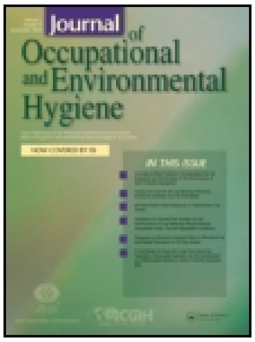

Journal of Occupational and Environmental Hygiene

ISSN: 1545-9624 (Print) 1545-9632 (Online) Journal homepage: https://www.tandfonline.com/loi/uoeh20

Effectiveness of Dust Control Methods for Crystalline Silica and Respirable Suspended Particulate Matter Exposure During Manual Concrete Surface Grinding

Farhang Akbar-Khanzadeh , Sheryl A. Milz , Cynthia D. Wagner , Michael S. Bisesi , April L. Ames , Sadik Khuder , Pam Susi & Mahboubeh Akbar-Khanzadeh

To cite this article: Farhang Akbar-Khanzadeh , Sheryl A. Milz , Cynthia D. Wagner , Michael S. Bisesi , April L. Ames , Sadik Khuder , Pam Susi & Mahboubeh Akbar-Khanzadeh (2010) Effectiveness of Dust Control Methods for Crystalline Silica and Respirable Suspended Particulate Matter Exposure During Manual Concrete Surface Grinding, Journal of Occupational and Environmental Hygiene, 7:12, 700-711, DOI: 10.1080/15459624.2010.527552

To link to this article: https://doi.org/10.1080/15459624.2010.527552

Published online: 02 Nov 2010.

Journal of Occupational and Environmental Hygiene, 7: 700–711
ISSN: 1545-9624 print / 1545-9632 online

DOI: 10.1080/15459624.2010.527552

Effectiveness of Dust Control Methods for Crystalline Silica and Respirable Suspended Particulate Matter Exposure During Manual Concrete Surface Grinding

Farhang Akbar-Khanzadeh,[1] Sheryl A. Milz,[1] Cynthia D. Wagner,[1] Michael S. Bisesi,[1] April L. Ames,[1] Sadik Khuder,[1] Pam Susi,[2] and Mahboubeh Akbar-Khanzadeh[1]

[1]University of Toledo, Department of Public Health & Preventive Medicine, Toledo, Ohio
[2]CPWR, The Center for Construction Research and Training, Silver Spring, Maryland

Concrete grinding exposes workers to unacceptable levels of crystalline silica dust, known to cause diseases such as silicosis and possibly lung cancer. This study examined the influence of major factors of exposure and effectiveness of existing dust control methods by simulating field concrete grinding in an enclosed workplace laboratory. Air was monitored during 201 concrete grinding sessions while using a variety of grinders, accessories, and existing dust control methods, including general ventilation (GV), local exhaust ventilation (LEV), and wet grinding. Task-specific geometric mean (GM) of respirable crystalline silica dust concentrations (mg/m^3) for LEV:HEPA-, LEV:Shop-vac-, wet-, and uncontrolled-grinding, while GV was off/on, were 0.17/0.09, 0.57/0.13, 1.11/0.44, and 23.1/6.80, respectively. Silica dust concentrations (mg/m^3) using 100–125 mm (4–5 inch) and 180 mm (7 inch) grinding cups were 0.53/0.22 and 2.43/0.56, respectively. GM concentrations of silica dust were significantly lower for (1) GV on (66.0%) vs. off, and (2) LEV:HEPA- (99.0%), LEV:Shop-vac- (98.1%) or wet- (94.4%) vs. uncontrolled-grinding. Task-specific GM of respirable suspended particulate matter (RSP) concentrations (mg/m^3) for LEV:HEPA-, LEV:Shop-vac-, wet-, and uncontrolled grinding, while GV was off/on, were 1.58/0.63, 7.20/1.15, 9.52/4.13, and 152/47.8, respectively. GM concentrations of RSP using 100–125 mm and 180 mm grinding cups were 4.78/1.62 and 22.2/5.06, respectively. GM concentrations of RSP were significantly lower for (1) GV on (70.2%) vs. off, and (2) LEV:HEPA- (98.9%), LEV:Shop-vac- (96.9%) or wet- (92.6%) vs. uncontrolled grinding. Silica dust and RSP were not significantly affected by (1) orientation of grinding surfaces (vertical vs. inclined); (2) water flow rates for wet grinding; (3) length of task-specific sampling time; or, (4) among cup sizes of 100, 115 or 125 mm. No combination of factors or control methods reduced an 8-hr exposure level to below the recommended criterion of 0.025 mg/m^3 for crystalline silica, requiring further refinement in engineering controls, administrative controls, or the use of respirators.

