Removal of delaminated concrete and cleaning the rust off the reinforcing bars using high-frequency forced pulsed waterjet

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ABSTRACT

The contractual work described in this paper consisted of refurbishing the ceiling of an underground parking garage using forced pulsed waterjet technique. The task was quite difficult as there were innumerable gas and water pipes, fire sprinklers, communication cables, which needed to be protected against possible damage. The use of pulsed technique resulted in savings of $200/m^2 compared to the chipping and sandblasting techniques, which were used earlier.

NOMENCLATURE

A: Total area of delaminated concrete to be treated, m^2
A_m: Area removal rate based on total operation time (t_M), m^2/hr
A_p: Rate of removal of delaminated concrete and cleaning rebars, m^2/hr
$A_{p\text{-}N}$: A/t, see Eq. 6
$A_{p\text{-}R}$: A/t, see Eq. 7
C: Speed of sound in water, m/s
E_m: Operational efficiency of the job
E_p: Overall job efficiency, Eq. 1
E_v: Specific energy, Eq. 8, kW-hr/m^3
M: Amplification of pressure = p_h/p_s
p_h: Waterhammer pressure, MPa
p_s: Static (~ pump) pressure on the target, MPa
t: Time used to estimate volume removal rate, Eq. 5, hr
t_J: Actual jetting duration, hr
t_M: Total operation time, hr
t_T: Total duration of the job, hr
V: Volume of concrete removed, m^3
V_J: Speed of waterjet, m/s
V_p: Rate of volume removal of concrete, m^3/hr
D: Density of water, kg/m^3

1 INTRODUCTION

A quick review of the literature shows that since the very first conference on waterjet technology, there has been a great deal of interest in the use of waterjet for cutting, demolishing or refurbishing of concrete [**1** to **20**; extensive references on the topic can be found in Ref. **20**]. The ubiquitous use of high-pressure continuous waterjet for refurbishing of delaminated concrete on the highways, bridges and floors of parking garages is quite well known [**20**]. What is not readily recognized is the danger posed by the delaminated concrete on the ceilings of the underground parking garages of multi-storied commercial, public and residential buildings. If not repaired promptly, the falling concrete debris may not only damage the vehicles parked in the garage, but can inflict serious injuries to the personnel.

The contract to investigate the feasibility of using forced pulsed waterjet for this application was awarded to VLN following a demonstration made in the laboratory to the personnel from PWGSC (Public Works and Government Services Canada). The demonstration, as shown in Fig. 1, was actually cutting hard, not the delaminated concrete. This clearly indicated the efficacy of the pulsed jet compared to the corresponding continuous waterjet. Furthermore, it was immediately obvious that the waterjet process would be much cheaper and safer than the slow two-step traditional chipping-sandblasting technique employed by the PWGSC. In this brief paper, the steps taken to address the tasks involved in removing the delaminated concrete and cleaning the rust off the rebars are described. The major emphasis was on the safety issues concerning the personnel (both VLN and PWGSC), the equipment and the sensitive areas, such as sprinklers and electrical components in the garage. Extensive details are described in Ref. 21.

2 BACKGROUND

2.1 Reasons for delamination

Figure 2 shows a cross-section of the concrete slab of the ceiling of the underground parking garage. According to PWGSC, the slab delaminates and spalls around corroded rebars and electrical conduits, which are buried in the slab. In the wintertime delamination is aggravated by: (i) the salt carried by the vehicles parked over the slab (on the upper level) and (ii) ice lenses formed in the cracks and the planes of delamination. Another factor that contributes to the failure of the concrete is buckling of the rods due to static and rolling loads on the upper level. When this happens, concrete above the rods is subject to tensile stresses and fails readily. As shown in Fig. 3, depending on the span of the columns supporting the ceiling, the extent of damage can be quite severe.

