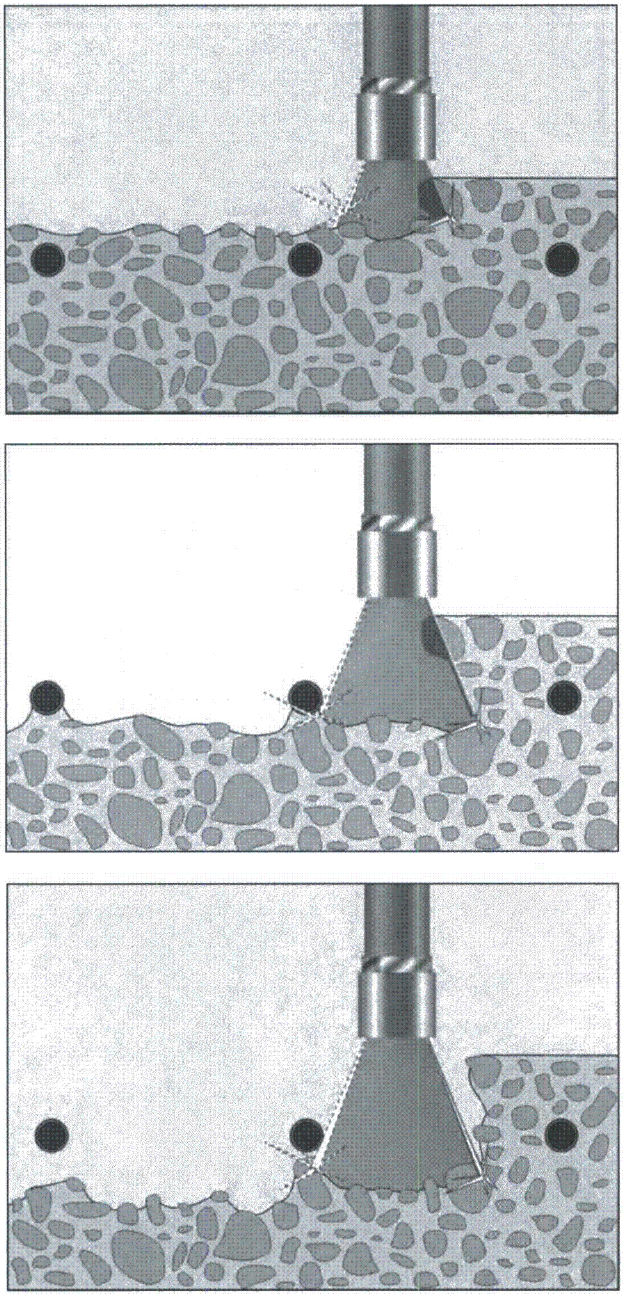

Fig. 22: Reinforcing steel blocks the water jet leaving a concrete "shadow" under the reinforcing. Increasing the removal depth will decrease the amount of shadowing

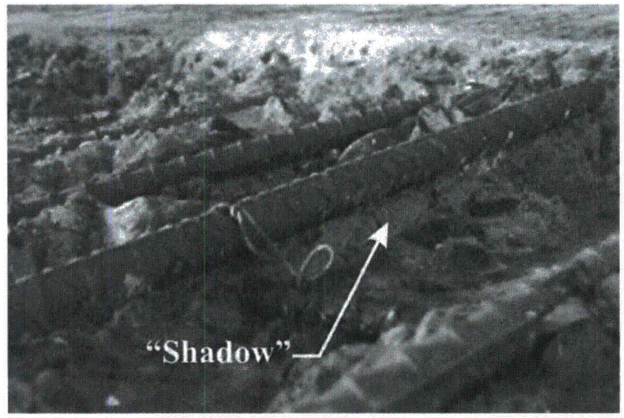

Fig. 23: "Shadow" under the rebar (note tie wire undamaged and in excellent condition)

depth of the reinforcing bar. Similarly, the oscillating nozzle moves from side to side as it traverses, directing the water jet at an angle to the surface, cutting under the reinforcing bar. The nozzle is angled forward as it traverses left, and at the end of the traverse, flips to face forward as it traverses right. To minimize concrete shadows, the required depth of removal should be at least 3/4 in. (19 mm) below a #5 reinforcing bar. Larger reinforcing bars will require a greater removal depth to minimize shadowing. While this additional removal may result in the removal of sound concrete, it will minimize the need for concrete removal under the reinforcing bar with chipping hammers or hand lances.

Considerations for Hydrodemolition Use

Issues that should be considered when evaluating the use of hydrodemolition for a repair project include:

Limited quantity of repair: Mobilization and set up of the hydrodemolition equipment can be expensive. If there are only minor repairs or a limited quantity of repairs, the mobilization cost may make the process uneconomical.

Increase in repair quantity: The traverse and advance function of the hydrodemolition robot results in removal areas that are rectangular. The removal areas may have to be "squared up" in order for the hydrodemolition equipment to efficiently remove the concrete. "Squaring up" the repair areas may lead to an increase in the removal quantity and the cost of the project.

Reinforcing bar size and concrete cover: Partial-depth removal normally requires clearance below the bottom reinforcing bar of the top mat of reinforcing. The size and quantity of the reinforcing bar and the concrete cover over the reinforcing bar should be determined in order to specify the correct removal depth to achieve the required clearance.

Potential for full-depth blow-throughs: Hydrodemolition of severely deteriorated structures may result in full-depth blow-throughs. Blow-throughs may take place where full depth slab cracks occur, especially if deterioration is evident on the slab underside. Shielding may be required to protect the area below from damage. Shoring below the blow-through may be damaged or destroyed. When the water jet is in the open air, as will happen when the water jet blows through the deck, it is extremely noisy (may exceed 130 db) and dangerous. Sound resistant partitions should be installed to contain the noise within the structure if blow-throughs are expected.

Extent of previous repairs: Repair materials may have a different compressive strength than the original concrete. Since the hydrodemolition jet is set to move at a uniform rate, the presence of dissimilar strengths of material will result in a variation in the depth of removal. Higher strength areas may require further concrete removals using chipping hammers or hand lances to achieve the specified depth of removal. Lower strength areas may result in deeper removals and possibly full-depth blow-throughs.

Occupied areas adjacent to or under the repair area: Occupied spaces such as stores or offices may occur in the structure. It may not be practical to perform hydrodemolition adjacent to or over these areas. Water from the hydrodemolition may leak to the occupied level below. As such, the repair area should be protected to prevent water from entering the occupied area.

Shoring requirements: During structural repairs, concrete may be removed from around the top reinforcing. An analysis of the structural capacity of the remaining slab section should be made by a qualified engineer to determine if shoring will be required. The weight of the hydrodemolition robot should be considered when determining shoring requirements.

Equipment location: The hydrodemolition equipment is transported on a trailer. If possible, the pumps should be located within 300 ft of the repair area. A suitable location next to the structure must be selected. Pump units that are powered by diesels engines should not be located next to the air intake of adjacent buildings. In congested metropolitan areas, the pumps may be removed from the trailer and placed within the structure. Diesel powered pumps will need to be located close to an exhaust shaft and the exhaust from the pumps piped to this location. A fuel tank will also have to be placed in the pump area and provisions made to fill the tank as required. Although electric pumps may be used inside the structure eliminating the fueling and exhaust concerns, they have a substantial power requirement and will need an electrical service installed. Due to the weight of the pumps, they may need to be placed on the slab on ground or in a shored area of the structure. Temporary shoring may be needed to move the pumps into the structure.

Available water sources: Pumps used for hydrodemolition require a steady supply of clean water at a sufficient volume to perform the work. Generally, local municipal water is used for hydrodemolition. Sources close to the work area, such as a nearby fire hydrant or water line feeding the structure, should be adequate. Specific water requirements will vary, depending on the hydrodemolition unit used for the project and the method of cleanup. Cleanup performed using a fire hose operating at 100 to 200 gpm (380 lpm to 760 lpm) will use substantially more water than an 8000 to 10,000-psi (55 to 70 MPa) water blaster operating at 8 to 12 gpm (30 to 45 lpm). In remote areas, water can be drawn from wells, fresh water lakes, rivers, or streams. This water must be pre-filtered to remove any suspended solids to avoid damage to the high-pressure pumps. Recycled water has been used for hydrodemolition, however, it can add substantially to the cost of the project due to collection and filtration of the water and the added wear to the equipment caused by dissolved minerals in the recycled water. When available, potable water is used. Water may have to be trucked into remote locations.

