In-Depth Survey Report

CONTROL TECHNOLOGY FOR DOWEL-PIN DRILLING IN CONCRETE PAVEMENT

ALAN ECHT, MPH, CIH; CAPTAIN, U.S. PUBLIC HEALTH SERVICE

KENNETH MEAD, PhD, PE; CAPTAIN, U.S. PUBLIC HEALTH SERVICE

H. AMY FENG, MS

DANIEL FARWICK

Division of Applied Research and Technology
Engineering and Physical Hazards Branch
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Surveys Conducted By:

Alan Echt, Industrial Hygienist

Kenneth Mead, Mechanical Engineer

H. Amy Feng, Statistician (Health)

Daniel Farwick, Engineering Technician

Employer Representatives Contacted:

Troy Kingan, Engineering / Production Supervisor

(419) 524-1000

Todd Jurjevic, Sales / Service / Marketing

(419) 524-1000

Employee Representatives: No Employee Representatives

Analytical Work Performed by: Bureau Veritas North America

Disclaimer

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Abstract

This study evaluated the ability of a commercially-available dust-control system to reduce respirable dust emissions during dowel drilling. Dowel drilling is a task performed during new concrete runway and highway construction (e.g., when a lane is added) or during full-depth repair of concrete pavement to provide load transfer across transverse pavement joints. Dowel drilling machines typically contain one or more pneumatic or hydraulic percussion drills aligned in parallel in a frame that acts to control drill alignment and prevent wandering. The dust control evaluated in this report included a close-capture hood surrounding each of the steels and bits at the work surface, a length of corrugated flexible hose connected to each hood, and dust collectors at the back of the dowel drill unit. Compared with the use of no dust control during dowel drilling in concrete, the dust-control system significantly ($p<0.0001$) reduced geometric mean respirable dust mass concentrations by 89% to 92% when measured with filter samples. Arithmetic mean respirable dust concentrations measured on filters were significantly ($p<0.0001$) reduced 88% to 90% by the use of the dust control system. The use of the dust control also significantly reduced respirable dust emissions ($p<0.0001$) by 86% to 88% when measured with a nephelometer. The different measurement techniques probably account for the disparity in results obtained with filter samples and the nephelometers. The measurements were conducted in a tent to exclude diesel exhaust particulate emitted by the compressor used to power the dowel-pin drill and isolate the drill from the effects of wind and weather during the tests. The use of this technique means that it would not be appropriate to compare the results to any exposure indices. Recommendations are offered at the end of the report to improve the system. These include recommending that the manufacturer consider installing a pressure gauge across each filter in the dust collectors to provide the drill operator with information needed to determine when to clean or change the filter.

Introduction

Background for Control Technology Studies

The National Institute for Occupational Safety and Health (NIOSH) is the primary Federal agency engaged in occupational safety and health research. Located in the Department of Health and Human Services, it was established by the Occupational Safety and Health Act of 1970. This legislation mandated NIOSH to conduct a number of research and education programs separate from the standard setting and enforcement functions carried out by the Occupational Safety and Health Administration (OSHA) in the Department of Labor. An important area of NIOSH research deals with methods for controlling occupational exposure to potential chemical and physical hazards. The Engineering and Physical Hazards Branch (EPHB) of the Division of Applied Research and Technology has been given the lead within NIOSH to study the engineering aspects of health hazard prevention and control.

Since 1976, EPHB has conducted a number of assessments of health hazard control technology on the basis of industry, common industrial process, or specific control techniques. Examples of these completed studies include the foundry industry; various chemical manufacturing or processing operations; spray painting; and the recirculation of exhaust air. The objective of each of these studies has been to document and evaluate effective control techniques for potential health hazards in the industry or process of interest, and to create a more general awareness of the need for or availability of an effective system of hazard control measures.

These studies involve a number of steps or phases. Initially, a series of walk-through surveys is conducted to select plants or processes with effective and potentially transferable control concept techniques. Next, in-depth surveys are conducted to determine both the control parameters and the effectiveness of these controls. The reports from these in-depth surveys are then used as a basis for preparing technical reports and journal articles on effective hazard control measures. Ultimately, the information from these research activities builds the data base of publicly available information on hazard control techniques for use by health professionals who are responsible for preventing occupational illness and injury.

Background for this Study

Crystalline silica refers to a group of minerals composed of silicon and oxygen; a crystalline structure is one in which the atoms are arranged in a repeating three-dimensional pattern [Bureau of Mines 1992]. The three major forms of crystalline silica are quartz, cristobalite, and tridymite; quartz is the most common form [Bureau of Mines 1992]. Respirable crystalline silica refers to that portion of airborne crystalline silica dust that is capable of entering the gas-exchange regions of the lungs if inhaled; this includes particles with aerodynamic diameters less than approximately 10 micrometers (µm) [NIOSH 2002]. Silicosis, a fibrotic disease of the lungs, is an occupational respiratory disease caused by the inhalation and deposition of respirable crystalline silica dust [NIOSH 1986]. Silicosis is irreversible, often progressive (even after exposure has ceased), and potentially fatal. Because no effective treatment exists for silicosis, prevention through exposure control is essential.

Crystalline silica is a constituent of several materials commonly used in construction, including brick, block, and concrete. Many construction tasks have been associated with overexposure to dust containing crystalline silica [Chisholm 1999, Flanagan et al. 2003, Rappaport et al. 2003, Woskie et al. 2002]. Among these tasks are tuckpointing, concrete cutting, concrete grinding, abrasive blasting, and road milling [Nash and Williams 2000, Thorpe et al. 1999, Akbar-Kanzadeh and Brillhart 2002, Glindmeyer and Hammad 1988, Linch 2002, Rappaport et al. 2003]. Highway construction tasks that have been associated with silica exposures include jackhammer use, concrete sawing, milling asphalt and concrete pavement, clean-up using compressed air, and dowel drilling [Valiante et al. 2004]. Linch [2002] also identified dowel drills as sources of dust emissions on highway construction sites.