2.2 Basics of forced pulsed waterjet technique

Detailed description of the pulsed waterjet technique is beyond the scope of this paper [**22 to 25**]. Briefly, the forced pulses of water are generated by using an ultrasonic probe (called 'microtip') in the nozzle (Fig. 4). The microtip is placed inside the regular nozzle and energized by an ultrasonic transducer placed outside of the nozzle. An ultrasonic generator rated to operate at a maximum power of 1.5-kW at 20-kHz, in turn, powers the transducer. The photographs show the process of modulation as the ultrasonic power is gradually increased from zero percent of the rated value. These photographs were taken with an Nd-Yag pulsed laser with a duration of 4 to 6-ns. When the power input is zero, the jet is a regular (continuous) waterjet. The diameter of this jet is almost equal to the diameter of the orifice, and eventually it breaks up into water droplets. The modulation of the continuous stream starts with a small power input (~ 5%), and when the input power is optimum, well-defined fully developed pulsed waterjet is produced. The shape of each pulse is like a mushroom, the size increasing with the standoff distance. The location of the probe in the nozzle is quite important.

The efficacy of the pulsed waterjet stems from the fact that:
(1) When a pulse impacts on the target to be treated, the pressure at the point of impact is the waterhammer pressure (p_h), which is equal to: DV_JC (D = density of water; V_J = speed of jet and C = speed of sound in water). If the static pump pressure is p_s, then the amplification of pressure ($M = p_h/p_s$) is equal to $2(C/V_J)$. For example, if the pump is operated at 69-MPa, theoretically the impact pressure would be of the order of 550-MPa. In practice, due to various inefficiencies involved in the process, the impact pressure would be about 340-MPa, equivalent to an UHP pump, (2) The diameter of each pulse increases with standoff distance and (3) High frequency (20-kHz) of impacts.

3 GENERAL DESCRIPTION OF THE GARAGE

A general view of the lower-level parking garage at the government owned building is shown in Fig. 5. The photograph also shows the high-pressure pump mounted on a mobile trailer, which could be moved from one location to the next by a truck provided by PWGSC. The point to note about the garage is the existence of abundant number of pipes and ducts carrying water and compressed air (close-up views of these can be seen in Figs. 8 and 11). Sprinklers on some of these pipes needed to be protected against the force of waterjets. In addition, there were plenty of light fixtures, plugs, communication cables, etc., in close vicinity of the delaminated concrete spots, which also needed to be protected. Personnel from the PWGSC were responsible for these tasks. Prior to waterblasting, they erected barricades (polythene sheets) isolating the delaminated spots (see Fig. 6), which also prevented unauthorized personnel entering the work area. In essence, these steps were in accordance with the guidelines recommended by WJTA [Ref. 26; although in this case hand-held gun was not used). The number of locations where the blasting had to be conducted was about 108. The sizes of the spots varied from about 0.046-m^2 to well over 0.93-m^2.

4 DESCRIPTION OF WATERJET SYSTEM

The waterjet system used in the investigation consisted of: (1) a trailer mounted Pratisolli triplex plunger pump, (2) the forced pulsed waterjet generator (called, '**RFM** – retrofit module'), (3) a special (improvised) manipulator to mount and manoeuvre waterjet gun over the delaminated spot to be treated and (4) the nozzle system.

Pump: The pump (Fig. 5) is capable of delivering 53-litre/min at the rated pressure of 69-MPa. A special feature of the pump is that it is equipped with a softstart (electrical hardware), which gradually increases the current required to start the motor, thus avoiding peak loads on the electrical circuit breakers (this was very useful for this project).

RFM: A general view of the **RFM** is depicted in Fig. 7. The **RFM** consists of an ultrasonic generator, which supplies electrical oscillations to the piezoelectric transducer mounted close to the swivel (see Fig. 8). Several devices are incorporated into the **RFM** to ensure operational safety. For instance, an air pressure sensor monitors airflow to the transducer. If the pressure is below a preset value, then it would not be possible to switch on the ultrasonic generator. The **RFM** can be operated in pulsed or non-pulsed mode simply by turning on or off the ultrasonic generator. As the size and weight of the RFM are only 0.177-m^3 and 131.5-kg respectively, it could be pushed around easily like a lawnmower. Furthermore, as it was done in the present case, it could be located at a distance of up to 30-m from the work area, and could be as far away from the pump as desired (if one can accept the pressure losses in the line for large distances).

Manipulator: The main purpose of the manipulator, shown in Fig. 8, was to eliminate hand-held operation of the gun. This was essential because hand-held work would have been quite tiring and could have slowed the pace of the project.