Post-tensioned structures: The use of hydrodemolition on post-tensioned structures has potentially severe risks and must be carefully evaluated to maintain a safe working environment, maintain structural integrity, and to preserve the long-term durability of the structure. Sudden release of anchorages can result in dangerous explosive energy and flying debris capable of causing damage to equipment and serious injury or death to workers. Tendons should be de-tensioned prior to removing concrete from around anchorages to prevent the sudden release of the anchorages and loss of pre-stress forces. The loss of pre-stress forces may result in the loss of structural integrity and result in the need for shoring. Careful evaluation must also be exercised when removing concrete around post-tensioning tendons. Removal of concrete around tendons can result in a change of tendon profile, which may also result in the loss of prestressing force and structural integrity.

The wires or strands of post-tensioning tendons are usually undamaged during hydrodemolition, however the sheathing and protective grease will be removed from unbonded tendons. In bonded post-tensioning tendons, the water jet may penetrate the duct and remove the grout inside. In either case, the hydrodemolition water may enter the tendon at the edge of the repair area and can be driven into the tendon outside the work area. Water remaining in the tendon can cause future corrosion affecting the long-term durability of the post-tensioning system. Each tendon must be carefully examined and any water that has entered the tendon removed. Both the grease and the protective sheathing must be restored.

It may not be possible to remove moisture that has entered the post-tensioning system during the hydrodemolition process. In addition, verification of the presence of moisture is difficult and may not be possible. Refer to ICRI Technical Guideline No. 03736, "Guide for the Evaluation of Unbonded Post-Tensioned Concrete Structures," for suggested procedures to detect water in post-tensioning tendons. Long term monitoring for future corrosion may also be prudent.

Conduit and embedded metal items: Embedded aluminum and steel conduit will not be damaged by hydrodemolition if they are in good condition. However, deteriorated portions of aluminum and steel conduit will be damaged and water will enter the conduit system. PVC conduit will be damaged during hydrodemolition. As a safety precaution, all conduits should be deenergized during demolition. Other metal items within the removal area such as shear connectors, shear studs, and anchorages will not be damaged by hydrodemolition.

Noise limitations: Hydrodemolition does not produce sound that is transmitted through a structure, however, the noise from the hydrodemolition unit in the work area is sufficiently loud to be objectionable to the public. Furthermore, noise can be excessive during full-depth repairs or blow-throughs. Sound reducing partition walls that separate the public from the work area may be required. Acoustical studies indicate that the sound waves created by hydrodemolition are low frequency and are best controlled using dense material such as sheet rock or concrete board. There are a variety of sound deadening materials supplied by various vendors that have proven effective in controlling noise. Partition walls should be protected from moisture. If properly sealed at the base, a water resistant sound reducing partition wall will also assist in containing the water within the work area.

Protection of lighting, sprinklers, and other services: Light fixtures, fire protection systems, and other services may be damaged by airborne debris from the hydrodemolition or clean up operation. If full depth removal or blow-throughs are anticipated, light fixtures may need to be removed and stored and temporary lighting installed. Sprinkler heads may need to be protected. Mist and high humidity in the work area could damage electrical panels and other services. Items remaining in the work area should be protected.

Temperature: When the temperature falls below freezing, the structure must be heated or the hydrodemolition stopped to prevent water from freezing in the work area.

Test Area

A test area should be designated to establish the operating parameters and to demonstrate that the equipment, personnel, and methods of operation are capable of producing satisfactory concrete removal results. The test should include sound and deteriorated concrete areas, each a minimum of 50 ft^2 (5 m^2). First the robot is set to remove sound concrete to the specified depth. Once the operating parameters have been determined, the equipment is moved to the deteriorated area and a second test is performed using the same operating parameters. If satisfactory results are achieved, the quality and depth of removal will become the standard for the project. If hand lances are to be used to perform concrete removals, they should also be demonstrated to show satisfactory results.

It is noted that the hydrodemolition robot will move the water jet over the surface in a constant motion and if the concrete is of uniform strength, the removal depth will be consistent. However, since concrete is seldom uniform, there will be variations in the removal depth on the project. Other factors affecting the removal depth include the extent and depth of deterioration, the size and quantity of reinforcing bar, the concrete cover over the reinforcing bar, and the presence of surface hardeners. As the equipment is used, nozzles will wear, changing the force created by the water jet. As such, the hydrodemolition equipment operator must monitor the depth and quality of removal and adjust the parameters of the robot to provide consistent removal throughout the project.

Wastewater Control

Controlling the wastewater has often been viewed as one of the more difficult tasks associated with the use of hydrodemolition. However, with preplanning and proper installation of a wastewater control system, the water can be properly managed (Fig. 24). Hydrodemolition wastewater should be

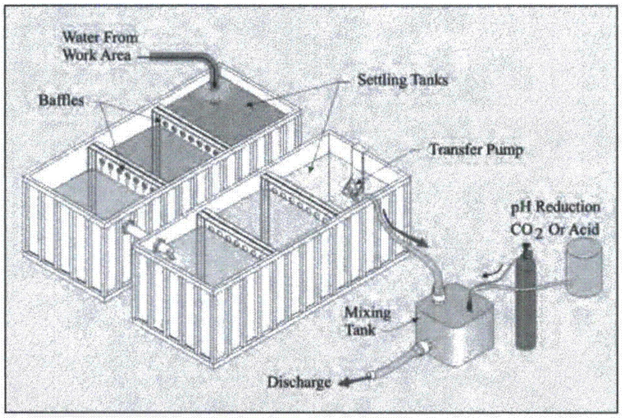

Fig. 24: Typical wastewater handling system

discharged to the storm or sanitary sewer or to the ground for absorption and/or evaporation under permit from the controlling authority. Discharge into an existing storm or sanitary line may occur in the structure or to a nearby storm or sanitary line accessed through a manhole. A 4-in. (100 mm) connection should be adequate. Wastewater may not be discharged directly to a wetland, stream, river or lake.

Hydrodemolition wastewater contains suspended particles and typically has a pH of 11 to 12.5. The wastewater is initially placed in settling tanks or ponds to reduce the suspended solids. The particles are heavy and settle out quickly as the water is allowed to stand. This can also be accomplished by allowing the water to pass through a series of berms that are lined with filter fabric or hay bales.

The controlling authorities for discharge have varying requirements for the level of suspended solids and the range of pH for discharge into their system. Typically the water should be clear and the pH range between 5 and 10. Ponding the water will clarify it, however, the pH of the wastewater may have to be reduced prior to discharge. This can be accomplished by the introduction of acid, CO_2 or other pH reducing materials into the wastewater. Adding flocculants can assist in reducing suspended solids. A location for settling ponds or tanks and pH reducing equipment should be determined.

The cost to discharge wastewater ranges from the cost of a discharge permit to charges for the actual water consumed and discharged. The cost of water consumed is generally that of commercial water usage within the community. The controlling authority may require monitoring and testing of the wastewater. Local ordinance requirements must be reviewed and met prior to discharge, including the obtaining of proper permits.

Water containment and collection systems will vary depending on the structure. Where possible, it is best to take advantage of gravity to move the water to the treatment area. In many structures, the slab on ground can be used to collect and treat the water. The water may be allowed to flow through the structure to the lowest level or through the existing drains, which have been disconnected just below the underside of the first supported level. All slab-on-ground drains should be plugged and water should not be allowed to enter the drainage system prior to treatment. Once the water is clear and the pH adjusted, it can be pumped directly to the discharge point. Additional treatment capacity may be necessary if rainwater cannot be separated from the wastewater.

Floor slabs and decks are commonly crowned or sloped to provide drainage. Since water will run to the low area, a simple method of water control involves the use of hay bales or aggregate dams, which can be set up along curb lines or the perimeter of the work area. As the water ponds in front of the hay bales or aggregate dams, the suspended solids will settle out. In areas where the drains are plugged, the water is forced to pass through the hay bales or aggregate dams. Retention ponds can be built at the end of the structure and the water directed or pumped to these ponds. Settling tanks can also be used and the water pumped from the structure to the tanks.