Dowel-pin drilling machines (or dowel drilling machines) are used to drill horizontal holes in concrete pavement. Steel dowels transfer loads between adjacent concrete pavement slabs [Park et al. 2008]. They are typically used in “transverse joints in rigid airport and highway pavement to transfer shear from a heavily loaded slab to an adjacent less heavily loaded slab” [Bush and Mannava 2000]. Typical dowel-pin drilling machines have one or more drills held parallel in a frame that aligns the drills and controls wandering [FHWA 2006]. The dowel-pin drilling machine may be self propelled or boom mounted, and may ride on the slab or on the subbase [FHWA 2006]. After drilling to a typical depth of 22.9 centimeters (cm) (9 inches (in)) (the diameter is determined by the use of cement-based grout or epoxy anchoring formulations), the hole is cleaned with a compressed air nozzle, the anchoring material is placed, and the dowel is installed [FHWA 2006].

The study by Valiante et al. [2004] reported that dowel drilling respirable crystalline silica exposures ranged from 0.05 milligrams per cubic meter (mg/m^3) to 0.16 mg/m^3, 8-hour (hr) time weighted average (TWA). Linch [2002] also documented silica exposures during dowel drilling. The Linch [2002] study reported 8-hr TWA quartz exposures for an operator and laborer using a boom-mounted dowel drilling machine. The operator’s 8-hr TWA exposure ranged from less than the limit of detection to 0.11 mg/m^3, with a geometric mean respirable crystalline silica exposure of 0.037 mg/m^3 for 8 samples. The highest result was 2.2 times the NIOSH Recommended Exposure Limit (REL) for crystalline silica of 50 micrograms per cubic meter (µg/m^3). The laborer’s 8-hr TWA respirable crystalline silica exposures ranged from 0.12 -1.3 mg/m^3 (2.4 – 26 times the NIOSH REL), with a geometric mean of 0.24 mg/m^3 (4.8 times the NIOSH REL) for 8 samples. Linch [2002] concluded his study of dowel drilling exposures with this statement:

> Means of controlling the respirable dust generated from concrete drilling during all operations needs to be developed, tested, and employed. Pneumatic drilling is the common method of drilling concrete pavement. Methods of using small amounts of water through the drill stem should be developed for these specific applications. High-velocity dust collection systems that effectively control respirable dust should be tested and made available.

There are only two American manufacturers of dowel-pin drills. Both manufacturers offer optional dust control systems for their machines. The manufacturers both make local exhaust ventilation (LEV) dust control systems to capture the dust generated by the dowel drilling process. In addition, they both sell water kits to suppress the dust that results from drilling holes for dowels. One manufacturer's water kit supplies water through the drill steel, while the other manufacturer's water kit sprays water on the surface to be drilled. This study aims to evaluate the effectiveness of current dust controls for dowel-pin drilling machines, work with manufacturers to improve dust controls if necessary, and promote the use of tools with dust controls.

Two approaches are planned to evaluate the effectiveness of current dust controls. The first will measure respirable dust emissions from dowel drilling machines in a controlled setting, isolated from the effects of wind, weather, and other sources of particulate, assessing the effectiveness of the controls in reducing emissions. Emissions with and without the use of controls will be compared. The second approach will assess personal respirable dust and respirable crystalline silica exposures of workers operating dowel drilling machines with dust controls in place in a real-world setting to determine the ability of the dust controls to limit exposures.

Background for this survey

In this survey, performed at the equipment manufacturer's factory, we sought to quantify the relative extent to which the LEV dust control system was able to reduce respirable dust emissions from a dowel drilling machine in a controlled setting. The LEV system utilized close-capture hoods (known as the "dust collector drill guide assembly") that surrounded the drill steels and bits and were in close contact with the concrete substrate. The dust was conveyed from the hoods to a dust collection system utilizing flexible corrugated hose. The dust collectors utilized pneumatic eductors (known as "transfer pumps") to provide suction and filtered the air prior to discharge to the atmosphere.

Plant and Process Description

Introduction

Minnich Manufacturing is located in Mansfield, Ohio. In addition to dowel pin drills, Minnich makes concrete vibrators, concrete paving vibrators and vibrator monitoring systems. Founded in 1968, Minnich began making dowel pin drills in

1985. The company manufactures pneumatically and hydraulically powered drills. A variety of models are produced, ranging from single drills to five-gang drills. Minnich produces manual, self propelled, and equipment-mounted (e.g., backhoes, skid steer loaders) machines. Each drill is tested on a slab behind the factory before it is shipped to a customer.

Process Description

The dowel drilling machine tested was a Minnich model A-5SCW five-drill, remote-control, self-propelled, on-slab unit. Throughout this study, the machine used "H" thread steels (22 millimeters (mm) (⅞-in) by 108 mm (4¼-in) shank, 61 centimeters (cm) (24-in) under collar) and 41 mm (1⅝-in) diameter bits (Brunner and Lay, Springdale, AR). Figure 1 shows the bit and steel used in this study. The drills (pneumatic rock drills) cause the steel and bit to rotate and impact to produce the desired hole in the concrete. The selection of the drill bit and steel was left to the manufacturer. While the type of bit and steel may influence dust generation, the study was not designed to compare one manufacturer's dust control with another. As long as the same bit and steel type was used for both "control on" and "control off" trials, the experimental design is adequate for determining the relative effectiveness of the dust control system.