As the contract was awarded on short notice, the manipulator was developed on an ***ad hoc*** basis, using an old existing hydraulically actuated crane. As shown clearly in Fig. 8, the nozzle system was bolted to a fixture to which a long bar with a handle was attached. The combination of the movable fixture and the bar made it possible to swing the nozzle (rotating or non-rotating) across the delaminated surface, or move up and down to adjust the standoff distance, and also to avoid striking the pipes, sprinklers, etc. The jumbo of the crane was actuated to set the nozzle as close to the ceiling as required. Initially, the crane was used with the existing small hard plastic wheels. However, during the trials on the first day it was noticed that it was not possible to move it fast enough across the surface due to (a) friction and (2) jamming by the concrete debris. Therefore, they were replaced with large rubber wheels to facilitate rapid movements, which improved the removal rates significantly.

Nozzle System: A close-up view of the nozzle system is shown in Fig. 8 (for the rotating configuration). The ultrasonic oscillations occur in the housing downstream of the transducer where high-pressure water enters. These oscillations travel with the stream to generate water pulses at the nozzle exit. The acoustically tuned swivel is custom designed to control the rotational speed by viscous damping. The nozzle assembly is designed in such a way that the thrust generated by the jets induces self-rotation, and orifices of various diameters could be easily inserted. As swivel is not required for single non-rotating jet, the nozzle can be screwed directly into the housing. The following nozzles were used in the investigation.

Twin-orifice rotating nozzles:	1.016 and 1.27-mm
Single-orifice non-rotating nozzle:	1.70-mm

5 DESCRIPTION OF DELAMINATION AND CLEANING TASKS

Since the feasibility investigation involved more than fifteen individuals (five from VLN and the rest from PWGSC), it was imperative that each person understood his role to ensure smooth and safe operation. While the responsibility of transporting and setting up the waterjet system rested with the VLN team, all other operations were in the hands of the PWGSC team. The steps used in the procedure were as follows:

- Initial meeting to examine the locations of delaminated concrete, to identify water and electrical power sources;
- As the work was performed after 18.00-hrs during the weekdays, and throughout the day and nights on the weekend, to make sure that no vehicles were parked in the vicinity of the work area;

- PWGSC to isolate the delaminated locations by setting up barricades (Fig. 6) and to protect all the sensitive components in the vicinity (electrical conduits, plugs, sprinklers, etc.);
- To make sure that everyone involved in the project to ***sign in*** upon arrival and ***sign out*** prior to leaving at the security office (strict government regulations);
- Crew hired by PWGSC to clean the work area prior to leaving the garage;
- PWGSC electrician to be readily available to connect the pump to the electrical power outlet in the building.

On the first day of the work, everyone involved in the project was requested to read, understand and endorse the safety plan distributed by the Chief Inspector of PWGSC. The work commenced once these formalities were completed.

The procedure was quite simple. Once the delaminated area was identified, the manipulator was moved into position, and the handle was maneuvered to (i) adjust the standoff distance and (ii) swing the jet across the area to remove the delaminated concrete and to remove the rust off the rebars (see Figs. 6 and 8). In retrospect, the fabrication of the manipulator was a good idea as it would have been quite difficult to finish the job in time by using hand-held gun (it is not easy to do the work on the ceiling). The delaminated area and the rust on the rebars can be seen clearly in Fig. 9. After each location was completed, the inspector (the last author of this paper) examined the area and evaluated the surface as satisfactory (including profile for patching with fresh concrete) or unsatisfactory. In the latter case, the procedure was repeated until the surface was certified as satisfactory. Figure 10 shows the result obtained with the twin-orifice rotating pulsed waterjet, and Fig. 11 the results achieved with the single-orifice pulsed waterjet. Generally, while the rotating waterjet was satisfactory for cleaning the rebars, the single jet was found to be more powerful in removing the delaminated concrete. The project was completed satisfactorily within the time allocated by the PWGSC.

6 DISCUSSION

6.1 General Remarks

Extensive work has been reported on the mechanism of interaction between a waterjet (also abrasive-entrained waterjet) and the structure and texture of concrete [**1, 2, 10, 14, 17, 18, 19 and 20**]. However, the interaction with pulsed waterjet is rather different. Simply stated, when the pulses impact the aggregates of concrete, the waterhammer pressure generated by the pulses knock off large pieces of delaminated concrete from the ceiling (Fig. 12). When the pieces stop falling, the location could be considered as restored, ready to be patched with fresh concrete.