Debris Cleanup and Disposal

Hydrodemolition debris consists of wet sand, aggregate, chips or chunks of concrete, and slurry water. Slurry contains cement particles and ranges from muddy water to a thick paste. Removal of the debris should occur as soon as possible to prevent the debris from solidifying and adhering to the surface, making cleanup more difficult.

Tools used for cleanup include: fire hoses, pressure washers, compressed air, sweepers, skid steer loaders, vacuum trucks, and manual labor.

The types of cleanup will vary based on the type of removal performed as follows:

1. *Above the reinforcing bar*—any removal depth above the top reinforcing bar of the top mat of reinforcing and the reinforcing bar remains supported by the concrete;
2. *Below the reinforcing bar*—any removal depth below the top mat of reinforcing bar in which the top reinforcing bar mat becomes unsupported by the original concrete; and

3. *Full-depth* removal.

During *above the reinforcing bar* clean up, equipment such as skid steer loaders, sweepers, and vacuum trucks may be driven over the surface to assist with the cleanup (providing they meet the weight requirements of the structure). The debris can be swept, pressure washed or air blown into piles where it is picked up by a loader. A vacuum truck may be used to vacuum the debris from the surface. In all cases, the surface must be pressure washed to remove any remaining cement slurry.

If the removal is *below the reinforcing bar* and the reinforcing bar is unsupported, it is difficult and possibly unsafe to drive equipment into the removal area. The debris can be removed by washing with a fire hose (large water consumption), pressure washing or blowing it onto the adjacent original surface where it can be picked up with a loader. A pressure washer operating at 8000 to 10,000 psi (55 to 70 MPa) and 8 to 12 gpm (30 to 45 lpm) is effective. Vacuuming has proven very effective in removing debris from around the reinforcing steel, however, the surface will require pressure washing to remove the cement slurry and paste.

During *full-depth removal*, the debris simply falls to the floor below where it can be picked up with a loader.

The debris, which consists of wet sand, aggregate, chips or chunks of concrete, and slurry is placed in dumpsters or hauled away in trucks and may be recycled or placed in a landfill in accordance with the requirements of the controlling authority.

Removal Depth Measurements

Following hydrodemolition, the surface profile is very rough and three depth measurements are possible (Fig. 25):

1. Minimum removal—original surface to the shallowest removal point.
2. Maximum removal—original surface to the deepest removal point.
3. Average depth of removal—The difference between the minimum and maximum removal at the same location.

Measuring the depth of removal can be accomplished using:

1. A straight-edge placed on the original surface;
2. A string-line pulled over the removal area; and
3. A surveyor's level.

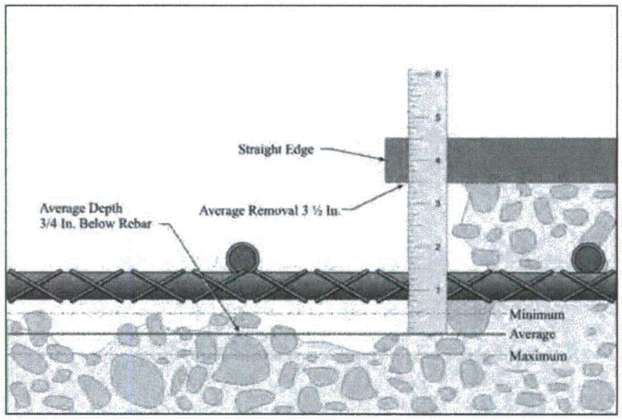

Fig: 25: Measuring depth of removal using a straight edge

The most common practice of measuring the depth of removal is to place a straightedge on top of the original surface and extend it over the removal area. Measurements are taken from the bottom of the straightedge to determine the depth of removal. This quick and simple technique can only be used during the removal process and is not applicable for final measurements in large removal areas.

A string line may be pulled over the removal area and measurements taken below the string. However, this method could provide incorrect results if slopes or crowns occur in the original surface. Surveying equipment may be used and is very accurate; however, to account for slopes, pitches and crowns in the original surface, a detailed survey must be made of the original surface prior to removal and measurements taken at the same locations after removal for comparison and determination of the actual removal depth.

Summary

Effective concrete removal and proper surface preparation are key elements to a successful repair project. A surface prepared using hydrodemolition is rough, irregular, and is excellent in creating a mechanical bond with the repair material. Hydrodemolition eliminates micro-fractures and damage to reinforcing steel, minimizes transmitted noise and dust, and cleans the reinforcing steel.

The use of hydrodemolition may not be appropriate for every structure and a careful review of the benefits and limitations of the process relative to each structure should be undertaken. Proper safety procedures must be observed at all times when using hydrodemolition.

Concrete Repair Guide

Reported by ACI Committee 546

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This document provides guidance on the selection and application of materials and methods for the repair, protection, and strengthening of concrete structures. An overview of materials and methods is presented as a guide for making a selection for a particular application. References are provided for obtaining in-depth information on the selected materials or methods.

Keywords: anchorage; cementitious; coating; concrete; joint sealant; placement; polymer; reinforcement; repair.

CONTENTS

ACI 546R-04 supersedes ACI 546R-96 and became effective September 23, 2004.

CHAPTER 1—INTRODUCTION

1.1—Use of this document

This document provides guidance on selection of materials and application methods for the repair, protection, and strengthening of concrete structures. The information is applicable to repairing damaged or deteriorated concrete structures, correcting design or construction deficiencies, or upgrading a structure for new uses or to meet more restrictive building codes.

This guide summarizes current practices in concrete repair and provides sufficient information for the initial planning of repair work and for selecting suitable repair materials and application methods for specific conditions. Many of the topics covered in this guide are more extensively covered in other ACI committee documents. Readers of this guide should refer to the appropriate documents of other ACI committees and other industry resources for additional information.

1.2—Definitions

corrosion—destruction of metal by chemical, electrochemical, or electrolytic reaction within its environment.

dampproofing—treatment of concrete or mortar to retard the passage or absorption of water, or water vapor, either by application of a suitable admixture or treated cement, or by use of preformed film, such as polyethylene sheets, placed on grade before placing a slab.

excavation—steps taken to remove deteriorated concrete, sound concrete, or both, designated for removal.

nonstructural repair—a repair that addresses local deterioration and is not intended to affect the structural capacity of a member.

protection—the procedure of shielding the concrete structure from environmental and other damage for the purpose of preserving the structure or prolonging its useful life.

repair—to replace or correct deteriorated, damaged, or faulty materials, components, or elements of a structure.

repair systems—the combination of materials and techniques used in the repair of a structure.

strengthening—the process of restoring the capacity of damaged components of structural concrete to its original design capacity, or increasing the strength of structural concrete.

structural repair—a repair that re-establishes or enhances the structural capacity of a member.

surface preparation—steps taken after removal of deteriorated concrete, including conditioning of the surface of substrate at bond line and the cleaning of existing reinforcing steel.

waterproofing—prevention of the passage of water, in liquid form, under hydrostatic pressure.

1.3—Repair methodology

A basic understanding of the causes of concrete deficiencies is essential to perform meaningful evaluations and successful repairs. If the cause of a deficiency is understood, it is much more likely that an appropriate repair system will be selected and, consequently, that the repair will be successful and the maximum life of the repair will be obtained.

Symptoms or observations of a deficiency should be differentiated from the actual cause of the deficiency, and it is imperative that causes and not symptoms be dealt with wherever possible or practical. For example, cracking can be a symptom of distress that may have a variety of causes such as drying shrinkage, thermal cycling, accidental overloading, corrosion of embedded metal, or inadequate design or construction. Only after the cause or causes of deficiency are determined can rational decisions be made regarding the selection of a proper repair system and the implementation of the repair process (Fig. 1.1).

1.3.1 *Condition evaluation*—The first step in concrete repair is to evaluate the current condition of the concrete structure. This evaluation may include a review of available design and construction documents, structural analysis of the structure in its deteriorated condition, a review of available test data, a review of records of any previous repair work, review of maintenance records, a visual inspection of the structure, an evaluation of corrosion activity, destructive and nondestructive testing, and review of laboratory results from chemical and petrographic analysis of concrete samples. Upon completion of this evaluation step, the personnel responsible for the evaluation should have a thorough understanding of the condition of the concrete structure and be able to provide insights into the causes of the observed deterioration or distress. Additional information on conducting surveys can be found in ACI 201.1R, 222R, 224.1R, 228.2R, 364.1R, and 437R.