Keywords concrete grinding, construction, crystalline silica dust, dust control methods

Address correspondence to: Farhang Akbar-Khanzadeh, University of Toledo Health Science Campus, College of Medicine, MS 1027, Department of Public Health & Preventive Medicine, 3000 Arlington Ave., Toledo, OH 43614; e-mail: Farhang.Akbar@UToledo.edu.

INTRODUCTION

Concrete surface grinding (polishing, finishing) is an industrial activity commonly performed by cement masons, concrete finishers, and other construction trades. The U.S. Department of Labor Bureau of Labor Statistics[(1)] reported that in 2008 more than 201,730 workers in the United States were directly involved in concrete grinding activities to "smooth and finish surfaces of poured concrete using a variety of hand and power tools." Decorative concrete work is currently the fastest growing trend in the concrete industry, requiring an increasing number of additional workers to perform manual grinding, often in poorly ventilated and/or enclosed workplaces, which generates high levels of silica dust. Other trades that perform concrete grinding include general laborers, brick masons, block masons, and stonemasons, as well as carpet, floor and tile installers and finishers, drywall installers, ceiling tile installers and tapers, plasterers, and stucco masons.[(1)]

Workers involved in concrete grinding are potentially exposed to high levels of crystalline silica dust that sometimes exceed more than 1000 times the criterion,[(2–9)] placing these workers at risk for a variety of respiratory diseases, such as silicosis and possibly lung cancer,[(10–15)] as well as rheumatoid arthritis, scleroderma, Sjogern's syndrome, lupus, and renal disease.[(16)]

In 2006, Flanagan et al.[(3)] compiled their findings of silica dust exposure monitoring in the construction industry. They reported that concrete surface grinding was one of the activities that generated the highest levels of dust exposure, and they concluded, "more research is needed to identify the factors that produce the highest exposure so that strategies can be identified to target and control them."[(p.152)]

Many factors can influence the outcome of silica dust generation during concrete surface grinding on actual construction sites, including construction setup; the composition and silica content of concrete materials; hand-held grinder characteristics such as manufacturer, design, size, or speed; grinding cup (wheel) characteristics such as size, shape, or structure; grinder attachments such as the use of a vacuum; the intermittency and duration of grinding work time; the number of workers grinding; and workers' characteristics and their grinding techniques or work habits as well as climatic conditions such as wind velocity and direction.[(6)]

The major objectives of this current study were two-fold. The first objective was to identify and quantify major factors as they relate to respirable crystalline silica dust and respirable suspended particulate matter (RSP) exposure. This goal was achieved by selective use of general ventilation, various hand-held electric angle grinders with various grinding cup sizes, different grinding surface orientations, and different lengths of grinding sessions. The second objective was to evaluate the effectiveness of some of the currently available dust control methods. This involved retrofitting commonly used grinders with a variety of local exhaust ventilation (LEV) systems that consisted of a dust shroud and dust extraction vacuum (LEV grinding), or with a system to provide a continuous water flow to the grinding surface (wet grinding), and then comparing the exposure levels with those generated with no local dust reduction accessories (conventional uncontrolled grinding). Personal, area, and background air samples were collected during a set of preplanned grinding sessions to determine the concentrations of crystalline silica dust and RSP.

METHODS AND MATERIALS

Air Sampling Campaign

This study was designed to include concrete surface grinding sessions that crossed each option of the factors below.

- General ventilation (GV). Two options: (1) off, and (2) on.
- Concrete slab surface orientation. Two options: (1) horizontal, and (2) inclined.
- Session lengths (air sampling time periods). Three (sometimes more) different session lengths were predetermined, dependent on the type of dust control method used: (1) short, (2) medium, and (3) long air sampling sessions.
- Size of angle grinders and diameter of diamond grinding cups. Three combinations: (1) a small grinder with a 100-mm (4-in.) or 115-mm (4.5 in.) grinding cup; (2) a medium grinder with a 125-mm (5 in.) grinding cup; and (3) a large grinder with a 180-mm (7 in.) grinding cup.
- Dust control methods. Six options: (1) LEV1:HEPA-Cyclone vacuum; (2) LEV2:HEPA-Tank vacuum; (3) LEV3:Shop-vacuum; (4) Wet grinding with operator-adjusted flow rate; (5) Wet grinding with researcher-adjusted flow rate; and (6) Conventional uncontrolled grinding.