6.2 Time Efficiencies

Time efficiency can be defined in two ways. In the first definition, the total time devoted to the contract is considered. For example, it includes the time lost due to electrical problems (which occurred on the first day of the job). In the second, such losses in time are neglected.

The total duration of the overall job, t_T, was 61 hours in 8 days (6 days in weekends, 2 days in weekdays). The actual jetting duration, t_J, the time recorded on the timer in the ultrasonic generator of the RFM (being turned on for the work), was 14 hours. The ratio of these two durations gives the overall job efficiency, E_p:

$$E_p = \frac{t_J}{t_T} = \frac{14}{61} = 22.95\% \qquad (1)$$

The total operation time, t_M (for example, this includes the time necessary to change the nozzles, etc.), on the other hand, is defined as the time taken from the start of work at the first location to completion of the last location, less the time taken for lunch breaks. This was estimated to be 40.0 hrs. The ratio of actual jetting time to the operation time gives the operational efficiency, E_m, of the job.

$$E_m = \frac{t_J}{t_M} = \frac{14}{40} = 35\% \qquad (2)$$

The overall job efficiency was rather low because of the problems encountered at the job site. Generally, in most contractual jobs, this has been found to be the case [**23**]. If such losses in time could be eliminated the efficiency would increase. Similarly, the operational efficiency could be increased to about 50 percent (considered to be normal) by taking appropriate steps. For example, prior work in the laboratory could have been very helpful in selecting appropriate nozzles, to design a motorized and semi-automated manipulator, etc.

6.3 Performance

According to the blueprint given by PWGSC, the total area, ‘A’ to be treated was ~186-m^2, distributed unevenly over 100 spots at various locations. Assuming 90 percent of the total area was completed over the duration of the project, the rate of removal of delaminated concrete and taking the rust off the rebars, based on the jetting time, is:

$$A_p = \frac{A}{t_J} = \frac{186 \times 0.9}{14} = 12 \;\; m^2/hr \qquad (3)$$

This is the actual removal rate achieved with the pulsed waterjet. However, based on the operation time t_M, the rate is:

$$A_m = \frac{A}{t_M} = \frac{186 \times 0.9}{40} = 4.2 \;\; m^2/hr \qquad (4)$$

It is also interesting to mention, in passing, the volume removal rate (often quoted in the literature). Volume removal rate could only be estimated for the single jet as it was used on an untreated (by chisel) delaminated spot. The area of this spot was ~ 0.5-m^2, with an average depth of cut of ~51-mm. The time to complete this area was about 10-min. Therefore, the removal rate, V_p, is:

$$V_p = \frac{V}{t} = \frac{0.5 \times 51/1000}{10/60} = 0.15 \;\; m^3/hr \qquad (5)$$

It is also worthwhile to compare the performance of single jet against the twin-orifice rotating jet. The estimation of the rate of removal achieved with the dual-orifice rotating nozzle is based on the data obtained on the 5 spots completed on the last day. The area removal rates for the single non-rotating jet (A_{p-N}), and the dual orifice rotating jet (A_{p-R}) are given respectively by Eq. (7) and Eq. (8) below:

$$A_{p-N} = \frac{A}{t} = \frac{1.52}{10/60} = 2.8 \;\; m^2/hr \tag{6}$$

$$A_{p-R} = \frac{A}{t} = \frac{16.7}{1.5} = 11 \;\; m^2/hr \tag{7}$$

For the rotating jets, the rate is the same as the value obtained by Eq. (3), confirming somewhat the accuracy of estimation. Although area removal is much better for the rotating jet, it is not powerful enough to remove massive amounts of concrete. A single-orifice rotating nozzle would probably be better for removing large amounts of delaminated concrete.

6.4 Comparison with the regular blasting

As pointed out earlier, extensive literature exists on regular waterblasting of concrete on bridges, highways, parking lots, etc. Generally comparison is not easy because of the uncertainty in the properties (both micro and macroscopic) of concrete investigated. *The comparison given here is for the sake of illustration only*. The results reported by IVS Hydro Inc. [**27**] on the road construction job in New York City (USA) and those obtained in the present project are summarized in **Table 1**. While the volume removal rate of 0.14-m^3/hr achieved in the present study appears to be low compared to 0.5-m^3/hr, the high magnitudes of pressure and hydraulic power employed by IVS must be noted.