1.3.2 *Determination of causes of deterioration or distress*—After the condition evaluation of a structure has been completed, the deterioration mechanism that caused the behavior to evaluate and design a structural repair, strengthening procedure, or both. Some design considerations follow and are discussed throughout this guide.

1.4.1 *Current load distribution*—In a deteriorated state, a structural member or system distributes dead and live loads differently than first assumed when the structure was new. Cracking, deteriorated concrete and corroded reinforcement alter the stiffness of members, which leads to changes in shear, moment, and axial load distribution. As concrete and reinforcement are removed and replaced during the repair operation, these redistributed forces are further modified. To understand the final behavior of the structural system, the engineer should evaluate the redistribution of the forces. To fully re-establish the original load distribution, a member should be relieved of the load by jacking or other means. The repaired member and the repair itself supports the loads differently than would be assumed in the original or a new structure.

1.4.2 *Compatibility of materials*—If a repair and the member have the same stiffness—for example, modulus of elasticity—the analysis of the repaired member may be the same as a new section. If the stiffness varies, however, then the composite nature of the repaired system should be considered. A mismatch of other material characteristics further exacerbates the effects of thermal changes, vibrations, and long-term creep and shrinkage effects. Different coefficients of thermal expansion of the repair and original material results in different dimensional changes. The engineer should design for the different movements, or the repair system should be similar to the thermal and dimensional characteristics of the original material.

1.4.3 *Creep, shrinkage, or both*—Reduction in length, area, or volume of both the repair and original materials due to creep, shrinkage, or both, affect the structures serviceability and durability. As an example, compared with the original material, high creep or shrinkage of repair materials results in loss of stiffness of the repair, redistributed forces, and increased deformations. The engineer should consider these effects in the design.

1.4.4 *Vibration*—When the installed repair material is in a plastic state or until adequate strength has been developed, vibration of a structure can result in reduced bonding of the repair material. Isolating the repairs or eliminating the vibration may be a design consideration.

1.4.5 *Water and vapor migration*—Water or vapor migration through a concrete structure can degrade a repair. Understanding the cause of the migration and controlling it should be part of a repair design consideration.

1.4.6 *Safety*— The contractor is responsible for construction safety. Nevertheless, as the engineer considers a repair design, which may involve substantial concrete removal, steel reinforcing cutting, or both, he or she should notify the contractor of the need and extent of shoring and bracing. The local repair of one small section can affect a much larger area, of which the contractor may not be aware.

1.4.7 *Material behavior characteristics*—When new and innovative materials and systems are used for repair and strengthening, the structural behavior of the repaired section can differ substantially from the behavior of the original section. For example, if a beam's steel reinforcement has corroded extensively and lost part of its load-carrying capacity, the steel reinforcement may be replaced by carbon fiber-reinforced polymer (CFRP) applied to the external bottom face of the beam. The original yielding behavior of the steel bar is replaced by FRP that is stronger, but has a more elastic and brittle behavior. The behavior assumptions of codes like ACI 318 are no longer valid. The engineer should consider the behavior and performance of the new repair under the actual service and ultimate load, and design the repair to provide at least an equivalent level of safety to the original design. Such a design is outside the scope of ACI 318.

1.5—Format and organization

Chapter 2 discusses removal of deteriorated concrete, preparation of surfaces to receive repair materials, general methods for concrete repair, and repair techniques for reinforcing and prestressing steel. Chapter 3 discusses various types of repair materials that may be used. The reader is urged to use Chapters 2 and 3 in combination when selecting the repair material and method for a given situation. Chapter 4 describes materials and systems that may be used to protect repaired or unrepaired concrete from deterioration. Chapter 5 provides methods for strengthening an existing structure when repairing deficiencies, improving load-carrying capabilities, or both. Chapter 6 provides references, including other appropriate ACI documents and industry resources.

CHAPTER 2—CONCRETE REMOVAL, PREPARATION, AND REPAIR TECHNIQUES

2.1—Introduction and general considerations

This chapter covers removal, excavation, or demolition of existing deteriorated concrete, preparation of the concrete surface to receive new material, preparation and repair of reinforcement, methods for anchoring repair materials to the existing concrete, and various methods that are available to place repair materials. The care that is exercised during the removal and preparation phases of a repair project can be the most important factor in determining the longevity of the repair, regardless of the material or technique used.

Specific attention should be given to the removal of concrete around prestress strands, both bonded and unbonded. The high-energy-impact tools, such as chipping hammers, should avoid contact with the strand because this will reduce the strands' load-carrying capacity and may cause the wire(s) to rupture, which may lead to strand failure.

2.2—Concrete removal

A repair project usually involves removal of deteriorated, damaged, or defective concrete. In most concrete repair projects, the zones of damaged concrete are not well defined. Most references state that all damaged or deteriorated material should be removed, but it is not always easy to determine when all such material has been removed or when too much good material has been removed. A common recommendation is to remove sound concrete for a defined distance beyond the delaminated area; thereby, exposing the reinforcing steel beyond the point of corroded steel.

Removal of concrete using explosives or other aggressive methods can damage the concrete that is intended to remain in place. For example, blasting with explosives or the use of some impact tools heavier than 12 kg (30 lb) can result in additional delamination or cracking. Delaminated areas can be identified by using a hammer to take soundings. In most cases, such delaminations should be removed before repair materials are placed.

Removal of concrete using impact tools may result in small-scale microcracking damage (termed bruising) to the surface of the concrete left in place. Unless this damaged layer is removed, a weakened plane may occur in the parent concrete below the repair material bondline. This condition can result in a low tensile rupture (bond) strength between the parent concrete and repair material. Thus, a perfectly sound and acceptable replacement material may fail due to improper surface preparation. All damaged or delaminated concrete, including bruising, at the interface of the repair and the parent concrete should be removed before placing the repair material. This may require one type of aggressive removal for gross removal followed by another type of removal for bruising.

In all cases in which concrete has been removed from a structure by primary means such as blasting or aggressive impact methods, the concrete left in place should be prepared by using a secondary method, such as chipping, abrasive blasting, or high-pressure water jetting, to remove any remaining damaged surface material. Careful visual inspections of the prepared surfaces should be conducted before placing repair materials. Wetting the surface may help to identify the presence of cracking. Determination of the tensile strength (ACI 503R, Appendix A) by pull-off testing is advisable on prepared surfaces to determine the suitability of the surface to receive repair material.

Removal of limited areas of concrete in a slab, wall, or column surface requires saw-cutting the perimeter of the removal area, providing an adequate minimum thickness of repair material at the edge of the repaired area, and mitigating the advancement of undetected incipient cracking. Feathering of repair materials generally should be avoided. The preparation for shotcreting is an exception. ACI 506R recommends tapered edges around the perimeter of such patches. Saw cutting can also improve the appearance of the repaired area. The general shape of the repaired areas should be as symmetrical as possible (ICRI 03730). Reentrant corners should be avoided. Large variations in the depth of removal in short distances should also be avoided. The texture of the prepared surface should be appropriate for the intended repair material (ICRI 03732).

Every precaution should be made to avoid cutting underlying reinforcement. Reviewing design drawings and using a covermeter or similar device provides data as to the location and depth of reinforcement. In addition, the removal of small areas of concrete is commonly used to confirm the location and depth of bars before saw cutting.

Sections 2.2.1 through 2.2.18 present descriptions of many of the commonly used concrete removal techniques to help in the selection process.

2.2.1 *General considerations*—Concrete removal addresses deteriorated and damaged material. Some sound concrete, however, may be removed to permit structural modifications and to ensure that all unsound material is removed. The effectiveness of various removal techniques can differ for deteriorated and sound concrete. Some techniques may be more effective in sound concrete, while others may work better for deteriorated concrete.

Concrete removal techniques selected should be effective, safe, economical, environmentally friendly, and minimize damage to the concrete left in place. The removal technique chosen may have a significant effect on the length of time that a structure will be out of service. Some techniques permit a significant portion of the work to be accomplished without removing the structure from service. The same removal technique, however, may not be suitable for all portions of a given structure. In some instances, a combination of removal techniques may be more appropriate to speed removal and limit damage to the remaining sound concrete. Trial field testing various removal techniques can help confirm the best procedures.

