Environmental Evaluation of Abrasive Blasting with Sand, Water, and Dry Ice

Lauren R. Millman*, James W. Giancaspro

Department of Civil, Architectural, and Environmental Engineering, University of Miami, Coral Gables, FL 33146, United States

Abstract: The objective of this case study was to perform an evaluation of the environmental effects of three surface preparation methods used in civil infrastructure: sand blasting, water jetting, and dry ice blasting. The study was based upon a bridge rehabilitation project in which surface preparation of the reinforced concrete pier caps was undertaken. The assessment considered four response variables: carbon dioxide (CO$_2$) emissions, fuel consumption, energy consumption, and project duration. The results indicated that for sand blasting and water jetting, CO$_2$ emissions stemming from vehicular traffic near the construction site was the primary factor contributing to environmental detriment. However, the CO$_2$ contribution from sublimation of the dry ice translated into 80% and 64% more CO$_2$ than sand blasting and water jetting, respectively. Compared to sand blasting and water jetting, dry ice blasting yielded the shortest project duration and reduced fuel consumption by 7.6% and 13%, respectively.

Keywords: Carbon dioxide, case studies, concrete construction, construction materials, emissions, environmental issues, life cycle, rehabilitation, sustainable development, surface preparation, blasting

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1 INTRODUCTION

Surface preparation of concrete and other structural materials has been a vital task in many engineering applications and has been typically accomplished using abrasive grit media, such as sand, or water propelled to high speeds. Sand blasting has been routinely used in industrial settings to remove corrosion and other chemical residues from intricate machinery components (Stratford 2000), while water jetting or hydro-blasting has been used to remove paint and coatings (Teimourian et al. 2010). In civil infrastructure, sand blasting and water jetting have been utilized to remove accumulated organic matter and other debris from substrates such as concrete, steel, and wood. Achieving a clean and uniform substrate is a vital prerequisite to the application of specialized coatings and repair materials (Mailvagnam et al. 1998).

Sand blasting produces vibrations, significant noise, and an effluent cloud consisting of dust, the waste sand, and the organic matter shed from the substrate. Moreover, the sand particles can act as a carrier to transport contaminants such as lead-based paint residue (Stout 1996). While sand blasting has remained a staple practice due to its simplicity, the byproducts are considered safety risks to on-site personnel and hazardous to the surrounding environment. Water jetting has become a principal practice and is advantageous in the reduction of dust exposure, especially for surfaces that contain lead-based paint or silica-based coatings. However, the contaminants could become aerosolized and inhaled (Rosenberg et al. 2006). To prevent environmental pollution and to protect the health of on-site workers, both sand blasting and water jetting must include careful containment, collection, treatment, and disposal of the effluent under strict regulations (ASTM E 1857 2004; Weston et al. 2005; Code of Federal Regulations 2006).

To circumvent many of the problems associated with sand blasting and water jetting, frozen carbon dioxide (dry ice) pellets can be utilized as the blasting media (Figure 1). This method is commonly known as dry ice blasting or cryoblasting and was developed by the Lockheed Corporation (Stratford 2000). Dry ice blasting was to serve as an alternative method of debris removal and stripping paint to overcome those is-

*Corresponding author. Email: l.millman1@umiami.edu
sues associated with sand blasting. The bond between the debris and the substrate is broken by three unique events: the kinetic energy of the dry ice pellets, the micro-thermal shock induced by the low temperature of $-79^\circ C (-174^\circ F)$, and the accompanying pressure wave (Stratford 2000; Spur et al. 1999). The primary advantage of using dry ice in lieu of sand or water is that the pellets sublimate (change from a solid to gas) immediately after impact, producing little waste other than the contaminate being removed. Hence, containment measures (like those associated with sand blasting and water jetting) are no longer essential unless environmental conditions warrant it. Sublimation of the pellets also permits surface preparation in complicated cavities and structural joints that would typically trap grit blast media.