Table 1. Comparison of performance of regular and forced pulsed waterjets.

Items to Compare	**Pulsed Jet (VLN)**	**Regular Jet (IVS Hydro)**
Volume removal rate, m^3/hr	0.14	0.5
Pressure, MPa	69	138
Flow rate, Litre/min	32.6	197
Hydraulic power, kW	37.3	452
Specific Energy, kW-hr/m^3	266	904

Therefore, a more valid comparison must be on the basis of specific energy (power consumed per unit volume of material removed). The smaller the magnitude of this parameter (performance indicator), the more efficient the performance is considered to be. Specific energy is given by:

$$E_v = \frac{E}{V} = \frac{W}{V/t} \text{ (kW-hr/m}^3\text{)} \tag{8}$$

The specific energy of IVS is 3.4 times that of pulsed waterjet. Comparison on this basis clearly shows the superior performance of pulsed waterjet vis-à-vis regular jet. Viewed from a different perspective, and if the value of specific energy remains constant at 266-kW-hr/m^3, then for the same power loading as IVS, the expected removal rate with the pulsed jet would be of the order of 1.7-m^3/hr.

6.5 Overall impression

The contract was performed on an ***ad hoc*** basis, and therefore, could be considered as a demonstration of the potential of the pulsed waterjet technique for this type of work. Most of the gadgets, for example the manipulator, were improvised as the project progressed from day to day. However, the lessons learnt have clearly indicated that there is considerable room for improvement. It is believed that the performance can be improved, at least by a factor of two, by: (1) eliminating most of the problems before commencing the work, (2) taking appropriate steps in rapid setting up of the equipment and (3) designing appropriate nozzles and guns by conducting some preliminary development work in the laboratory.

6.6 Analysis of Costs

Prior to awarding this project to VLN, PWGSC had already refurbished a number of delaminated locations at the garage using the traditional techniques of chipping the concrete using a chisel, followed by sandblasting, to clean the rust from the rebars. The cost of chipping and sandblasting were \$206/m^2 and \$210/m^2 respectively. In the pulsed waterjet technique, the sandblasting technique was totally eliminated. Since the cost of a waterjet system is considerably higher than the chipping technique, the cost of repair (removing the concrete and simultaneously cleaning the rebars) is assumed to be of the order of \$216/m^2. Therefore, PWGSC saved, on the average, \$200/m^2, which is considered to be substantial.

7 CONCLUSIONS

The following conclusions can be drawn from this brief, but intensive project:

1. The pulsed waterjet technique was found to be quite satisfactory, the actual jetting time being of the order of only 14 hours.
2. Dual-orifice rotating nozzle was found to be good for cleaning action, but not for removing large amounts concrete debris.
3. Single orifice non-rotating nozzle was found to be quite effective for removing large amounts of concrete debris, but not as effective for cleaning the rust.
4. The estimated rate of cleaning with the dual-orifice rotating nozzle was ~ 11-m^2/hr.
5. The estimated volume removal rate with the single non-rotating nozzle was 0.14-m^3/hr.
6. Preliminary comparison with the data published in the literature showed that pulsed waterjet is significantly better for this application.
7. Over the duration of the project the pulsed waterjet machine performed without any major problems.

8 ACKNOWLEDGMENTS

Several individuals were involved in carrying out this project. The collaboration was truly remarkable as each individual contributed his/her utmost effort to ensure project completion before the deadline. From this standpoint, this was an excellent collaborative project between the public and private sectors. Special thanks to Mr. Adel Iskandar, Project Manager (PWGSC) for the contract, who managed the project very well and kept everyone informed on a timely basis.

