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Effective Dust Control Systems on Concrete Dowel Drilling Machinery

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Abstract

Rotary-type percussion dowel drilling machines, which drill horizontal holes in concrete pavement, have been documented to produce respirable crystalline silica concentrations above recommended exposure criteria. This places operators at potential risk for developing health effects from exposure. United States manufacturers of these machines offer optional dust control systems. The effectiveness of the dust control systems to reduce respirable dust concentrations on two types of drilling machines was evaluated under controlled conditions with the machines operating inside large tent structures in an effort to eliminate secondary exposure sources not related to the dowel-drilling operation. Area air samples were collected at breathing zone height at three locations around each machine. Through equal numbers of sampling rounds with the control systems randomly selected to be on or off, the control systems were found to significantly reduce respirable dust concentrations from a geometric mean of 54 mg per cubic meter to 3.0 mg per cubic meter on one machine and 57 mg per cubic meter to 5.3 mg per cubic meter on the other machine. This research shows that the dust control systems can dramatically reduce respirable dust concentrations by over 90% under controlled conditions. However, these systems need to be evaluated under actual work conditions to determine their effectiveness in reducing worker exposures to crystalline silica below hazardous levels.

Keywords

Concrete dowel drilling; crystalline silica; dust control systems; respirable dust

Introduction

Dowel drilling machines are used to drill horizontal holes in concrete pavement during full-depth repair of highway pavement or new airport runway construction. Dowel drilling using rotary-type core drills or rotary- type percussion drills is required during runway construction in the United States by the Federal Aviation Administration.[1] Steel dowels

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transfer shear loads between adjacent concrete pavement slabs in highways and runways.[2,3] Typical dowel drilling machines have one or more pneumatically powered rock drills held parallel in a frame that aligns the drills and controls wandering.[4] The dowel drilling machine may be self-propelled or boom mounted, and may ride on the slab or on the sub-base.[4] After drilling to a typical depth of 23 cm into the side of the existing slab, the anchoring material is placed, and the dowel is installed. Approximately half of the dowel's length remains exposed. The diameter of the hole is determined by the dowel diameter and whether cement-based grout or an epoxy compound is used to anchor the dowels.[4] Figure 1 shows dowel drilling on an airport runway without dust control.

Construction and repair of concrete pavement involves runways, bridges, streets, and highways. Highway construction tasks associated with respirable dust and crystalline silica exposures include jackhammer use, concrete sawing, milling asphalt and concrete pavement, clean-up using compressed air, and dowel drilling.[5] Linch[6] also identified dowel drills as sources of dust emissions on highway construction sites.

Silicosis, a fibrotic disease of the lungs, is an occupational respiratory disease caused by the inhalation and deposition of respirable crystalline silica (RCS) dust.[7] 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. Exposure to RCS is also associated with autoimmune disorders, kidney disease, and lung cancer.[8]

The National Institute for Occupational Safety and Health (NIOSH) Recommended Exposure Limit (REL) for RCS is 0.05 mg/m^3 as a time weighted average (TWA) determined during a full-shift sample for up to a 10-hr workday during a 40-hr workweek to reduce the risk of developing silicosis, lung cancer, and other adverse health effects.[8] When source controls cannot keep exposures below the NIOSH REL, "NIOSH also recommends minimizing the risk of illness that remains for workers exposed at the REL by substituting less hazardous materials for crystalline silica when feasible, by using appropriate respiratory protection …, and by making medical examinations available to exposed workers."[8] The American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Value (TLV) for α-quartz and cristobalite (respirable fraction) is 0.025 mg/m^3 as an 8-hr TWA.[9] On March 25, 2016, the Occupational Safety and Health Administration published their final rule on occupational exposure to respirable crystalline silica, which included a Permissible Exposure Limit (PEL) of 0.05 mg/m^3 as an 8-hr TWA.[10]