From a sustainability viewpoint, one obvious drawback of dry ice blasting is the intentional release of CO$_2$ into the atmosphere (Figure 2). The typical coverage rate of dry ice blasting (0.28 $m^2$/min) is about one-third of that for sand blasting (0.79 $m^2$/min) (Cold Jet 2009; Foster 2006) and similar to that of water jetting (0.14 $m^2$/min) (Schmid 2005) as reported by equipment manufactures and literature. However, the overall duration of a surface preparation project using dry ice may be shorter than using sand or water because the need for waste containment is potentially eliminated in most circumstances. This reduction in project duration also reduces the CO$_2$ emissions associated with on-site construction equipment and traffic congestion. Therefore, it was hypothesized that dry ice blasting may offer a higher degree of sustainability than sand blasting or water jetting.

To test the hypothesis, this case study compared the

**Figure 2.** Modes of CO$_2$ release into atmosphere for the dry ice blasting system
environmental effects of dry ice blasting, sand blasting, and water jetting by quantifying the environmental impact of two key indicators, namely, CO$_2$ emissions and fuel consumption. The assessment considered the commitment of environmental resources originating from the construction staging area until the final disposal (end of construction activities) for a bridge repair project undertaken in Rhode Island (USA). The analysis consisted of (1) a baseline study to identify the variables that had the most significant effect on the environment, and (2) a sensitivity analysis to examine the variation of those critical variables identified in the baseline study.

2 METHODOLOGY

To compare the processes, this case study analyzed a bridge repair project undertaken in South Kingstown, Rhode Island (USA) (Giancaspro et al. 2009). The rehabilitation included the application of fiber-reinforced polymer (FRP) overlays to the reinforced concrete pier substrate preparation and cleaning system. The functional unit was the Salt Pond Road Bridge rehabilitation project.

Scope of the Study

The scope was to determine the most environmentally conscious (with an equivalent mechanical effectiveness) substrate preparation and cleaning system. The functional unit was the Salt Pond Road Bridge rehabilitation project.

System Boundaries

The study covered the implementation processes of the three systems and measured the energy required and CO$_2$ emission from project start to end, and from construction staging area to the final disposal of the blasting media at the landfill or wastewater treatment plant.

Assumptions

The assumptions of the baseline study were based on equipment specifications, collected field data, and approximations based on the authors’ experience. These included:

1. Near the construction zone, an imposed reduction in vehicle speed of 64 to 32 km/h (40 to 20 mph) created traffic congestion, which increased fuel consumption and CO$_2$ emissions.
2. To achieve the same degree of surface cleaning (aggressiveness), dry ice blasting and water jetting required longer dwell times (8.97 min/m$^2$) and (7.18 min/m$^2$), respectively, than sand blasting (4.45 min/m$^2$); the equivalent blasting coverage rates were 0.11 m$^2$/min, 0.14 m$^2$/min, and 0.22 m$^2$/min, respectively.
3. Each pier cap was approximately 15.5 m (50.8 ft) long with a surface area of 72.4 m$^2$ (779 ft$^2$) and supported seven prestressed concrete girders. The bridge consisted of two separate roadways - one for northbound traffic and another for southbound traffic. Both pier caps were identical in design.
4. A 2-lane principal arterial road passed beneath the bridge and was parallel to the bridge columns. Rehabilitation activities in the designated construction zone created a 50% reduction in vehicle speeds (congestion) from 64 to 32 km/h (40 to 20 mph) over a 0.5 km (0.31 mile) stretch of the road.
5. The average daily traffic flow on the principal arterial was taken as 4,250 vehicle/lane/day. This was based on traffic data collected in 2008 by the Federal Highway Administration (FHWA 2008).
6. Each workday permitted 8 hours of work to be performed; therefore, one-third of the daily traffic flow was affected by the reduced speed and congestion, namely, 1,417 vehicles/lane/day.
7. Approximately 2.35 kg of CO₂ gas were released for each liter, L, of gasoline a vehicle consumed (19.6 lb/gal) (Marland 2009; EPA 2009).
8. An additional 0.062 kg of CO₂ was released per kilometer (0.221 lb/mile) per vehicle for the aforementioned reduction in speed. For the 0.5 km (0.311 mile) stretch of road, this equated to 0.031 kg (0.069 lb) (Barth and Boriboonsomsin 2008).
9. Similar construction equipment (diesel-powered generators and air compressors) of the same capacity were used for all surface preparation methods. Diesel fuel consumption was 2.27 L/h (0.60 gal/h) (Diesel Service & Supply Inc. 2009).
10. Scaffolding setup and removal each required 2.3 days per pier cap for each system (RSMeans 2008).
11. The transportation modes and travel distances of the materials (blasting media) from the construction staging area were identical and not considered in terms of CO₂ emission, fuel or energy consumption, or project duration.
12. The travel distance of the waste byproducts to the landfill or waste water treatment plant was assumed negligible. Although sand blasting and water jetting yielded more waste, the waste from all methods was transported the same distance to their end location (a landfill or wastewater treatment plant).