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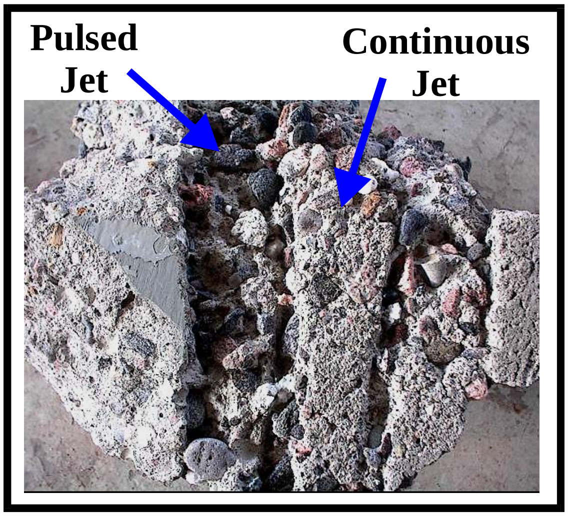

Fig. 1. Comparison of performance of pulsed against continuous waterjet (P = 69 MPa).

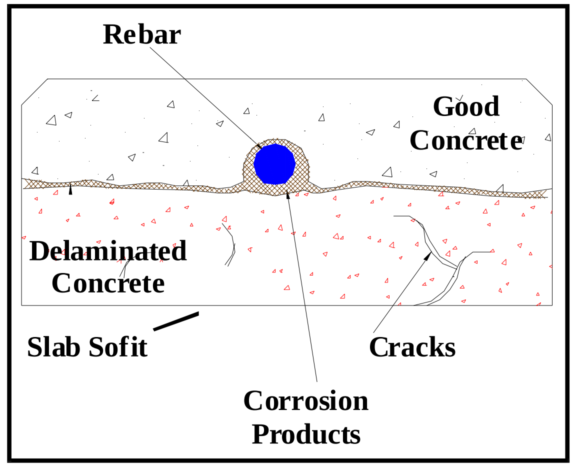

Fig. 2. A typical cross-section of concrete slab of ceiling of underground parking garage (cracks and other openings may contain ice lenses).

Fig. 3. A close-up view showing the extent of damage and the rusted rebars at one of the locations of the ceiling.

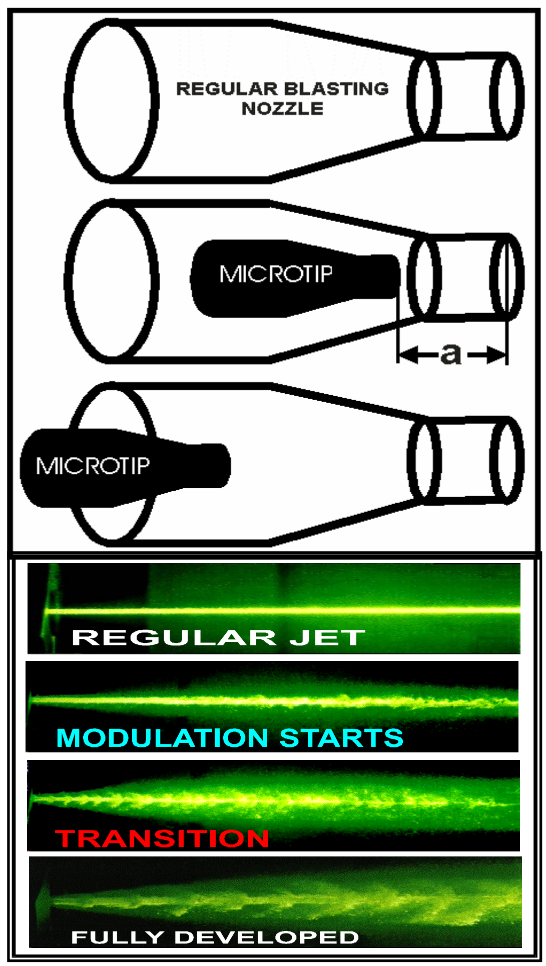

Fig. 4. Method of modulation and typical appearance of forced pulsed waterjet (25).

Fig. 5. A general view of the lower-level parking garage of the government building in Ottawa, Canada. The network of pipes on the ceiling must be noticed. Trailer mounted pump was located away from the work area.

Fig. 6. A general view of the work in progress showing (a) barricades (polythene sheets) set up to protect the pipes carrying compressed air, electrical components, sprinklers, etc.