Methodology

Sampling Strategy

The aim of this survey was to determine the relative reduction in respirable dust emissions achieved through the use of the LEV system. This reduction was measured by comparing the respirable dust emissions when the LEV system was in operation ("control on") with the respirable dust emissions when the LEV system was not in operation ("control off"). In order to measure this reduction, trials of the dowel drilling machine dust control were conducted in sampling rounds consisting of two paired trials in each sampling round – one "control on" trial and one "control off" trial. The order of the trials was randomized within each sampling round. Real-time and on-filter dust samples were collected during each trial.

Each dowel-pin drilling machine trial consisted of using a five-gang dowel-pin drilling machine (Model A-5SCW, Minnich Mfg. Co., Mansfield, OH) equipped with a wireless remote control to drill holes in blocks of concrete laid on their long side in the outdoor testing area behind the Minnich Manufacturing facility located in Mansfield, OH. The dowel-pin drilling machine was placed on top of a 1.8 meter (m) (6-foot (ft)) by 3 m (9¾-ft) concrete pad. A row of three solid blocks of 20,684 kilopascals (kPa) (3,000 pounds/square-inch (psi)) concrete 51 cm (20-in) wide by 91 cm (36-in) long by 28 cm (11-in) high (Moritz Concrete, Inc., Mansfield, OH) were placed against the front of the concrete pad (Figure 2). The blocks were poured on June 1, 2010. The pneumatically-powered dowel-pin drilling machine was maneuvered on the pad in order to drill four or five new 41 mm (1⅝-in) diameter holes for each trial. The dowel-pin drilling machine was positioned in order to avoid drilling a hole in a joint between the blocks. It was also placed so that none of the close-capture hoods in use covered a joint or a portion of an existing hole. These spacing requirements sometimes prohibited the use of all five drills. However, the same number of holes (either 4 or 5) were consistently drilled within each half of a "control-on"/"control-off" pair. The position of the dowel-pin drilling machine was also adjusted in order to place the hoods in contact with the surface of the concrete block. Blocks were replaced as needed to continue the tests. The dowel-pin drilling machine could be driven from side to side and steered, and the array of drills raised or lowered as a unit. Each of the drills was capable of being switched on or off independently of the others. For all test runs, the pneumatic air discharge outlets on the bottom of each drill were oriented away from the concrete surface. This was done to reduce the potential of the discharge air to aerosolize concrete dust and affect the sampling results. The dowel-pin drilling machine and its dust collectors were powered by a 21.2 m^3/min (750 cubic feet per minute (cfm)) diesel-powered air compressor (IR 750, Ingersoll-Rand, Mocksville, NC).

In order to conduct the evaluation in a controlled environment, free from the effects of the wind and to minimize interference from diesel exhaust particulate, the dowel-pin drilling machine, slab and blocks were placed inside a tent (10 x 20 Garage - Unicage, Item No. MAC-GAR04, MAC-Automotive, Inc. Laverne, CA) equipped with a roll-up front door that could be closed with two zippers. Polyethylene sheeting (0.1 mm (4-mil), Film-Gard, Covalence Plastics, Minneapolis, MN) was duct-taped to the bottom of the side and rear walls to reduce air infiltration and to inhibit dust from escaping. The bottom edge of the polyethylene sheeting was held to the ground using two lengths of metal chain ballast (9.5 mm (⅜-in) by 9.1 m (30-ft) grade 43 zinc-plated chain, Hi-Test Chain, Crown Bolt, Aliso Viejo, CA).

Sampling Procedures

Respirable dust emission concentrations under the "control on" and "control off" conditions were assessed using Personal Dataram (Model pDR-1000AN, Thermo Electron Corp., Franklin, MA) instruments. The pDR is nephelometer that uses light scattering to produce a measure of dust over a size range of 0.1-10 µm and a concentration range of 0.001 to 400 mg/m^3. These readings are relative to a gravimetric calibration performed by the manufacturer in mg/m^3 using standard SAE fine (ISO fine) test dust. For this study, the pDRs were programmed to record the average dust concentration once every second.

Respirable dust samples were collected using pre-weighed 37-mm diameter, 5-µm pore size polyvinyl chloride filters in 3-piece cassettes and Higgins-Dewell type respirable dust cyclones (Model 4L, BGI, Inc., Waltham, MA). The front cover of the filter cassette was removed and the open-faced cassette was connected to the cyclone. The outlet of the filter cassette was connected to a length of flexible tubing using a tapered Leur-type fitting. The other end of the tubing was connected to a battery-powered personal sampling pump (Aircheck Sampler model 224, SKC, Inc., Eighty Four, Pennsylvania) calibrated to a flow rate of 2.2 liters/minute. Samples were collected and analyzed according to NIOSH Method 0600 (respirable dust).

Each pDR and air sampling pump with cyclone and filter were placed in tripod-mounted brackets approximately 1.5 m (60-in) above grade (either the ground or the concrete pad) to sample at personal breathing zone height (Figure 3). The tripods were placed at three locations: in front of the dowel drilling machine, next to the operator's position, and adjacent to the dust collector behind the dowel drilling machine. A reference point was marked on the center of the top panel of the dowel drilling machine to orient the tripods so that they could be easily repositioned before each trial. The tripod in front of the dowel drilling machine was aligned with the center of the drilling array and placed about 2.5 m (97-in) in front of the mark on the center panel. The tripod to the left of the dowel-pin drilling machine was placed 61 cm (24-in) from the mark. The tripod behind the dowel drilling machine was aligned with center of the middle dust collector and placed about 1.5 m (60-in) to the rear of the center of the dowel drilling machine which was 61 cm (24-in) behind the exhaust outlet riser on the middle dust collector.