In general, the engineer responsible for the design of the repair should specify the objectives to be achieved by the concrete removal, and the repair contractor should be allowed to select the most economical removal method, subject to the engineer's acceptance. In special circumstances, the engineer may also need to specify the removal techniques to be used and those that are prohibited.

The mechanical properties of the concrete and the type and size of aggregate to be removed provide important information to determine the method and cost of concrete removal. The mechanical properties include compressive and tensile strengths. This information is also necessary for the engineer to specify the prepared surface condition and select the repair material, and it should be made available to contractors for bidding purposes.

2.2.2 *Monitoring and shoring during removal operations*—It is essential to evaluate the removal operations to limit the extent of damage to the structure and to the concrete that remains. Structural elements may require shoring, removal of applied loads, or both, before concrete removal to prevent structural deformations, possible collapse, buckling, or slippage of reinforcement. Care should be used during removal of concrete to avoid cutting and damaging reinforcing steel. Because reinforcement is often misplaced, unanticipated damage may occur when saw cutting, impacting, or removing concrete.

Careful monitoring is required throughout the concrete removal operation. This can be accomplished by visual inspection, sounding, use of a covermeter, or other means to locate reinforcement. The project specifications should assign responsibilities for the inspection of the prepared concrete.

Sounding is an excellent means to detect delaminated concrete adjacent to the outermost layers of reinforcing steel. Subsurface cracks, the extent of deterioration, or other internal defects, however, may not be identified by this method alone. Other means of evaluation should be used to properly identify the extent of concrete to be removed. In addition, sounding usually does not indicate near-surface microcracking or bruising. Only microscopic examination or bond testing may disclose near-surface damage.

Subsurface evaluation (examination of the substrate) can provide valuable information about the condition of the concrete. This information may be obtained by the following methods before, during, or after concrete removal (ACI 228.2R):

a) Taking cores for visual examination, microscopic examination, compressive strength tests, and splitting-tensile strength tests;

b) Pulse-velocity tests;

c) Impact-echo tests;

d) Bond tests (pull-off testing, ACI 503R Appendix A);

e) Covermeter or similar equipment to locate reinforcement and determine its depth below the surface;

f) Infrared thermography; and

g) Ground-penetrating radar (GPR).

Many of these methods are discussed in ACI 228.2R.

2.2.3 *Quantity of concrete to be removed*—In most repair projects, all damaged or deteriorated concrete should be removed; however, the quantity of concrete to be removed is directly related to the elapsed time between preparation of the estimate and actual removal. Substantial overruns are common. Estimating inaccuracies can be minimized by a thorough condition survey as close as possible to the time the repair work is executed. Potential quantity overruns, based on field-measured quantities, should be taken into account. When, by necessity, the condition survey is done far in advance of the repair work, the estimated quantities should be increased to account for continued deterioration. Because most concrete repair projects are based on unit prices, repair areas should be accurately measured before forms are installed. This is usually done jointly by the engineer and the contractor. It is not uncommon for estimated quantities to increase significantly between the detectable quantities and the actual quantity removed. ICRI 03735 provides guidelines for methods of measurement for concrete repair work.

2.2.4 *Classification of concrete removal methods*—Removal and excavation methods can be categorized by the way in which the process acts on the concrete. These categories are blasting, cutting, impacting, milling, hydrodemolition, presplitting, and abrading. Table 2.1 provides a general description of these categories, lists the specific removal techniques within each category, and provides a summary of information on each technique. The techniques are discussed in detail in the following sections.

2.2.5 *Blasting methods*—Blasting methods generally employ rapidly expanding gas confined within a series of bore holes to produce controlled fracture and removal of the concrete. The only blasting method addressed in this report is explosive blasting.

Explosive blasting is the most cost-effective and expedient means for removing large quantities of concrete—for example, portions of large mass concrete foundations or walls. This method involves drilling bore holes, placing an explosive in each hole, and detonating the explosive. Controlled-blasting techniques minimize damage to the material that remains after blasting. One such technique, cushion blasting, involves drilling a line of 75 mm (3 in.) diameter or smaller bore holes parallel to the removal face, loading each hole with light charges of explosive (usually detonating cord) distributed along its length, cushioning the charges by stemming each hole completely or in the collar with wet sand, and detonating the explosive with electric blasting caps. The uniform distribution and cushioning of the light charges produce a relatively sound surface with little overbreak.

Blasting machines and electrical blasting-cap delay series are also used for controlled demolition and employ proper timing sequences to provide greater control in reducing ground vibration. Controlled blasting has been used successfully on numerous repair projects. The selection of proper charge weight, borehole diameter, and borehole spacing for a repair project depends on the location of the structure, the acceptable degree of vibration and damage, and the quantity and quality of concrete to be removed. If at all possible, a pilot test program should be implemented to determine the optimum parameters. Because of the inherent dangers in the handling and usage of explosives, all phases of the blasting project should be performed by qualified, appropriately licensed personnel with proven experience and ability.

2.2.6 *Cutting methods*—Cutting methods generally employ mechanical sawing, intense heat, or high-pressure water jets to cut around the perimeter of concrete sections to permit their removal. The size of the sections that are cut free is governed by the available lifting and transporting equipment. The cutting methods include high-pressure water jets, saw cutting, diamond wire cutting, mechanical shearing, stitch drilling, and thermal cutting.

a) *High-pressure water jet (without abrasives)*—A high-pressure water jet uses a small jet of water driven at high velocities, commonly producing pressures of 69 to 310 MPa (10,000 to 45,000 psi). A number of different types of water jets are currently being used. The most promising are the ultra high-pressure jet and the cavitating jet. Section 2.2.10 describes using a water jet as a primary removal method. Water jets used with abrasives are described in Section 2.2.11.

b) *Saw cutting*—Diamond or carbide saws are available in sizes ranging from small (capable of being hand-held) to large (capable of cutting depths of up to 1.3 m [52 in.]).

c) *Diamond wire cutting*—Diamond wire cutting is accomplished with a wire containing nodules impregnated with diamonds. The wire is wrapped around the concrete mass to be cut and reconnected with the power pack to form a continuous loop. The loop is spun in the plane of the cut while being drawn through the concrete member. This system can be used to cut a structure of any size as long as the wire can be wrapped around the concrete. The limits of the power source determines the size of the concrete structure that can be cut. This system provides an efficient method for cutting up and dismantling large or small concrete structures.

d) *Mechanical shearing*—The mechanical shearing method employs hydraulically powered jaws to cut concrete and reinforcing steel. This method is applicable for making cutouts through slabs, decks, and other thin concrete

Table 2.1— Summary of features and considerations/limitations for concrete removal methods