Valiante et al.[5] reported that RCS exposures for workers using single-drill on-slab dowel drills ranged from 0.05 mg per cubic meter (mg/m^3) to 0.16 mg/m^3, 8-hr TWA. Linch [6] reported 8-hr TWA RCS exposures for operators and laborers using boom-mounted three-drill dowel drilling machines. The operators' 8-hr TWA exposures ranged from less than the minimum detectable concentration of 0.029 mg/m^3 up to a concentration of 0.11 mg/m^3, with a geometric mean (GM) RCS exposure of 0.037 mg/m^3 (n = 8). The laborers' 8-hr TWA RCS exposures ranged from 0.12–1.3 mg/m^3 with a GM of 0.24 mg/m^3 (n = 8). When boom-mounted dowel drills are used, the operator typically sits in the cab of the backhoe to maneuver the boom, and the laborer stands next to the dowel drill to operate it. That difference in positions (i.e., the length of the boom) likely explains the difference in exposures between the two job classifications. Linch[6] concluded that controls for the respirable dust generated from concrete drilling during all operations need to be developed, tested, and used.

There are only two U.S. manufacturers of dowel drilling machines. Both of those manufacturers offer dust control systems as optional equipment and 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 during drilling. One manufacturer's water kit supplies water through the drill steel, while the other's sprays water on the surface to be drilled.

The dust control systems on the dowel drills, like many LEV systems, consist of hoods, ducts, air cleaners, and air movers.[11] On the dowel drill, the hoods attach to a frame supporting the rock drill. The hoods surround the steel and bit to create a temporary enclosure around their interface with the work surface. The concrete dust is collected in an air stream directed toward the hood through the use of compressed air that flows through the steel and out through an orifice on the bit. Exhaust air flowing through flexible ducts captures and conveys the dust and air to the air cleaner where it is filtered from the airstream. To prevent clogging, the air mover must produce sufficient air flow to carry the dust despite energy losses due to friction in the ducts, fittings, bends, and hood entry.[11]

The testing procedure used in this study utilized a field-portable method incorporating a large tent that could accommodate the machinery and its dust control system, the concrete to be drilled, and instrumentation for measuring dust emissions. The aim of this study was to determine the relative reduction in respirable dust emissions achieved through the use of the LEV dust control system. This is the first study to systematically evaluate dust controls for large dowel drilling machines.

Methods

Process description

Two dowel drilling machines were tested in this study. One was a four-drill, self-propelled, on-slab unit. The machine used 2.2 cm diameter whirlibits (Brunner and Lay, Springdale, AR) to drill holes 46 cm deep. The other was a five-drill, remote-control, self-propelled, on-slab unit. That machine used "H" thread steels and 4.1 cm diameter bits (Brunner and Lay, Springdale, AR) to drill holes to a depth of 34.3 cm.

On both machines, the drills (rotary-type pneumatic rock drills) cause the bit to rotate and impact to produce the desired hole in the concrete. The drill steel is hollow; air flows through the center of the steel and through an orifice (or orifices) in the bit to flush the cuttings from the hole as it is drilled.

The selection of the depth of the hole, drill bit, and steel was left to the manufacturer based upon their typical post-production tests. 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 of a given dowel drill, the experimental design is adequate for determining the relative effectiveness of the dust control system.

The four-drill machine was placed on top of a 25-cm thick slab of 24 megapascal (MPa) concrete (Perry Ready Mix, Perry, OK). The dowel drilling machine was maneuvered on the slab to drill four new 22-mm diameter holes for each trial. The dowel drilling machine was positioned so that none of the close-capture hoods in use covered a portion of an existing hole. On the second day of the evaluation, the hoods were also positioned to avoid any spalling around previously-drilled holes. The position of the dowel drilling machine was adjusted to place the hoods in close contact with the surface of the concrete. The drill advanced along the length of the slab as needed to continue the tests.

The five-drill machine was placed on top of a 1.8 m by 3 m concrete pad. A row of three solid blocks of 21 MPa concrete 51 cm wide by 91 cm long by 28 cm high (Moritz Concrete, Inc., Mansfield, OH) were placed against the front of the concrete pad. The dowel drilling machine was maneuvered on the pad to drill four or five new 41-mm diameter holes for each trial. The dowel drilling machine was positioned 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 four or five) were consistently drilled within each half of a "control-on"/"control-off" pair. The position of the dowel-pin drilling machine was also adjusted to place the hoods in contact with the surface of the concrete block. Blocks were replaced as needed to continue the tests.