Measurement Of Control Parameters

Exhaust air and bailing air flow rates were measured using a Sierra Instruments, Inc. (Monterey, CA) model 730-N5-1 fast response in-line mass flow meter (range 0-2.83 m^3/min (0-100 cfm)). A Sierra Instruments, Inc. Model 904M Flo-Box was used to read the signal from the meter. Bailing air flushes the cuttings out of the drill hole. It is conveyed through the hollow steel and an outlet in the bit.

Bailing air was measured using the mass flow meter. To conduct the measurement, a sampling tube was created to contain and channel the bailing air into the mass flow meter. The large end of a 10 cm (4-in) to 7.6 cm (3-in) PVC-DWV Schedule 40 adapter was slipped onto to the rubber outer tube on the exhaust hood on the number 5 drill (duct tape was used to make the connection secure and reasonably air tight). The small end of the adapter was connected to a 61 cm (2-ft) length of 7.6 cm (3-in) diameter PVC-DWV Schedule 40 pipe. This length of pipe surrounded the drill steel and bit and allowed them to move freely. The length of 7.6 cm (3-in) diameter pipe was connected to a 7.6 cm (3-in) to 5 cm (2-in) PVC-DWV Schedule 40 adapter. This adapter was connected to a 30 cm (12-in) long piece of 5 cm (2-in) diameter PVC-DWV Schedule 40 pipe. A threaded 5 cm (2-in) to 5 cm (2-in) adapter connected the assembly to the inlet of the mass flow meter. A second threaded adapter connected the mass flow meter outlet to a 27 cm (10½-in) long piece of PVC-DWV Schedule 40 pipe. The sampling tube assembly is shown in Figure 4. Bailing air flow measurements were made at the number 5 drill position, with the drill running but the exhaust air system off.

Exhaust air flow measurements were made in three ways. First, the same sampling tube assembly was used in the same position as above except the mass flow meter was reversed to align properly with the direction of the air flow. For this measurement, the drill was off and the exhaust system was running.

Second, the flow meter was placed in line between the exhaust hose from the number 5 drill and the number 3 dust collector (Figure 5). This required an extended straight inlet into the duct collector. A 5 cm (2-in) to 5 cm (2-in) flexible coupling (Model RC 50, American Valve, Greensboro, NC) was used to attach a 30 cm (12-in) long piece of PVC-DWV Schedule 40 pipe to the dust collector inlet. A threaded 5 cm (2-in) to 5 cm (2-in) adapter connected the pipe to the outlet of the mass flow meter. A second threaded 5 cm (2-in) to 5 cm (2-in) adapter was connected to the inlet of the mass flow meter. This adaptor was attached to a 27 cm (10½-in) long piece of PVC-DWV Schedule 40 pipe. A second 5 cm (2-in) to 5 cm (2-in) flexible coupling was used to connect this pipe to the flexible exhaust hose. The number 3 dust collector serves the hoods on the number 4 and 5 drills. While both hoods were connected to the collector, only the flow from the hood on the number 5 drill was measured. The hood on the number 4 drill was in tight contact with the concrete block surface.

The third set of measurements was made at the number 3 dust collector at the inlet for the number 5 drill (Figure 6). This also required an extended straight inlet to properly accommodate the flow meter. A 5 cm (2-in) to 5 cm (2-in) flexible coupling (Model RC 50, American Valve, Greensboro, NC) was used to attach a 30 cm (12-in) long piece of PVC-DWV Schedule 40 pipe to the dust collector inlet. A threaded 5 cm (2-in) to 5 cm (2-in) adapter connected the pipe to the outlet of the mass flow meter. A second threaded 5 cm (2-in) to 5 cm (2-in) adapter was connected to the inlet of the mass flow meter. This adaptor was attached to a 27 cm (10½-in) long piece of PVC-DWV Schedule 40 pipe. The other end of the pipe was open to the atmosphere. The hood on the number 4 drill was in contact with the concrete block surface.

Test Procedure

For a given trial, the drills were positioned on the blocks. The NIOSH researchers started the data collection period with each of the samplers and recorded the sampling start time. The NIOSH researchers lowered the tent door and closed its zippers. A Minnich employee started the dowel drilling machine from outside the tent using the wireless remote control. The NIOSH researchers recorded the drill start time. The drills shut off automatically and withdrew from the holes after reaching a pre-set depth of 34.3 cm (13½) inches. The NIOSH researchers recorded the last drill stop time. The NIOSH researchers waited five minutes after the last drill stopped. They donned half-facepiece dual-cartridge respirators with HEPA filters, unzipped and raised the tent door, entered the tent and stopped the data collection period for each of the samplers. The NIOSH researchers recorded the sampling stop time. Next, they opened the front tent door and raised the tent flap in the right rear corner and installed a 76 cm (30-in) fan (Maxx Air High Velocity, Ventamatic, Ltd., Mineral Wells, TX) to push air into the tent. They continued to purge the tent until the respirable dust concentration fell below 0.05 mg/m^3 (equal to the NIOSH REL for crystalline silica) as indicated by a handheld pDR temporarily located on top of the dowel drilling machine's center panel. Once the concentration had dropped to this level, Minnich personnel entered the tent and repositioned the dowel drilling machine for the next test. The NIOSH researchers then moved the samplers to the designated positions relative to the dowel drilling machine, attached new filter cassettes to the cyclones, removed the fan and re-sealed the tent flap, and repeated the process. For the "control off" trials, the exhaust hose was physically disconnected from each hood by loosening a screw, moving a clamp, and sliding the hose off the hood connection. After each control-off trial, visible concrete dust which had fallen to the ground beneath each drill was removed so as not to be a source of aerosolized dust during future trials. Five rounds of sampling were conducted in this manner on June 15, 2010 and two and a half rounds of sampling were conducted on June 16, 2010. The half round resulted when one set of "control on" trials was repeated and replaced the "control on" trials in round 6 when it was noted that the number 2 drill hood clogged because a NIOSH scientist connected it incorrectly.