Category	Features	Considerations/Limitations
2.2.5 *Blasting* Uses rapidly expanding gas confined within a series of boreholes to produce controlled fracture and removal of concrete.	*Explosives* Most expedient method for removing large volumes where concrete section is 10 in. (250 mm) thick or more. Produces good fragmentation of concrete debris for easy removal.	Requires highly skilled personnel for design and execution. Stringent safety regulations must be complied with regarding the transportation, storage, and use of explosives due to their inherent dangers. Blast energy must be controlled to avoid damage to surrounding improvements resulting from air blast pressure, ground vibration, and flying debris.
2.2.6 *Cutting* Uses perimeter cuts to remove large pieces of concrete.	*High-pressure water jet (without abrasives)* Applicable for making cutouts through slabs, decks, and other thin concrete members. Cuts irregular and curved shapes. Makes cutouts without overcutting corners. Cuts flush with intersecting surfaces. No heat, vibration, or dust is produced. Handling of debris is efficient because bulk of concrete is removed in large pieces.	Cutouts for removal limited to thin sections. Cutting is typically slower and more costly than diamond blade sawing. Moderate levels of noise may be produced. Controlling flow of waste water may be required. Additional safety precautions are required due to the high water pressure produced by the system.
2.2.6 *Cutting* (continued)	*Diamond saw* Applicable for making cutouts through slabs, decks, and other thin concrete members. Makes precision cuts. No dust or vibration is produced. Handling of debris is efficient because bulk of concrete is removed in large pieces.	Cutouts for removal limited to thin sections. Performance is affected by type of diamonds and the diamond-to-metal bond in blade segments (segment selection is based on aggregate hardness). The higher the percentage of steel reinforcement in cuts, the slower and more costly the cutting. The harder the aggregate, the slower and more costly the cutting. Controlling flow of waste water may be required.
2.2.6 *Cutting* (continued)	*Diamond wire cutting* Applicable for cutting large and/or thick pieces of concrete. The diamond wire chain can be infinitely long. No dust or vibration is produced. Large blocks of concrete can be easily lifted out by a crane or other mechanical methods. The cutting operation can be equally efficient in any direction.	The cutting chain must be continuous. Access to drill holes through the concrete must be available. Water must be available to the chain. Controlling the flow of waste water may be required. The harder the aggregate and/or concrete, the slower and more costly the cutting. Performance is affected by the quality, type, and number of diamonds as well as the diamond-to-metal bond in the chain.
2.2.6 *Cutting* (continued)	*Mechanical shearing* Applicable for making cutouts through slabs, decks, and other thin concrete members. Steel reinforcement can be cut. Limited noise and vibration are produced. Handling of debris is efficient because bulk of concrete is removed in large pieces.	Limited to thin sections where an edge is available or a hole can be made to start the cut. Exposed reinforcing steel is damaged beyond reuse. Remaining concrete is damaged. Extremely rugged profile is produced at the cut edge. Ragged feather edges remain after removal.
2.2.6 *Cutting* (continued)	*Stitch drilling* Applicable for making cutouts through concrete members where access to only one face is feasible. Handling of debris is more efficient because bulk of concrete is removed in large pieces.	Rotary-percussion drilling is significantly more expedient and economical than diamond core drilling; however, it results in more damage to the concrete that remains, especially at the point of exit from the concrete. Depth of cuts is dependent on accuracy of drilling equipment in maintaining overlap between holes with depth and diameter of the boreholes drilled. The deeper the cut, the greater borehole diameter required to maintain overlap between adjacent holes and the greater the cost. Uncut portions between adjacent boreholes will hamper or prevent the removal. Cutting reinforced concrete increases the cutting time and increases the cost. Aggregate toughness for percussion drilling and aggregate hardness for diamond coring will affect cutting cost and rate. Personnel must wear hearing protection due to high noise levels.

members. It is especially applicable where total demolition of the member is desired. The major limitation of this method is that cuts should be started from free edges or from holes made by hand-held breakers or other means.

e) *Stitch drilling*—The stitch-drilling method employs the use of overlapping boreholes along the removal perimeter to cut out sections for removal. This method is applicable for making cutouts through concrete members where access to only one face is possible, and the depth of cut is greater than can be economically cut by the diamond-blade method. The primary drawback of stitch drilling is the potential for costly removal complications if the cutting depth exceeds the accuracy of the drilling equipment, so that uncut concrete remains between adjacent holes.

f) *Thermal cutting*—This method requires powder torch, thermal lance, and powder lance, which develop intense heat generated by the reaction between oxygen and powdered metals to melt a slot into concrete. The thermal device's ability for removing concrete from structures mainly depends on the rate at which the resulting slag can flow from the slot. These devices use intense heat and are especially effective for cutting reinforced concrete; however, they are considered slow, relatively expensive, and are not widely used.

Table 2.1 (cont.)—Summary of features and considerations/limitations for concrete removal methods

Category	Features	Considerations/Limitations
2.2.6 *Cutting* (continued)	*Thermal cutting* Applicable for making cutouts through heavily reinforced decks, beams, walls, and other thin to medium concrete members. An effective means of cutting reinforced concrete. Cuts irregular shapes. Produces minimal noise, vibrations, and dust.	Limited availability commercially. Not applicable for cuts where slag flow is restricted. Remaining concrete has thermal damage with more extensive damage occurring around steel reinforcement. Produces smoke and fumes. Personnel must be protected from heat and hot slag produced by cutting operation.
2.2.7 *Impacting* Uses repeated striking of the surface with a mass to fracture and spall the concrete.	*Hand-held breakers* Applicable for limited volumes of concrete removal. Applicable where blow energy must be limited. Widely available commercially. Can be used in areas of limited work space. Produces relatively small and easily handled debris.	Performance is a function of concrete soundness and aggregate toughness. Significant loss of productivity occurs when breaking action is other than downward. Removal boundaries will likely require saw cutting to avoid feathered edges. Concrete that remains may be damaged (microcracking). Produces high levels of noise, dust, and vibration.
	Boom-mounted breakers Applicable for full-depth removal from slabs, decks, and other thin concrete members and for surface removal from more massive concrete structures. Can be used for vertical and overhead surfaces. Widely available commercially. Produces easily handled debris.	Blow energy delivered to the concrete may have to be limited to protect the structure being repaired and the surrounding structures from damage due to high cyclic energy generated. Performance is a function of concrete soundness and aggregate toughness. Damages remaining concrete. Damages reinforcing steel. Produces feathered edges. Produces high level of noise and dust.
2.2.7 *Impacting* (continued)	*Scabblers* Low initial cost. Can be operated by unskilled labor. Can be used in areas of limited work space. Removes deteriorated concrete from wall or floor surfaces efficiently. Readily available commercially.	High cyclic energy applied to a structure will produce fractures in the remaining concrete surface area. Produces high level of noise and dust. Limited depth removal.
2.2.8 *Milling* Uses scarifiers to remove concrete surfaces.	*Scarifier* Applicable for removing deteriorated concrete surfaces from slabs, decks, and mass concrete. Boom-mounted cutters are applicable for removal from wall and ceiling surfaces. Removal profile can be controlled. Method produces relatively small and easily handled debris.	Removal is limited to concrete without steel reinforcement. Sound concrete significantly reduces the rate of removal. Can damage concrete that remains (microcracking). Noise, vibration, and dust are produced.
2.2.9 *Hydrodemolition* Uses high-pressure water to remove concrete.	Applicable for removal of deteriorated concrete from surfaces of bridges and parking decks and other deteriorated surfaces where removal depth is 6 in. (150 mm) or less. Does not damage the concrete that remains. Steel reinforcing is left clean and undamaged for reuse. Method produces easily handled, aggregate-sized debris.	Productivity is significantly reduced when sound concrete is being removed. Removal profile will vary with changes in depth of deterioration. Method requires large source of potable water to meet water demand. Waste water may have to be controlled. An environmental impact statement may be required if waste water is to enter a waterway. Personnel must wear hearing protection due to the high level of noise produced. Flying debris is produced. Additional safety requirements are required due to the high pressures produced by these systems.

2.2.7 *Impacting methods*—Impacting methods are the most commonly used concrete removal systems. They repeatedly strike a concrete surface with a high-energy tool or a large mass to fracture and spall the concrete. The use of these methods in partial-depth concrete removal can result in microcracking on the surface of the concrete left in place. Extensive microcracking results in a weakened plane below the bond line. Currently, the committee is unable to provide definitive guidelines to prevent such damage when using impact methods; however, factors such as the weight and size of the equipment should be considered to minimize microcracking. Determination of the tensile strength by pull-off testing is recommended to determine the suitability of the surface to receive repair materials. Additionally, after impacting secondary methods, such as sandblasting, abrasive blasting, and water blasting, may be required to remove excessive microcracking.

a) *Hand-held breakers*—The hand-held breaker or chipping hammer is probably the best known of all concrete removal devices. Hand-held breakers are available in various sizes with different levels of energy and efficiency. These tools are generally defined by weight and vary in size from 3.5 to 41 kg (8 to 90 lb). (Note: the larger the hammer, such as 14 kg [30 lb] and larger, the greater the potential for microcracking.) The smaller hand-held breakers, such as 7 kg (15 lb) and smaller, are used in partial removal of unsound concrete or concrete around reinforcing steel because they do little damage to surrounding concrete. Larger breakers are used for complete removal of large volumes of concrete or delaminations. Care should be exercised when selecting the size of

(0.1 to 4 in.). Milling operations usually leave a sound surface with less microfractures than impact methods (Virginia Transportation Research Council 2001).

2.2.9 *Scarifier*—A scarifier is a concrete cutting tool that employs the rotary action and mass of its cutter bits to rout cuts into concrete surfaces. It removes loose concrete fragments (scale) from freshly blasted surfaces and removes concrete that is cracked and weakened by an expansive agent. It also is the sole method of removing deteriorated and sound concrete in which some of the concrete contains form ties and wire mesh. Scarifiers are available in a range of sizes. The scarifier is an effective tool for removing deteriorated concrete on vertical and horizontal surfaces. Other advantages include well-defined limits of concrete removal, relatively small and easily handled concrete debris, and simplicity of operation.