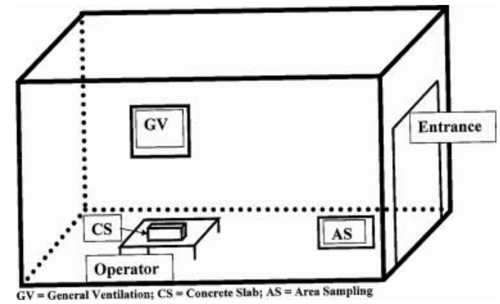

FIGURE 1. Field laboratory setup used in our study to grind concrete slab and monitor dust; a concrete slab is positioned on top a bench.

Therefore, $2 \times 2 \times 3 \times 3 \times 6 = 216$ grinding/air sampling sessions were originally planned to include 36 sessions for each of the six dust control methods. Of these, a total of 201 grinding/air sampling sessions were completed for final data analysis.

Field Laboratory

Concrete grinding activities were performed in an enclosed and relatively small workplace setting—the lab (Figure 1). The lab, created from a converted truck-wash bay within an industrial facility, measured approximately 7.32 m deep × 4.69 m tall × 5.27 m wide (24 × 15.4 × 17.3 ft). The front/south wall contained a large drive-through opening, 3.60 × 3.63 m (11.8 × 11.9 ft) that served as an entrance to the lab from the interior of the host facility. During grinding sessions, this large opening could be sealed off with a large drop-down tarp from inside the lab and plastic curtains affixed on the outside of the lab.

General Ventilation (GV)

The right/east wall of the lab contained an industrial fan connected to the lab by an air inlet opening of 81.3 ×81.3 cm (32 × 32 in.), with the center of the opening located at a height of 4.14 m (13.6 ft) from the floor and at a distance of 1.96 m (6.42 ft) from the back wall. The fan exhausted to the exterior of the facility and provided dilution (general) ventilation for the lab at a rate of 62 room exchanges/hr. The flow rate of GV was determined by using air velocity measurements (pitot tube model 8385A/8386A; TSI Inc., Shoreview, Minn.) and the method recommended by ACGIH®.[(17)] This rate was chosen to simulate a relatively high efficient GV and to rapidly clean the lab from dust pollution. The GV could be turned *on* or *off* easily by the researchers.

Concrete Slabs and Surface Orientation

Concrete slabs were selected from those originated from the flooring of the same demolition site to ensure similar age and concrete composition. A total of nine concrete slabs, each approximately 43 × 53 × 10 cm (17 × 21 × 4 in.), were ground during this study. A total of 12 bulk material samples were collected from settled concrete dust, concrete slurry, and small chips generated during concrete grinding, and analyzed for percentage silica content. During grinding, concrete slabs were placed horizontally or at an incline (almost vertical) to simulate floor grinding or wall grinding, respectively.

Session Lengths (Air Sampling Times)

Concrete grinding session lengths (air sampling time periods) were predetermined for each of the dust control methods, based on anticipated levels of dust generation. LEV grinding sessions were scheduled for 45, 60, and 90 min; wet grinding sessions for 30, 45, and 60 min; and uncontrolled grinding sessions for 5, 15, and 25 min. During each session, the operator divided his time between the task-specific concrete grinding activity inside the lab (about 10 min, on average) and resting outside the lab (usually 2 or more min), at his discretion, without changing the end time or affecting the total length of each session. Air monitoring was conducted for the entire length of each grinding session time. Task-specific grinding and break times were recorded. Generally, the operator took an additional break (up to 45 min depending on the length of the session) between any two consecutive sessions.

Concrete Grinding Equipment

Angle Grinders

Three sizes of hand-held electric angle grinders of similar type and from the same manufacturer (Metabo; Metabowerke GmbH, Nürtingen, Germany) were selected as representative of those commonly used for concrete grinding in the construction industry. A 115-mm (4.5-in.) angle grinder (model W7-115 Quick, 11,000 rpm, 8 amps) was selected as representative of the smallest commonly available angle grinder. A 150-mm (6-in.) angle grinder (model WE14-150 Quick, 9000 rpm, 8.5 amps) was selected as representative of what is most commonly used for manual concrete grinding in Northwest Ohio, where this study was conducted. A 180-mm angle grinder (model W23-180, 8500 rpm, 15 amps) was selected as representative of the largest hand-held angle grinder that is feasible to use for concrete grinding. Although angle grinders are manufactured and marketed for metal grinding, they are the preferred and most commonly used equipment for manual concrete grinding.