Statistical Methods

Study variables included location (center, front, and rear) and control condition ("control on" and "control off"), and respirable dust measurements. The pDR and respirable dust on filter samples measure the respirable fraction directly. Data collection using both dust sampling methods (respirable dust on filters and pDR) was started shortly before the drills started and stopped approximately five minutes after the last drill stopped. However, difference in the pDR instrument response and the type of data collected required the creation of an algorithm for those data to determine the range of data (in time) to be included in the analyses. For example, the pDR automatically calculates the average respirable dust concentration during the sampling period. However, since the data collection began before the drills started, that average includes the background dust concentration in the tent for the period between the sample start and the drill start, plus the time required for the dust concentration to reach a steady response. In order to exclude those data from the analyses, for the pDR data analyses the initial time for each analysis was determined by finding the time the dust concentration first rose 2 mg/m^3 above baseline and adding 1 minute to that time. The four minutes of data after that point were included in the analyses. The dust on filter results were corrected for field and laboratory blank values. In three cases, the result was less than the limit of detection (LOD) of 40 µg/sample. For those three results, that LOD divided by the square root of 2 ($LOD/\sqrt{2}$) was used in place of the sample mass to calculate the dust concentration [Hornung and Reed 1990].

For each data series, the logarithm was calculated for each value of the data sets defined above. The arithmetic mean of the log values was then computed. These mean values were used for analyses, including calculating the geometric means and geometric medians of the data, and for mixed model analyses.

Geometric means for each location and control condition were calculated. The geometric mean reduction ratio (1-geometric mean "control on"/geometric mean "control off') was also calculated. SAS version 9.2 (SAS Institute Inc., Cary, NC) was used to analyze the data. The mixed model procedure was used to estimate the lower 95% confidence limit for the reduction ratio.

Control Technology

The application of the control principles used by Minnich Manufacturing for dowel-pin drilling is discussed below. LEV systems “operate on the principle of capturing a contaminant at or near its source” [ACGIH 2010]. Four components make up a typical LEV system: the hood(s), duct(s), an air cleaner, and a fan [ACGIH 2010]. The hood(s) collects the contaminant, which is produced in an air stream directed toward the hood. Duct(s) convey the contaminant and air to the air cleaner. The air cleaner removes the contaminant from the airstream. The fan must produce the desired air flow despite losses due to friction, fittings, and hood entry [ACGIH 2010].

Description Of The Engineering Control Technology

Each of the steels and bits was surrounded by a close-capture hood at the work surface (Figure 7). Each hood take-off was attached to a length of 5 cm (2-in) diameter corrugated flexible hose (the interior surface is corrugated as well). The other end of the hose was attached to a dust collector at the back of the dowel drill unit (Figure 8). There were five hoods and three dust collectors on the unit tested, hoods 1 and 2 were attached to the dust collector on the left, hood 3 was connected to the middle dust collector, and hoods 4 and 5 were served by the dust collector on the right. Suction is provided by a pneumatic transfer pump. There are two each on the left and right dust collector and one on the center dust collector. A 2-in deep pleated Merv 13 cartridge filter (P/N P148646-016-340, Donaldson Company, Inc., Bloomington, MN) in each dust collector traps the dust captured by the hood and transported to the collector through the hose. The dust build-up collected on the filter falls into a catch can at the bottom of the dust collector for disposal. A reverse pulse system is used to remove the dust build up.

The Model A-5SCW dowel-pin drill is equipped with a wireless remote control. The operator’s controls and platform have been removed from the machine. This allows the operator to stand away from the drill while it is operating.

Results

Sampling Results From Dowel-Pin Drilling

The study was performed in about a day and a half utilizing the tent described above. The goal was to assess the effectiveness of the dust controls by comparing emissions measured during “control on” and “control off” trials. There were 7 rounds of sampling included in the data analyses. Data were collected in three locations, in both "control on" and "control off" trials. This resulted in the analysis of 42 filter samples and 42 sets of pDR data.

Ventilation Measurements

The average bailing air flow was 23 cfm at the number 5 drill. The average exhaust air flow at the exhaust hood of the number 5 drill was 39 cfm. The average exhaust air flow at the number 3 dust collector with the flow meter in line between the exhaust hose and the dust collector was 57 cfm. The average exhaust air flow at the number 3 dust collector with the exhaust hose disconnected was 82 cfm.

Respirable Dust Filter Sampling Results

The results of the respirable dust samples collected on filter cassettes are presented in Table 1. For the three respirable dust results less than the LOD of 40 µg/sample, the representative estimated concentration was calculated by using a value of the LOD/√2 in the numerator and the sample volume in the denominator [Hornung and Reed 1990]. The "control on" results ranged from a low of 1.6 mg/m^3 to a high of 12 mg/m^3. The "control off" results ranged from 39 mg/m^3 to 70 mg/m^3. Table 2 provides measures of central tendency for the respirable dust samples by location and test condition (i.e., "control on" and "control off"). The mean respirable dust concentration during "control on" trials ranged from 5.3 mg/m^3 at the rear to 7.3 mg/m^3 in the front sampling location. The geometric mean of the "control on" respirable dust samples ranged from 4.7 mg/m^3 at the center to 6.6 mg/m^3 in front of the drill array. The "control off" arithmetic means were 54 mg/m^3 at the rear and 60 mg/m^3 at the other two locations. The "control off" geometric mean respirable dust concentrations were 59 mg/m^3 at the front and center sampling locations and 53 mg/m^3 at the rear of the machine.