2.2.10 *Hydrodemolition*—High-pressure water jetting (hydrodemolition) can be used to remove concrete to preserve and clean the steel reinforcement for reuse and to minimize microcracking to the remaining in-place concrete. The method also has a high efficiency. Hydrodemolition disintegrates concrete, returning it to sand and gravel-sized pieces. This process works on sound or deteriorated concrete and leaves a rough profile. Hydrodemolition punches through the full depth of slabs in small areas when the concrete is unsound or when full-depth patches are inadequately bonded to the side walls. Hydrodemolition should not be used in structures with unbonded tendons, except under the direct supervision of a structural engineer.

High-pressure water jets in the 70 MPa (10,000 psi) range require 130 to 150 L/min (35 to 40 gal./min). As the pressure increases to 100 to 140 MPa (15,000 to 20,000 psi), the water demand varies from 75 to 150 L/min (20 to 40 gal./min) (Nittenger 1997). The equipment manufacturer should be consulted to confirm the water demand. Ultra-high-pressure equipment operating at 170 to 240 MPa (25,000 to 35,000 psi) has the capability of milling concrete to depths of 3 to 150 mm (0.1 to 6 in.). Containment and subsequent disposal of the water are requirements of the hydrodemolition process. Many localities require this water to be filtered and then treated to reduce the alkalinity and particulates before the water can be released into a storm or wastewater system.

Water jet lances operating at pressures of 70 to 140 MPa (10,000 to 20,000 psi) and having a water demand of 75 to 150 L/min (20 to 40 gal./min) are available. They are capable of cutting sections of concrete or selectively removing surface concrete in areas that are difficult to reach with larger equipment (ICRI 03737).

2.2.11 *Presplitting methods*—Presplitting methods use hydraulic splitters, water pressure pulses, or expansive chemicals used in boreholes drilled at points along a predetermined line to induce a crack plane for the removal of concrete. The pattern, spacing, and depth of the boreholes affect the direction and extent of the crack planes that propagate. Presplitting is generally used in mass concrete structures or unreinforced concrete.

a) *Hydraulic splitter*—The hydraulic splitter is a wedging device that is used in predrilled boreholes to split concrete into sections. This method has potential as a primary means for removal of large volumes of material from mass concrete structures. Secondary means of separating and handling the concrete, however, may be required where reinforcing steel is involved.

b) *Water-pulse splitter*—The water-pressure pulse method requires that the boreholes be filled with water. A device, or devices, containing a very small explosive charge is placed into one or more holes, and the explosive is detonated. The explosion creates a high-pressure pulse that is transmitted through the water to the structure, cracking the concrete. Secondary means may be required to complete the removal of reinforced concrete. This method does not work if the concrete is so badly cracked or deteriorated that it does not hold water in the drill holes.

c) *Expansive product agents*—Commercially available cementitious expansive product agents, such as those containing aluminum powder, when correctly mixed with water, exhibit a large increase in volume over a short period of time. By placing the expansive agent in boreholes located in a predetermined pattern within a concrete structure, the concrete can be split in a controlled manner for removal. This technique has potential as a primary means of removing large volumes of material from concrete structures and is best suited for use in holes of significant depth. Secondary means may be required to complete the separation and removal of concrete from the reinforcement. A key advantage to the use of expansive agents is the relatively nonviolent nature of the process and the reduced tendency to disturb the adjacent concrete.

2.2.12 *Abrading blasting*—Abrading blasting removes concrete by propelling an abrasive medium at high velocity against the concrete surface to abrade it. Abrasive blasting is typically used to remove surface contaminants and as a final surface preparation. Commonly used methods include sandblasting, shotblasting, and high-pressure water blasting.

2.2.13 *Sandblasting*—Sandblasting is the most commonly used method of cleaning concrete and reinforcing steel in the construction industry. The process uses common sands, silica sands, or metallic sands as the primary abrading tool. The process may be executed in one of three methods.

2.2.14 *Dry sandblasting*—Sands are projected at the concrete or steel in a stream of high-pressure air in the open atmosphere. The sand particles are usually angular and may range in size from passing a 212 to a 4.75 mm (No. 70 to a No. 4) sieve. The rougher the required surface condition, the larger the sand particle size.

The sand particles are propelled at the surface in a stream of compressed air at a minimum pressure of 860 kPa (125 psi). The compressor size varies, depending on the size of the sandblasting pot. Finer sands are used for removing contaminants and laitance from the concrete and loose scale from reinforcing steel. Coarser sands are commonly used to expose fine and coarse aggregates in the concrete by removing the paste or tightly bonded corrosion products from reinforcing steel. Although sandblasting has the ability to cut quite deeply into concrete, it is not economically practical to remove more than 6 mm (0.25 in.) from the concrete surface.

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PROGRESS ENERGY SERVICE COMPANY, LLC
CRYSTAL RIVER THREE (CR3) NUCLEAR PLANT
CRYSTAL RIVER, FLORIDA

HYDRODEMOLITION WORK PLAN

PROJECT

Create a temporary opening in the CTMT wall removing all concrete using high pressure Hydrodemolition technology.

HYDRODEMOLITION EQUIPMENT

2 – 2000HP diesel pumping unit power packs. Each power pack contains 3 high pressure pumping units delivering 50 gpm @ 20,000 psi per pump to a Hydrodemolition nozzle mounted on the Hydrodemolition concrete removal track.

HYDRODEMOLITION CONCRETE REMOVAL TRACK

Stationed on access platform at temporary opening location. Track frame mounted on CTMT wall exterior outline of concrete to be removed 28' wide x 24' high.
Frame has two Hydrodemolition concrete manipulators mounted side by side, each covering 14' wide x 24' high
Each manipulator contains three Hydrodemolition nozzles. Each nozzle is connected to a high pressure pump in the power pack.

HYDRODEMOLITION PROCESS

Each manipulator passes over the surface removing concrete as it travels width wise one pass then index up 2 inches repeating the process until it reaches the top of the track (24' level). To prevent over cutting steel stops are installed at the 24' level.

When rebar is exposed manipulator is locked in place above the top (24') level while crews remove the rebar below. (Approx. 12 hours)
When rebar is removed Hydrodemolition resumes until Tendons are exposed. When tendons are exposed manipulators are locked in place above the top (24') level while crews remove and plug the tendons below. (Approx. 12 hours)

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When tendons are removed Hydrodemolition resumes until Liner plate is completely exposed.

When Liner plate is completely exposed Manipulators are locked in place until clear access is available to dismantle Frame.

RUBBLE CONTROL

As Hydrodemolition is in progress the water and concrete rubble will fall down to the platform into a chute running down to rubble and wastewater containers located on the ground.

To prevent rubble from escaping the immediate area a screen hoarding will be erected around the Hydrodemolition track.

HYDRODEMOLITION EQUIPMENT STAGING

2 active Hydrodemolition power packs to be setup approx. 400' from reactor opening location.
Three hoses will run from each power pack to the Hydrodemolition Track. =
2 – power packs = 6 hoses supplying two 3 nozzle manipulators mounted on the Hydrodemolition track.
1 backup power pack ready to operate less high pressure hoses will be staged also.

WATER CONTROL

Wastewater will be pumped from bins at the CTMT to wastewater treatment location in the staging area approx.400' away.
Discharged waste water will be:

- 6.0-9.0 PH
- Total suspended solids, 30ppm
- Oil in water, daily maximum of 18.4 ppm with a monthly average below 13.8 ppm
- List of all fluids, lubricants will be submitted for approval

ACTIVITIES

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- 6 months prior to commencing Hydrodemolition submit superintendent name for security clearance

- 2-3 months (to be determined) prior to commencing Hydrodemolition Mac & Mac superintendent arrives onsite

- 2 -3 months prior to commencing Hydrodemolition submit crew names for security clearance

- 3 weeks prior to commencing Hydrodemolition crew arrives for Security, Fitness-For-Duty, Health Physics, Badging, Setup equipment,

- 3 weeks prior to commencing Hydrodemolition, Hydrodemolition power packs, tracks, manipulators/robots, all accessories and supplies arrive on site.