The assumptions specific to dry ice blasting included:
1. The dry ice blasting apparatus consumed 190 kg (427 lb) of dry ice per hour (Cold Jet 2012).
2. The blasting (or coverage) rate was 0.13 m²/min (1.4 ft²/min), which was based on actual measurements taken by the authors.
3. The blasting apparatus was estimated to consume approximately 0.0117 MW·h of energy (Cold Jet 2012).

The assumptions relevant to sand blasting included:
1. In addition to scaffolding, sealed containment areas to contain the blasting media and dust cloud were constructed along the perimeter of the scaffolding. Setup and removal each required 0.39 days per pier cap (RSMeans 2001).
2. The coverage rate during blasting was 0.22 m²/min (2.4 ft²/min), which was based on actual measurements taken by the authors.
3. The blasting apparatus consumed 0 MW·h of energy (Kramer Industries 2009). The apparatus operated using air pressure and did not require additional energy.

Assumptions specific to water jetting included:
1. The water blasting apparatus consumed 2,730 kg (6,000 lb) of water per hour (US Jetting, Inc. 2012).
2. The blasting (or coverage) rate was 0.14 m²/min (1.5 ft²/min) (Schmid 2005).
3. The blasting apparatus was estimated to consume approximately 1.60 MW·h of energy (OJ Højtryk 2012).

2.2 Inventory Analysis
The system flow for the dry ice blasting process included the sublimation of pellets upon impact and the CO₂ gas released into the atmosphere. The contaminant shed from the substrate was transported to its end location (landfill).

The system flow for the sand blasting process began with the sand propelled at the substrate using compressed air, then the mixture of waste and sand were collected after use. The waste was transported to the end location for disposal.

The system flow for the water jetting process began with the water propelled at the substrate using compressed air, and the mixture of shed contaminant and water were collected after use. The waste was transported to the end location for disposal.

For each system, the environmental effects were categorized into several project stages (or sources): site setup and deconstruction, equipment operation (usage), vehicular traffic, media sublimation, and disposal of process wastes. More specifically:

1. The site setup and deconstruction included the erection and breakdown of scaffolding, setup and removal of containment measures, and the removal of debris.
2. The equipment source included the fuel consumption and CO₂ emissions from the equipment during the actual blast cleaning of the concrete surface. Since the blasting aggressiveness (ability to remove a layer of concrete with specified thickness) depended on the abrasive properties of the blasting media, the coverage rate (or dwell time) was varied.
3. The vehicular traffic source included the additional CO₂ emissions produced from vehicle traffic due to the project.
4. The media sublimation source was applicable only to the dry ice blasting system and included the total CO₂ emissions from media sublimation.
5. The disposal or process wastes stage included the collection and transportation of waste to a landfill.

2.3 Impact Assessment
The impact factors included project duration, CO₂ emissions, and fuel and energy consumption. The blasting process found to have the lesser values was considered the process with the least environmental impact. Tables 1 and 2 show the CO₂ emissions and energy consumed by project stage, respectively.
### Table 1. CO₂ emissions and fuel consumption for blasting methods (baseline study)