Table 3 reports the reductions in respirable dust emissions measured at each sampling location. Comparison of the geometric means resulted in an 89% reduction at the front, a 91% reduction at the rear, and a 92% reduction at the center sampling position. Using the arithmetic means for comparison resulted in a 90% reduction in emissions at the rear and center samplers and an 88% reduction at the front position. Table 4 shows the lower 95% confidence limit for the reduction based on a mixed model. These ranged from 83% at the front to 88% at the center sampling location ($p<0.0001$). This result means that if the test were repeated, in 95% of the repeated tests, the observed reduction will be greater than or equal to that lower limit (but in 5% of the tests, it will not be).

Direct-Reading Respirable Dust Mass Results

Table 1 presents the pDR results for each trial, including the average concentration calculated by the instruments and the concentration used for the subsequent analyses. Table 5 reports several results from the pDR data. For the "control on" condition, the geometric mean of the arithmetic means of the logarithms of the measured respirable dust concentrations ranged from 12.0 mg/m^3 at the front to 13.9 mg/m^3 at the center. During "control off" testing, the range for that statistic was 94.1 mg/m^3 at the front of the drill to 112.1 mg/m^3 at the center sampling location. The geometric median of the arithmetic means of the logarithms of the respirable dust concentrations ranged from 11.6 mg/m^3 at the rear to 13.5 mg/m^3 at the center for the “control on” results and from 90.2 mg/m^3 at the front to 110.8 mg/m^3 at the center for the “control off” measurements.

Table 6 shows the emission reductions achieved through the use of the dust control. The effectiveness is expressed as the reduction in the geometric median and geometric mean respirable dust concentrations measured with the pDRs. These ranged from 86.4% at the rear to 87.6% at the center sampling location. The differences in the mean log concentration between the “control on” and “control off” conditions was statistically significant ($p<0.0001$). Table 7 provides the lower 95% confidence limit for the reduction based on a mixed model for the pDR data. These ranged from 82% at the rear to 84% at the center sampling location ($p<0.0001$).

Discussion

This study was not designed to compare the manufacturers’ controls, and the results should not be used for that purpose. The results reflect the dust emissions from the machine in a controlled environment, and should not be compared to occupational exposure limits. In addition to the effects of wind and weather on a construction site, personal exposures are influenced by work practices, the aerodynamic effects of placing the sampler on a worker, the non-uniform distribution of dust in the workplace air, and other factors.

Ventilation testing results show that the ratio of exhaust air flow to bailing air flow was 1.7:1 at the hood for drill number 5. This value is relatively close to the lowest ratio (2:1) identified by Page et al. [2008] that was shown to respond positively to decreases in shroud leakage area for a large rock drill. Since the Minnich shroud design appeared to have tight contact with the drilled surface, it is believed to similarly benefit from the low leakage area design. The Page et al. [2008] study further showed that significant improvements (contaminant concentration reductions exceeding 60% and 90%) for already tight-fitting shrouds could also be obtained by increasing the ratio of exhaust air flow to bailing air flow from 2:1 to 3:1 or even 4:1.

The observed decrease in the exhaust air flow as measured at the collector (82 cfm) compared to the hood (39 cfm) is likely due to the way the flow was measured at the collector, where the presence of the long straight inlet at the collector (see Figure 5) aerodynamically improved the collector’s inlet airflow characteristics. This difference in inlet airflow conditions can be seen by comparing the bends in the hoses in the background of Figure 5 to the straightened flow imposed by the measurement technique. Removing those bends by using a straight length of pipe is believed to be responsible for the difference. This result illustrates the performance value in minimizing the bends and length of the hose, using smooth-walled (preferably rigid) duct, and increasing the length of the straight inlet pipe into the collector.

The velocity of 1788 feet per minute (fpm) (based on a flow rate of 39 cfm through a 2-in diameter duct) may not be sufficient to prevent concrete dust from settling in the duct and reducing flow or plugging the duct. ACGIH [2010] recommends a duct velocity of 3500 to 4000 fpm for dusts such as granite dust, limestone dust, brick cutting, and clay dust. However, the repeated flexing of the duct that occurs when the drills are raised and lowered coupled with the turbulence in the flexible duct may act to prevent plugging at the lower transport velocity. Use of a smooth-walled duct would reduce the clogging potential. Installation of suction pressure indicators near the hood inlet could also serve to warn the operator of the development and presence of clogs. Monitoring customer reports of plugged ducts or reduced system performance should determine if clogging due to settling is a problem.

The results of this study demonstrate that the evaluated dust control system was very effective. Respirable dust samples collected on filters show that it was capable of reducing respirable dust emissions by as much as 92% (from 89% to 92%) as shown in Table 3 and is predicted to be capable of reducing respirable dust emission concentrations by at least 83% (from 83% to 88%) during repeated tests (Table 4).

Comparing the mass data from the filter samples and the pDR results in Table 1 reveals a slight discrepancy between the results depending upon the method used. The filter data provides a direct and reliable means to assess the difference in emissions between “control on” and “control off,” but those data include the period before the drill started. Comparing the pDR data in the next column with the filter data shows that the pDR tends to overestimate the dust concentration in comparison with the filter data, but not by a consistent ratio. Wu et al. [2005], citing their data and three previous studies, report that the pDR is on average 1.5 times higher than co-located gravimetric measurements. However the ability to edit the pDR data to exclude the period before the drills started makes the pDR data a useful measure for “control on” “control off” comparisons. The pDR is calibrated using standard SAE fine (ISO fine) test dust, while this study measured concrete dust, which may in part explain the discrepancy on individual trial results. The pDR’s manufacturer recommends performing a “field gravimetric calibration” to correct the individual pDR concentrations. This is accomplished by multiplying individual pDR data points by the ratio of the gravimetric concentration to the average pDR concentration. However, studies have shown that samples collected side-by-side can vary, so this correction was not carried out with the data in this study [Kauffer et al. 2010, Werner et al. 1996]. This correction was also not performed because the design of this study compares the dust measured with the “control on” with the dust measured with the “control off,” so it is the relationship between those measures that is of interest. Applying the same correction factor to both the numerator and denominator of such a ratio does not affect the result.