- 3 weeks prior to commencing Hydrodemolition all wastewater equipment, tanks, pumps arrive on site

- 3 weeks prior to commencing Hydrodemolition all vacuum truck units arrive on site

THIRD WEEK BEFORE COMMENCING HYDRODEMOLITION

- Crew clearance completed (4 days)
- Stage Hydrodemolition power packs in Staging area approx. 400' from CTMT
- Stage and Assemble wastewater treatment facility in Staging area approx. 400' from CTMT

SECOND WEEK BEFORE COMMENCING HYDRODEMOLITION

- Run High Pressure lines to CTMT location
- Run Wastewater lines from CTMT to Staging area approx. 400' from CTMT
- Run fresh water line from source to Hydrodemolition power packs in staging area approx. 400' from CTMT
- Install trash pump at containment bin to pump water to treatment facility approx. 400' from CTMT
- Install piping from treatment center to settling pond
- Build berm around equipment in staging area

MAC & MAC HYDRODEMOLITION SERVICES INC.

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ASSEMBLE HYDRODEMOLITION TOWER

- Assemble Tower on the ground outside of compound – small (60 ton) crane required for 3 days and a 8,000lb forklift
- Lift Assembled Tower onto chipping platform – crane required
- Bolt Tower Guide Legs onto chipping platform
- Run all hydraulic (water soluble oil), electrical, and pressure lines from Power Pack located outside of compound to Tower. (run lines under fence)
- Hookup high pressure hoses, hydraulic and electrical lines to Hydrodemolition manipulators (Manipulators are attached to the track. Track is attached to Tower)
- Place 125 ft. manlift in position
- Mount Hydrodemolition Control box in 125 ft. manlift bucket (Operator/Technician location / station)
- Test High pressure lines, electrical and hydraulic lines and controls
- Place 8' x 20' (2-8x10) sheets of steel on platform against reactor wall for testing system
- Test: Tower / Track system, High pressure system, hydraulic and electrical controls

ONE WEEK BEFORE COMMENCING HYDRODEMOLITION

- Complete projects (if any) not completed in week 2
- Fine tune all equipment
- Standby ready to begin Hydrodemolition 3 days prior to commencement date and time.

HYDRODEMOLITION COMMENCED

• Cutting Concrete removing 13% (13% of total)	4 Hours
• Remove rebar	12 Hours by others
• Cutting Concrete removing 17% (30% of total)	6 Hours
• Remove and plug tendons	12 Hours by others
• Cutting Concrete removing 23% (53% of total)	8 Hours
• Cutting Concrete removing 24% (77% of total)	8 Hours
• Cutting Concrete removing 13% (90% of total)	4 Hours
• Cutting Concrete removing 10% (100% of total)	4 Hours

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- Cutting concrete perimeter clean up allowance 8 hours
- Hydrodemolition Equipment Demob 2 Days
- Water Treatment Demob 4 Days

At all times Mac & Mac's project superintendent will keep Progress Energy representatives aware of our project progress and status.

10/28/2009 Interview Dave McNeill on phone

Present: Dave McNeill (Mac&Mac, Vancouver), Craig Miller, Chong Chiu, Patrick Berbon

Hydrolazing uses high-pressure pumps (triplex) with plungers (3 cylinders per pump).

Have X-Y machine on the platform.

Using 6 pressure pumps (1 pump per nozzle).

17,000-17,500 psi water pressure.

Flow rate 40-45 gallons/minute/nozzle.

Running 2 x 3 nozzles at the same time (3 nozzles per head, 2 heads).

Nozzle rotates at 500 rpm and projects water at a 5 degrees angle around the axis of rotation. Spin rate can be adjusted from 250 to 1,000 rpm. Was fixed at 500 rpm here.

Cut about 4 feet wide per head (total width of cut about 8' per pass).

Travels 1 ft/s along the beam, then move up 1.5 in, travels back 1 ft/s.

Each pass cuts 1in to 1.5in deep.

Nozzles are 7 inches apart.

Water is taken from Progress large holding tank. It is pumped up from the tank and filtered to 1 micron. It is recovered and re-filtered at the end (not recycled, dumped in settling pond after use).

Supply water is usually around 60 F. it was 85 F in this case. The pumping added an additional 25 F so that the water exited the nozzle around 110 F.

Mac&Mac works on many bridge decks. First nuclear project for the company.

Their in-house calculations for 17,000 psi, 500 rpm rotation, 40 gal/min water, 1ft/s travel, shows a force on the wall of 100 psi.

Nozzle is 1/8 inch.

First nozzle is 2-4 in from the wall, second nozzle is 3-5 in, third nozzle is 4-6 in (nozzles are in same plane, but distance increases as material is removed by each nozzle).

Takes approximately 35 min for one pass.

Pump is diesel powered (1,800 rpm), runs at 500 rpm.

Pistons are 1.5 in diameter, and move back-and-forth at 500 rpm.

10/29/2009 Interview Bob Nettinger at American Hydro

Present: Chong Chiu, Dan Fiorello (Exelon), Partha Ghosal (Southern Company), Patrick Berbon

Bob Nettinger is with American Hydro. They are a competitor company to Mac & Mac, who performed the hydro-blasting for the CR3 containment.

They have done 7 post-tensioned containments.

They use 6 HP pumps, 2 robots.

Rotating jets lead to a better cut.

20,000 psi water, 150 gal/min/nozzle.

Use a plunger pump.

Wayne Younger (also works at American Hydro) would know the numbers for vibration and rpm.

Tower is 50ft high, can move on the platform, 4-wheel vehicle, 6ft wide cut top to bottom and back, 25ft from the wall.

1.5 inches deep cut per nozzle.

Nozzle is 6 inches from the wall.

They use nozzle extensions to get closer to the wall as they hydro-blast.

Use potable water as input into the pumps.

They are starting at TMI on Sunday, 11/1. John Piazza, structural engineer, senior design engineer on SG replacement at TMI.

Wayne Younger and Bob Nettinger called back later. They require PII to sign a NDA before giving additional information. It seems there is a lawsuit going on between American Hydro and Mac & Mac.

The water pressure fall off rapidly as the water cone area grows. Figure 1 shows the pressure drop from a nominal pressure of 17,000 psi at the nozzle, assuming the water cone has a 5° angle and the water is uniformly distributed in the cone.

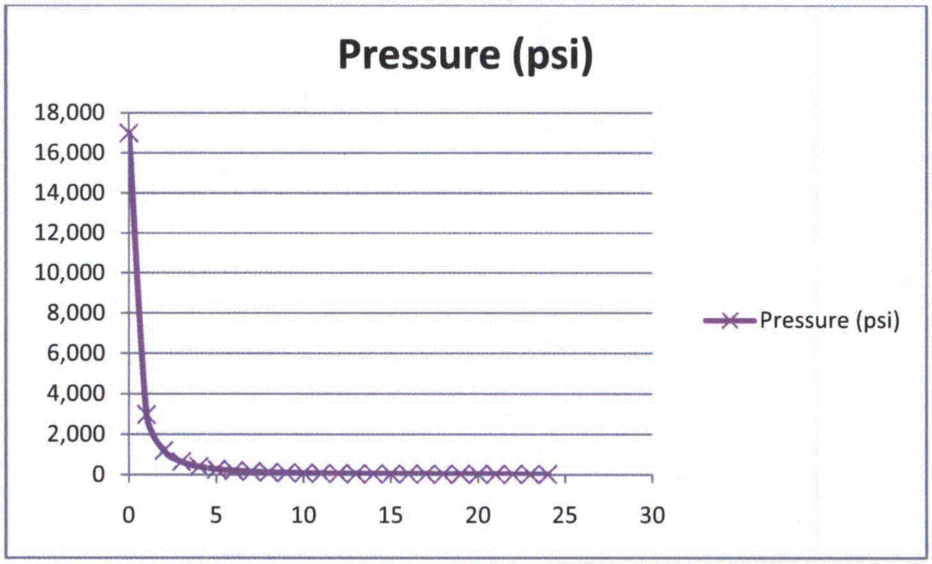

Figure 2 shows the pressure drop from a nominal pressure of 17,000 psi at the nozzle, assuming the water cone has a 5° angle and the water remains distributed in a ring 1/16" wide within the periphery of the cone.