Experimental set-up and conditions

The relative reduction in respirable dust emissions was measured by comparing the respirable dust emissions when the LEV system was in operation ("control on") with the respirable dust emissions when that system was not in operation ("control off"). To measure this reduction, the equipment was operated 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. The equipment was operated in the same manner in each trial. Respirable dust samples were collected during each trial.

In each dowel drilling machine trial, holes were drilled in concrete at outdoor testing areas behind the manufacturer's facility. To conduct the evaluation in a controlled environment, free from the effects of the wind and to minimize interference from diesel exhaust particulate from the air compressor that powered the drills, the dowel-drilling machines were placed inside a tent (10 × 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, Film-Gard, Covalence Plastics, Minneapolis, MN) was duct-taped to the bottom of the side and rear walls of the tent to reduce air infiltration and inhibit dust from escaping. The bottom edge of the polyethylene sheeting was held to the ground using lengths of metal chain at one site and lumber at the other site.

Sampling procedures

Respirable dust samples were collected using preweighed 37-mm diameter, 5-µm pore size polyvinyl chloride filters in three-piece cassettes and Higgins-Dewell type respirable dust cyclones (Model BGI-4L, Mesa Labs, Inc., Butler, NJ). 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 Luer-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 L/min before and after each day of sampling. Field blanks were collected at a rate of one blank for every ten samples. Sample results were corrected by subtracting the average mass of the field blanks for that set.

Samples were collected and analyzed according to NIOSH Method 0600 (particulates not otherwise regulated, respirable).[22] The filters were allowed to equilibrate for a minimum of 2 hr before weighing. A static neutralizer was placed in front of the balance (model AT201, Mettler-Toledo, Columbus, OH), and each filter was passed over the neutralizer before weighing. At manufacturer 1, the limit of detection (LOD) was 50 µg/sample, and the limit of quantitation (LOQ) was 160 µg/sample. At manufacturer 2, the LOD was 40 µg/sample and the LOQ was 130 µg/sample.

Each air sampling pump with the attached cyclone and filter was placed in tripod-mounted brackets approximately 1.5 m above ground level to sample at personal breathing zone height. The tripods were placed at three locations: in front of the dowel drilling machine, at the side of the machine near the control panel, and at the rear of the machine adjacent to the dust collector. Because of the size of the tent and the size of the machinery, the positions differed somewhat at each of the two sites. For example, there was room behind the five-drill machine to position a tripod behind the dust collector, while the tripod had to be placed to the side of the dust collector when testing the four-drill machine.

Test procedure

For each trial, the drills were positioned on the concrete to be drilled. The samplers were started, and the sampling start times were recorded. The tent door was lowered, and the zippers were closed. The drilling machine was started from outside the tent by remote control. The automated operation of the machinery precluded the need to place an operator inside the tent with the dowel drilling machine. Machines with multiple drills were tested based on the assumption that it would be more challenging to control dust emissions from the larger units. The drilling start time was recorded. The drills shut off automatically and withdrew from the holes after reaching a preset depth. The last drill stop time was recorded. Five minutes after the last drill stopped, the tent door was unzipped. The samplers were stopped, and the stop time was recorded. Only a single set of holes was drilled during each trial.

Following each trial, the tent door and a tent flap in the right rear corner were raised. A 76-cm diameter fan (Maxx Air High Velocity, Ventamatic, Ltd., Mineral Wells, TX) was placed in the right rear corner to push air into the tent. The tent was purged until the respirable dust mass concentration fell below 0.05 mg/m^3 (equal to the NIOSH recommended exposure limit for crystalline silica)[8] as indicated by a portable nephelometer-type respirable dust monitor placed on top of the dowel drilling machine's center panel. Once the concentration had dropped to this level, manufacturer personnel entered the tent and repositioned the dowel drilling machine for the next test. The samplers were placed in the designated positions relative to the new dowel drilling machine position and new filter cassettes were attached to the cyclones. The fan was removed, the tent flap lowered and sealed, and the process was repeated.