Fig. 7. A general view of the forced pulsed waterjet generator called the RFM (Retrofit Module). The enclosure contains all the controls to ensure safety at the workplace. The maximum power of ultrasonic generator in the RFM is 1.5-kW at 20-kHz.

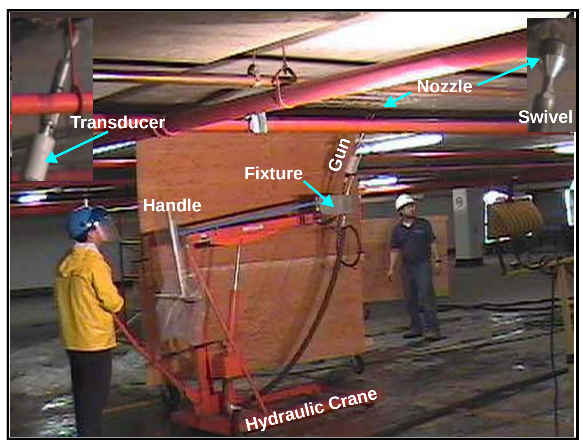

Fig. 8. A general view of the specially designed (improvised) manipulator (hydraulically controlled crane) for mounting the high-pressure lance with the ultrasonic transducer and the nozzles. Pipes and sprinklers are visible.

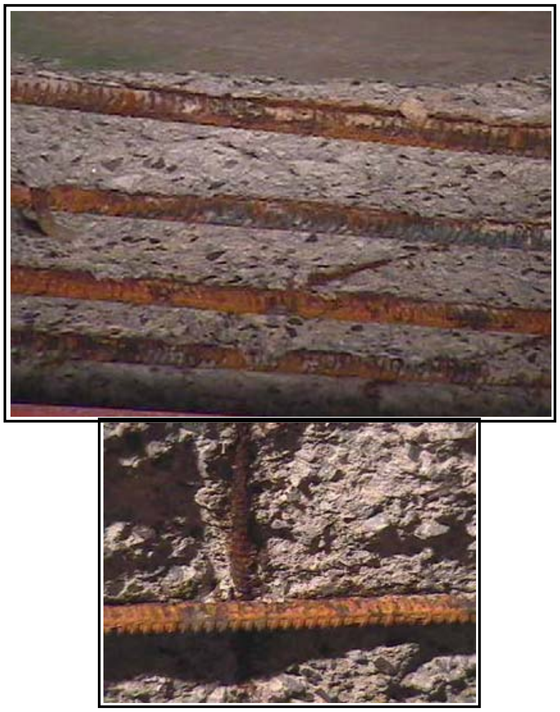

Fig. 9. Typical appearance of delaminated area showing the rust on the rebars.

Fig. 10. Typical appearance of the sound concrete and rust-free rebars achieved with the twin-orifice rotating waterjet.

Fig. 11. Typical appearance of the sound concrete and rust-free rebars achieved with the nonrotating single-orifice waterjet.

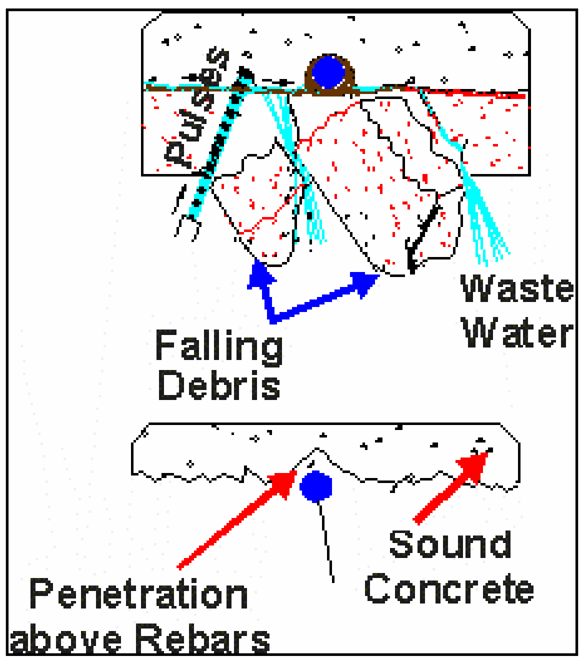

Fig. 12. Mode of action of pulsed waterjet on delaminated concrete and rebars.