<table>
<thead>
<tr>
<th>Source and Assumptions</th>
<th>Dry Ice Blasting</th>
<th>Sand Blasting</th>
<th>Water Jetting</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Scaffolding erection = 4.67</td>
<td>4.67</td>
<td>4.67</td>
<td></td>
</tr>
<tr>
<td>Blasting area = 72.4</td>
<td>72.4</td>
<td>72.4</td>
<td></td>
</tr>
<tr>
<td>1 Setup of containment measures = 0</td>
<td>0.78</td>
<td>0.78</td>
<td></td>
</tr>
<tr>
<td>Removal of scaffolding = 4.67</td>
<td>4.67</td>
<td>4.67</td>
<td></td>
</tr>
<tr>
<td>2 Removal of debris = 0.27</td>
<td>0.67</td>
<td>0.80</td>
<td></td>
</tr>
<tr>
<td>Deconstruction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Removal of scaffolding = 4.67</td>
<td>4.67</td>
<td>4.67</td>
<td></td>
</tr>
<tr>
<td>Setup of containment measures = 0</td>
<td>0.78</td>
<td>0.78</td>
<td></td>
</tr>
<tr>
<td>Fuel consumption rate for equipment = 2.27</td>
<td>2.27</td>
<td>2.27</td>
<td></td>
</tr>
<tr>
<td>Fuel consumption = 24.6</td>
<td>12.3</td>
<td>19.7</td>
<td></td>
</tr>
<tr>
<td>CO₂ emission = 57.7</td>
<td>28.9</td>
<td>46.2</td>
<td></td>
</tr>
<tr>
<td>Construction duration = 11.0</td>
<td>12.2</td>
<td>12.8</td>
<td></td>
</tr>
<tr>
<td>Arterial road capacity = 2 Lanes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Avg. traffic = 4,250 Vehicles/lane/day</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Additional CO₂ = 0.031 kgs CO₂/vehicle</td>
<td>88</td>
<td>88</td>
<td>88</td>
</tr>
<tr>
<td>CO₂ emissions from vehicle traffic = 969</td>
<td>1,082</td>
<td>1,129</td>
<td></td>
</tr>
<tr>
<td>Additional fuel consumed = 0.0133 L/vehicle</td>
<td>412</td>
<td>460</td>
<td>481</td>
</tr>
<tr>
<td>CO₂ emissions from dry ice blasting = 2,077</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Total CO₂ emissions = 3,104</td>
<td>1,111</td>
<td>1,176</td>
<td></td>
</tr>
<tr>
<td>Total additional fuel consumed = 437</td>
<td>473</td>
<td>500</td>
<td></td>
</tr>
</tbody>
</table>


### Table 2. Energy consumption for blasting methods (baseline study)

<table>
<thead>
<tr>
<th>Stage in Process</th>
<th>Dry Ice Blasting</th>
<th>Sand Blasting</th>
<th>Water Jetting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Consumed (MW·h)</td>
<td>Consumption Rate (MW)</td>
<td>Time (h)</td>
<td>Energy Consumed (MW·h)</td>
</tr>
<tr>
<td>Blasting project</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site setup and deconstruction</td>
<td></td>
<td>74.8</td>
<td>0.0</td>
</tr>
<tr>
<td>Equipment Blaster</td>
<td>~ 0</td>
<td>~ 0</td>
<td>10.82</td>
</tr>
<tr>
<td>Compressor</td>
<td>0.403</td>
<td>0.037</td>
<td>10.82</td>
</tr>
<tr>
<td>Generator</td>
<td>~ 0</td>
<td>~ 0</td>
<td>10.82</td>
</tr>
<tr>
<td>Vehicular traffic</td>
<td>20.3</td>
<td>0.231</td>
<td>87.7</td>
</tr>
<tr>
<td>Disposal of process wastes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cleaning and separating sand from waste</td>
<td>N/A</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Collection and transportation to landfill</td>
<td>0.224</td>
<td>0.224</td>
<td>1.0</td>
</tr>
<tr>
<td>Total</td>
<td>21.0</td>
<td>23.1</td>
<td>25.8</td>
</tr>
</tbody>
</table>

3 DISCUSSION AND INTERPRETATION

3.1 Baseline Case Study

Project Duration

Table 1 facilitates an equivalent comparison of the durations of the projects for the baseline study. The setup and removal of scaffolding required a total of 9.4 days regardless of the blasting media employed. The actual surface preparation (blasting) time using dry ice was 10.8 hours, while that for sand blasting was 5.42 hours and 8.66 hours for water jetting. Because the dry ice blasting was nearly twice as long as sand blasting, it may seem that sand blasting was the faster method. However, this misconception can be disproven by comparing the overall project durations of the methods. Sand blasting required 12.2 days, dry ice blasting required 11.0 days, and water jetting required 12.8 days. Comparing the dry ice and sand, the difference of 1.2 days was a 10.4% reduction in time for the scenario employing the dry ice. This significant savings in time stems from the 1.6 days needed for the combined setup and removal of containment measures, which was unnecessary for the dry ice blasting. Because the dry ice sublimates, the overall project duration was reduced by 10.4% as compared to sand blasting, and by 14.3% as compared to water jetting. This reduction in time translated into reduced traffic delays and, hence, less CO$_2$ emissions from vehicular traffic.