Conclusions and Recommendations

The dust control system functioned very effectively. Compared with the use of no dust control during dowel drilling in concrete, the dust-control system significantly ($p<0.0001$) reduced geometric mean respirable dust mass concentrations by 89% to 92% when measured with filter samples. Arithmetic mean respirable dust concentrations measured on filters were significantly ($p<0.0001$) reduced 88% to 90% by the use of the dust control system. The use of the dust control also significantly reduced respirable dust emissions ($p<0.0001$) by 86% to 88% when measured with a nephelometer. While these results should not be compared with occupational exposure limits, they indicate that the dust control system tested should be effective in reducing exposures. Actual occupational exposure measurements must be conducted at dowel drilling work sites with the dust control in use to assess whether or not the reductions result in exposures below applicable occupational exposure limits. Those occupational exposure measurements will also be collected as a future part of this study.

The ventilation system's duct velocity may be too low to prevent dust settling and plugging of the ducts. The manufacturer should be alert to reports from customers about plugged ducts or decreased duct collection system performance. If problems with settling emerge, the transport velocity can be increased somewhat by installing rigid and/or smooth-walled ductwork to the extent possible in place of the flexible corrugated hose. The material selected should be durable enough to withstand the abrasive nature of concrete dust. Increasing the length of straight-duct into the dust collector may also be worth investigating. The length of duct and number of elbows should be kept to a minimum. Another step to take to increase the transport velocity, if needed, is to increase the system's volumetric flow rate. Consider installing a pressure gauge across each filter in the dust collectors to provide the drill operator with information needed to determine when to clean or change the filter. The filter manufacturer should be able to provide the reference data needed to provide this information. Consider installing static pressure taps near the duct connection to each hood that can be connected to vacuum gauges on the operator's instrument panel. These taps would be used to measure the "hood static pressure" which is a valuable monitoring metric that can be used to determine if the dust collecting system is working properly. Measuring the hood static pressure when the system is working as designed can provide the baseline value for future comparison. Finally, consider extending the discharge outlets from the dust collectors to aid in the dispersal of any emissions. If desired, NIOSH can provide more detailed guidance on how to implement these recommendations.

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Table 1 – Respirable Dust Results

Round	Position	Control Condition	Respirable Dust on Filters (µg/sample)	Sample Duration (minutes)	Pump Sample Volume (L)	Respirable Dust on Filters (mg/m^3)	pDR Overall Average (mg/m^3)	pDR Average Used for Analyses (mg/m^3)	Notes
1	Front	on	(55)	0:08	17.2	3.2	4.9	5.5	5 drills running
1	Front	off	790	0:06	12.9	61	83	80	5 drills running
1	Rear	on	ND	0:08	17.2	1.6	5.4	6.8	5 drills running
1	Rear	off	760	0:06	12.9	59	70	96	5 drills running
1	Center	on	ND	0:08	17.6	1.6	6.1	8.1	5 drills running
1	Center	off	820	0:06	13.2	62	100	128	5 drills running
2	Front	on	(110)	0:06	13.2	8.3	15	16	5 drills running
2	Front	off	730	0:07	15.4	48	70	81	5 drills running
2	Rear	on	(85)	0:06	12.9	6.6	14	14	5 drills running
2	Rear	off	720	0:07	15.1	48	67	87	5 drills running
2	Center	on	(95)	0:06	12.9	7.4	17	18	5 drills running
2	Center	off	760	0:07	15.1	51	84	109	5 drills running
3	Front	off	730	0:07	15.4	48	64	79	4 drills:1,2,4,5
3	Front	on	(130)	0:06	13.2	9.9	17	20	4 drills:1,2,4,5
3	Rear	off	580	0:07	15.1	39	51	70	4 drills:1,2,4,5
3	Rear	on	(65)	0:06	12.9	5.0	20	21	4 drills:1,2,4,5
3	Center	off	760	0:07	15.1	50	78	111	4 drills:1,2,4,5
3	Center	on	150	0:06	12.9	12	26	29	4 drills:1,2,4,5
4	Front	off	1100	0:07	15.1	73	95	102	4 drills:2,3,4,5
4	Front	on	140	0:06	12.9	11	16	14	4 drills:1,2,4,5
4	Rear	off	1000	0:07	15.4	65	85	113	4 drills:2,3,4,5
4	Rear	on	(110)	0:06	13.2	8.3	17	18	4 drills:1,2,4,5
4	Center	off	1200	0:07	15.2	79	123	155	4 drills:2,3,4,5
4	Center	on	150	0:06	13.0	12	18	19	4 drills:1,2,4,5