Sample size calculations

Sample size calculations were performed on the basis of the relative standard deviation of the results of a pilot study and a reduction in emissions of at least 75%.[23] Using a one-sided test for a log-normal distribution, a split-plot design, control vs. no-control, it was determined that at least four test rounds were required to achieve a power of 0.80 and 95% confidence.[24] Four test rounds conducted with a sample collected at each of three locations under each condition meant that 24 samples in total were collected: 12 with the control on, and 12 with the control off.

Statistical methods

All data analyses were performed using SAS 9.2 statistical software (SAS Institute Inc., Cary, NC). The univariate procedure was used to evaluate the distribution for lognormality. The results confirmed that the data were lognormally distributed. The respirable dust concentrations were transformed to their natural logarithms (ln), and analyses were conducted using the ln concentration as the dependent variable. Study variables included company, location (side, front, and rear), and control condition ("control on" and "control off"), and respirable dust measurements (dependent variable).

The respirable dust mass results were corrected for average blank values. After blank correction, for test sample results less than the limit of detection, the LOD divided by the square root of 2 (LOD/SQRT 2) was used in place of the sample mass to calculate the dust concentration based upon the geometric standard deviation of the data.[25]

GM dust concentrations for each sampling location and control condition were calculated. The GM reduction ratio (1-GM "control on"/GM "control off") was also calculated to determine the effectiveness of the dust control. T-tests were used to evaluate the hypothesis that the mean emissions with dust controls did not equal the mean emissions without dust controls. The general linear model procedure was used to construct a model of the emissions.

Results

A total of 90 respirable dust samples were collected at both manufacturers. Forty-eight respirable dust samples were collected at manufacturer 1 during eight rounds of sampling in three locations: 24 samples with the controls "on" and 24 samples with controls "off." Three rounds of sampling were conducted on the first day at manufacturer 1, and five rounds of sampling were conducted on the second day. Sampling times ranged from 6–9 min. Fourteen samples were below the LOD and 10 samples were between the LOD and LOQ at manufacturer 1. All of those samples were collected with the dust control in operation.

At manufacturer 2, 42 samples were collected during seven rounds of sampling in three locations over two days; 21 samples with controls “on” and 21 samples with controls “off.” Six rounds of sampling were conducted on the first day, and one and a half rounds of sampling were conducted on the second day. The “control-on” half of round 6 was repeated on the second day and replaced the data collected on the first day after it was noted that the number 2 drill hood clogged because it was attached incorrectly before the “control-on” trial. Sampling times ranged from 6–8 min. Three samples were less than the LOD and 12 were between the LOD and LOQ. All of those samples were collected with the control “on.”

A summary of the results of the dust measurements with controls “off” and “on” are presented in Table 1. The results show that dust levels were dramatically reduced when control measures were used. Overall, a highly significant average drop of over 50 mg/m^3 occurred in airborne dust levels with the control devices operational. Similar results were obtained for both dowel drilling machines evaluated when controls were used, with a significant ($p < 0.0001$) reduction in GM dust levels. Overall, the emissions without the dust control in use were 14 times greater than when the control was used. In other words, the dust control reduced emissions by 93%.

Analysis using the general linear model procedure showed that the location of the sample was not significant ($p = 0.3488$), but control measures significantly reduced dust levels ($p < 0.0001$).

Discussion

Current research on the effectiveness of engineering controls for dust in construction is carried out using a variety of testing protocols.[12–17] Tests are typically conducted in a laboratory, at a worker training facility, at a worksite, or using some combination of those locations. The dust controls tested are a mix of those sold as after-market add-ons, those offered by original equipment manufacturers, and controls built in the employer’s shop or by the researcher. Exposures may be evaluated over a full shift or during repeated performance of a task, with the controls on and off to assess the performance of the dust control. Each approach has advantages and disadvantages. However, as a result of this mixed approach to evaluation, it is difficult for tool users and purchasers seeking effective silica dust controls to make informed purchasing decisions about tools and controls beyond the few tested. It is also difficult to evaluate dust controls for large pieces of construction equipment in a systematic way. Mead et al.[18] used a tracer-gas technique to measure the effectiveness of LEV systems on hot-mix asphalt pavers. Fitz and Bumiller[19] evaluated the emission rate of particulate matter from different street sweeper types using a ventilated tent open at both ends, with sand spread on the floor.