CO$_2$ Emissions

As shown in Table 1, the dry ice blasting scenario produced 57.7 kg of CO$_2$ from the setup and equipment stages, 969 kg of CO$_2$ from vehicular traffic, and 2,077 kg of CO$_2$ directly from blasting with dry ice (sublimation) for a total of 3,104 kg. The sand blasting project produced 28.9 kg of CO$_2$ during the setup and equipment stage, and 1,082 kg of CO$_2$ from vehicular traffic, for a total of 1,111 kg. The water jetting project produced 46.2 kg of CO$_2$ during the setup and equipment stage, and 1,129 kg of CO$_2$ from vehicular traffic, for a total of 1,176 kg. Thus, the sand blasting released 1,993 kg less than that of dry ice blasting and 65 kg less than water jetting; this corresponded to reductions of 64.2% and 5.5%, respectively. The majority of these reductions in CO$_2$ for sand blasting stemmed from the blasting duration component. The sand blasting cleaning rate was about double the rates for dry ice blasting or water jetting which allowed for a faster cleaning time and shorter blasting duration. For the sand blasting and water jetting scenarios, vehicular traffic contributed the largest amount of the total CO$_2$ emissions as shown in Table 1 (31.2% for dry ice blasting, 97.4% for sand blasting, and 96.0% for water jetting). Because the blasting duration overwhelmingly governed the total CO$_2$ emissions, the release of CO$_2$ via dry ice sublimation was equitably significant.

Energy Consumption

The energy consumption analyses in Table 2 considered the energy consumed on a system-wide perspective, which included contributions from vehicular traffic. Energy consumption for dry ice blasting was 20.7 MW·h during blasting, and 0.22 MW·h for disposal (total of 21.0 MW·h). For sand blasting and water jetting, energy consumption was comparable to that of dry ice for the disposal stage (0.22 MW·h). However, the blasting stage (for sand) consumed 22.9 MW·h, which was 10.5% more energy than that consumed for the dry ice. For water jetting, the blasting stage consumed 25.6 MW·h, which was 23.6% more energy than that for dry ice. This difference in energy consumption was due to the longer project durations, which increased vehicular traffic for both the sand blasting and water jetting systems. Additionally, the blasting apparatus of the equipment stage increased the total energy consumption for the water jetting system. In terms of the total energy consumed, the dry ice scenario used 21.0 MW·h whereas the sand blasting scenario used 23.1 MW·h and the water jetting scenario used 25.8 MW·h. These differences equated to 10.0% and 23.2% less energy when using the dry ice blasting process.

Fuel Consumption

As expected, the reduction in vehicle speeds due to congestion increased the fuel consumption per vehicle. For all systems, the assumed increase was 0.0133 L of fuel per vehicle, as shown in Table 1. Vehicles in the dry ice blasting system consumed an additional 437 L of fuel during the project, while traffic for the sand blasting system consumed 8.2% more (total of 473 liters) and the water jetting scenario consumed 14.4% more (total of 500 liters).

3.2 Sensitivity Analyses

The results of the baseline study indicated that the variable with the most significant environmental impact stemmed from traffic disruptions. To further examine the sensitivity of this variable, two scenarios were evaluated:

1. Scenario 1: variation of number of traffic lanes from 0 to 8 (Figure 3).
2. Scenario 2: variation of the average daily traffic flow from 0 to 12,000 vehicles/lane (Figure 4).