Round	Position	Control Condition	Respirable Dust on Filters (µg/sample)	Sample Duration (minutes)	Pump Sample Volume (L)	Respirable Dust on Filters (mg/m^3)	pDR Overall Average (mg/m^3)	pDR Average Used for Analyses (mg/m^3)	Notes
5	Front	on	(110)	0:07	15.1	7.3	10	10	4 drills:1,2,4,5
5	Front	off	940	0:06	12.9	73	100	105	4 drills:2,3,4,5
5	Rear	on	(110)	0:07	15.4	7.2	11	12	4 drills:1,2,4,5
5	Rear	off	940	0:06	13.2	71	104	116	4 drills:2,3,4,5
5	Center	on	ND	0:07	15.2	1.9	9.4	9.7	4 drills:1,2,4,5
5	Center	off	880	0:06	13.0	68	103	107	4 drills:2,3,4,5
6	Front	off	830	0:07	15.6	53	87	105	4 drills:1,2,4,5
6	Front	on	45	0:07	15.6	2.9	8.7	10	4 drills:1,2,4,5
6	Rear	off	740	0:07	15.5	48	76	90	4 drills:1,2,4,5
6	Rear	on	55	0:07	15.5	3.5	9.2	10	4 drills:1,2,4,5
6	Center	off	800	0:07	15.5	52	75	85	4 drills:1,2,4,5
6	Center	on	55	0:07	15.5	3.5	8.9	10	4 drills:1,2,4,5
7	Front	off	950	0:07	15.6	61	99	113	4 drills:2,3,4,5
7	Front	on	(120)	0:06	13.3	9.0	15	14	4 drills:1,2,4,5
7	Rear	off	790	0:07	15.5	51	94	110	4 drills:2,3,4,5
7	Rear	on	(65)	0:06	13.3	4.9	15	15	4 drills:1,2,4,5
7	Center	off	860	0:07	15.5	55	85	101	4 drills:2,3,4,5
7	Center	on	(65)	0:06	13.3	4.9	13	12	4 drills:1,2,4,5

Notes: ND indicates a result less than the limit of detection of 40 µg/sample. Numbers in parentheses indicate a result between the limit of detection and the limit of quantitation of 130 µg/sample.

Table 2 – Respirable Dust on Filter Concentrations by Location and Test Condition

Location	Control	Number of Trials	Arithmetic Mean (mg/m^3)	Standard Deviation (mg/m^3)	Geometric Mean (mg/m^3)	Geometric Standard Deviation (mg/m^3)
Center	off	7	60	11	59	1.2
Center	on	7	6.1	4.2	4.7	2.2
Front	off	7	60	11	59	1.2
Front	on	7	7.3	3.1	6.6	1.7
Rear	off	7	54	11	53	1.2
Rear	on	7	5.3	2.3	4.8	1.7

Table 3 – Geometric Mean Reduction Ratios for Respirable Dust on Filter Results

Location	Geometric Mean Control On (mg/m^3)	Arithmetic Mean Control On (mg/m^3)	Geometric Mean Control Off (mg/m^3)	Arithmetic Mean Control Off (mg/m^3)	Percent Reduction from Geometric Means	Percent Reduction from Arithmetic Means
Center	4.7	6.1	59	60	92	90
Front	6.6	7.3	59	60	89	88
Rear	4.8	5.3	53	54	91	90

Table 4 – Estimated Lower Reduction Limit from Mixed Model for Respirable Dust on Filters

Location	Estimate	Standard Error	Degrees of Freedom	t-value	Probability	Lower Reduction Limit (percent)
Center	-2.5	0.25	16	-10	<0.0001	88
Front	-2.2	0.25	16	-8.9	<0.0001	83
Rear	-2.4	0.25	16	-9.8	<0.0001	86

Table 5 – pDR Respirable Dust Concentrations by Location and Test Condition

Location	Control	Number of Trials	Geometric Mean of Arithmetic Means of Log Concentration (mg/m^3)	Geometric Standard Deviation of Arithmetic Means of Log Concentration (mg/m^3)	Geometric Mean of Arithmetic Medians of Log Concentration (mg/m^3)	Geometric Standard Deviation of Arithmetic Medians of Log Concentration (mg/m^3)
Center	off	7	112	1.21	111	1.20
Center	on	7	13.9	1.57	13.5	1.56
Front	off	7	94.1	1.17	90.2	1.20
Front	on	7	12.0	1.51	11.6	1.55
Rear	off	7	96.1	1.20	93.0	1.22
Rear	on	7	13.0	1.46	12.7	1.47

Table 6 – Reduction Ratios for pDR Respirable Dust Results

Location	Geometric Mean Control On Median (mg/m^3)	Geometric Mean Control On Mean (mg/m^3)	Geometric Mean Control Off Median (mg/m^3)	Geometric Mean Control Off Mean (mg/m^3)	Percent Reduction from Geometric Mean of Arithmetic Medians	Percent Reduction from Geometric Mean of Arithmetic Means
Center	13.5	13.9	111	112	87.8	87.6
Front	11.6	12.0	90.2	94.1	87.2	87.3
Rear	12.7	13.0	93.0	96.1	86.4	86.4

Table 7 – Estimated Lower Reduction Limit from Mixed Model for pDR Respirable Dust Results

Location	Estimate	Standard Error	Degrees of Freedom	t-value	Probability	Lower Reduction Limit (percent)
Center	-2.1	0.16	12	-13	<0.0001	84
Front	-2.1	0.16	12	-13	<0.0001	83
Rear	-2.0	0.16	12	-13	<0.0001	82

Figure 1 - "H" Thread Steels and 1 ⅝-in Diameter Bits Were Used in this Study

Figure 2 - Holes Were Drilled in Three Solid Concrete Blocks Placed in Front of a Concrete Slab

Figure 3 - Samplers Were Placed at Breathing Zone Height

Figure 4 - Set Up for Measuring Bailing Air Flow and Exhaust Air Flow at the Hood

Figure 5 - Exhaust Air Flow was also Measured with the Meter in Line Between the Hood and the Dust Collector

Figure 6 - Measuring Air Flow at the Dust Collector

Figure 7 - A Hood Surrounds Each Steel and Bit

Figure 8- Dust Collectors are Mounted on the Back of the Machine

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