A test protocol was developed based upon one currently used in Germany and pioneered in Sweden.[20,21] Those test methods permit the tools to be tested as a system that includes the tool, material to be worked, expendables (bits, grinding wheels, etc.), and the dust control system. The German and Swedish investigators evaluated the emissions from a variety of hand-held construction tools with and without dust controls. The tools in those studies were used by a skilled operator in a room that included the measuring instrumentation, tools, dust controls, and stock (e.g., concrete, brick). Their approach tested the effectiveness of the dust control under what could be described as worst-case conditions.

The results of this study demonstrated that the evaluated dust control systems were very effective at reducing the amount of dust generated by the drills. The control systems were capable of reducing respirable dust emissions by 93% overall. The study was not designed to compare the manufacturers' controls, and the results should not be used for that purpose. Furthermore, 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 worker, 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. Actual occupational exposure measurements while the drills are used at concrete paving sites with the dust control in use must be collected to assess whether or not the reductions quantified in this study result in exposures below applicable occupational exposure limits.

The short sampling times utilized in this study led to some limitations. While the sampling times were governed by the short time required to drill a set of holes, the Higgins-Dewell type cyclones used in this study resulted in a number of samples less than the LOD due to their lower collection volume. These cyclones were selected to avoid overloading the samples during the "control-off" tests. The use of a higher flow cyclone, such as the BGI GK2.69 (Mesa Labs, Inc., Butler, NJ) at 4.2 L/min would have nearly doubled the sample volume in the same sampling period, but the higher volume samplers could have increased the potential for overloading in the "control-off" tests. Alternatively, the samples could have been allowed to run longer than 5 minutes after the drills stopped. The short-term trials also limited the ability to assess the performance of the dust controls over a whole shift, when issues such as clogged ducts due to insufficient transport velocity might have become apparent. While the tent was closed during the tests, and an attempt was made to limit air infiltration and prevent dust from escaping, the tent was not airtight, which might have introduced some error. In addition, while the tent was purged between tests, the tent, slab, and drills were not cleaned between tests, which may have resulted in dust being re-suspended during the tests. That might have added some positive bias to both the "control-on" and "control-off" results.

Conclusions

This laboratory study of dowel drilling dust controls successfully demonstrated the utility of an expedient method of evaluating the effectiveness of dust controls on construction equipment by enclosing the equipment in a tent and measuring emissions with the controls on and off. While the results cannot be compared to exposure limits, the control parameters associated with the emissions measurements can serve as a benchmark to improve the performance of the controls. The ease of using this method makes the process of testing improved controls to optimize their performance much easier than using exposure studies to do so.

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Figure 1.
Dowel drilling without dust control on an airport runway.

Table I

Summary Respirable Dust Concentrations by Manufacturer Comparing Drills with Dust Controls Off Versus On

	Number of Samples	Geometric Mean (mg/m^3)	Geometric Standard Deviation	GM 95% CI	Range (mg/m^3)	p-Value
			Manufacturer 1			
Control OFF	24	54	1.3	48.6 – 60.0	30 – 82	<0.0001
Control ON	24	3.0	1.5	2.6 – 3.5	<LOD – 6.0	
			Manufacturer 2			
Control OFF	21	57	1.2	52.7 – 61.6	39 – 79	<0.0001
Control ON	21	5.3	1.9	4.0 – 7.0	<LOD – 12	
			Overall			
Controls OFF	45	55	1.3	50.9 – 59.4	30 – 82	<0.0001
Controls ON	45	3.9	1.8	3.3 – 4.6	<LOD – 12	