Scenario 1

The number of traffic lanes was varied from 0 to 8 lanes, though the average daily flow remained constant at 4,250 vehicles/lane. Zero lanes of traffic corresponded to bridges that do not have roads passing beneath them; thus, vehicular traffic would not be affected. For these bridges, the environmental effects from traffic disruptions were removed and the effect of dry ice sublimation became more pronounced and significant.
To demonstrate this effect, consider the CO$_2$ emissions for zero lanes of traffic in Figure 3. Dry ice blasting released 2,140 kg, while that for sand blasting and water jetting were negligible. When the number of lanes was increased to 1, both the sand blasting and water jetting methods contributed nearly equal amounts of CO$_2$ (540 kg). This trend continued, although diverging slightly with an increasing number of lanes (about 4% for 8 lanes of traffic), and with water jetting contributing the greater amount of CO$_2$. Thus, sand blasting and water jetting released less CO$_2$ if traffic was unaffected by the construction or if the number of traffic lanes was limited to 1 lane. Dry ice blasting consistently contributed more CO$_2$ than sand blasting or water jetting. This was attributed to the additional release of CO$_2$ via sublimation. Regardless of the number of traffic lanes, fuel consumption for water jetting and sand blasting was always greater than that for dry ice blasting. However, the difference was marginal (only about 10% for 8 lanes of traffic). This was expected since...
the construction equipment consumed fuel at a constant rate; the blasting method with the longer overall project duration would consume more fuel.

Scenario 2

To examine the sensitivity of the environmental effects to variations in traffic volume, the average daily traffic flow was varied from 0 to 12,000 vehicle/lane (Figure 4). The minimum value of 0 vehicle/lane corresponded to bridges that did not span other roadways. In this scenario, the traffic flows were broadly categorized as either 4-lane, low volume/rural arterials or 8-lane, high volume/urban arterials or interstates (FHWA 2007). Figure 4 demonstrates that sand blasting and water jetting released less CO\textsubscript{2} than dry ice blasting at daily flow rates below 6,000 vehicle/lane.

4 CONCLUSIONS AND RECOMMENDATIONS

The analysis presented in this study compared the environmental effects of sand blasting, water jetting, and dry ice blasting based on an actual bridge rehabilitation project. For the specific project conditions and assumptions, the following conclusions were drawn for the baseline study:

1. Since the dry ice blasting process did not require containment measures, its duration was 1.2 days shorter (9.8%) than that of the sand blasting and 1.8 days shorter (14%) than that of the water jetting.
2. The dry ice blasting process permitted direct release of CO\textsubscript{2} via sublimation; it released 80% more CO\textsubscript{2} than the sand blasting scenario, and 64% more than the water jetting scenario.
3. Fuel consumption for the dry ice blasting was 7.6% lower than that of the sand blasting and 13% lower than that of the water jetting.
4. All processes consumed comparable amounts of energy during the material acquisition and disposal phases, though dry ice blasting required 19% less energy than water jetting and sand blasting required 10% less energy than water jetting during the blasting (cleaning) phase.

Since traffic-related CO\textsubscript{2} emissions and fuel consumption comprised the majority of the environmental detriment, both response variables were most sensitive to variations in traffic volume. When explored in the sensitivity analyses, the results led to the following conclusions:

1. As the number of traffic lanes or the vehicular flow rate decreased, CO\textsubscript{2} emissions from dry ice sublimation became more pronounced and dominated the total CO\textsubscript{2} emissions from the project.
2. As the number of traffic lanes or vehicular flow rate increased, the fuel consumption from the dry ice blasting method was consistently lower. At 8 lanes of traffic and 12,000 vehicle/lane/day, dry ice blasting was 10% lower than water jetting and about 7% lower than sand blasting.

Considering the amount of CO\textsubscript{2} emitted, the surface preparation method using sand blasting may be the most environmentally conscious option. If project duration, fuel and energy consumption, and volume of debris are of importance, then the dry ice blasting method may be a better alternative. In urban projects where significant traffic disruptions are anticipated, surface preparation using sand blasting may be the better option. Although dry ice blasting does yield more carbon dioxide emissions, it may be a preferred alternative for use on bridges located near delicate ecosystems, or where the use of containment measures would be difficult to implement. Water jetting appears to be a suitable intermediate option between dry ice and sand blasting. Of course, this assumes that the structural rehabilitation requirements can be achieved using the specified blasting media. Further analyses and studies may encompass economic considerations and statistical variations.

REFERENCES