Concrete Grinder

The Eibenstock Concrete Grinder (model EBS 1801, 125 mm, 10,000 rpm, 16 amp; Elektrowerkzeuge GmbH, Eibenstock, Germany), with a dust collection shroud and ventilation port as an integral part of its design, was used for a few extra LEV grinding sessions. This concrete grinder is available in only one size, and it accommodates a grinding cup of 125 mm (5 in.) maximum size. This grinder represents one of a limited number of hand-held grinders that are manufactured specifically for concrete grinding.

Grinding Cup-Wheels (Cups)

Three different sizes of diamond grinding cups, each from two different manufacturers, were chosen. All the grinding cups were of a similar double-row, segmented style. From Diamond Products Inc., Helena, Montana, the Standard Gold Segmented Cup Grinders, in 100 mm (4 in., D5S-07429), 125 mm (5 in., D5S-07431), and 180 mm (7 in., D5S-07434) sizes were used. From Joe Due Blades & Equip Inc. (Mauston, Wisc.) the Double Row, Premium Cup-Wheels in 100 mm (4 in., 04-DR58), 115 mm (4.5 in., 04-DR58), and 180 mm (7 in., 04-DR58) sizes were used. The 100-mm (4-in.) grinding cups were used in the 115-mm (4.5-in.) angle grinder. The 115-mm (4.5-in.) and 125-mm (5-in.) grinding cups were used in the 150-mm (6-in.) angle grinder. The 180-mm (7-in.) grinding cups were used in the 180-mm angle grinder. These pairings were consistent with industry practice. It was necessary to use grinding cups from two different manufacturers to obtain cups of two different depths. The deeper Joe Due cups were required to function under the retrofitted dust shrouds for LEV grinding. The shallower Diamond Products cups fit under the standard wheel guards of the angle grinders for wet and conventional uncontrolled grinding, and with the Eibenstock concrete grinder (Elektrowerkzeuge GmbH).

Local Exhaust Ventilation (LEV) Equipment

Dust Shrouds

Retrofitting the angle grinders for LEV grinding was accomplished by replacing the standard metal wheel guard from each angle grinder with a heavy-duty urethane dust shroud that covered the grinding cup and provided a side outlet to which a vacuum hose was attached (Dustless Surface Grinder Assembly, Joe Due). A 125-mm urethane shroud was used on the 115-mm angle grinder to cover the 100-mm grinding cup and on the 150-mm angle grinder to cover the 115-mm and 125-mm grinding cups. The 180-mm urethane shroud was used on the 180-mm angle grinder to cover the 180-mm grinding cup.

Vacuums

Three different options of dust extraction vacuums were tested for their efficiency in local exhaust ventilation for concrete grinding: (1) a high-quality, portable, cyclone-type vacuum (model DC 2800c; Dustcontrol Inc., Wilmington, N.C.) equipped with a high-efficiency particulate air (HEPA) filter; (2) a high-quality, portable, tank-type vacuum, (Eibenstock 1500; Elektrowerkzeuge GmbH) with optional HEPA filters installed; and (3) a common shop vacuum (model 85L575; Shop-Vac Corporation, Williamsport, Pa.) equipped with a dust filter. Each vacuum was attached to the outlet of a dust shroud with the same vacuum hosing—the hosing provided with the dust shrouds—to eliminate any differences that might result from the different lengths and diameters of the hosing supplied with each vacuum.

LEV1: HEPA-Cyclone Control Method

Each of the three sizes of angle grinders were retrofitted with a heavy-duty urethane dust shroud and attached to the Dustcontrol cyclone vacuum with HEPA filter for all testing by the LEV1:HEPA-Cyclone dust control method. The high-efficiency cyclone vacuum was operated continuously during task-specific grinding time for LEV1. The reverse pulse-cleaning flap was utilized, and then the vacuum was turned off during the operator's rest times within each session. The HEPA filter was removed and cleaned on a regular basis.

LEV2: HEPA-Tank Control Method

Two different styles of grinders were studied for LEV use, both with the Eibenstock tank vacuum equipped with HEPA filters (HEPA-Tank). Metabo angle grinders, manufactured and marketed for metal grinding but commonly used for concrete grinding, were retrofitted with Joe Due heavy-duty urethane dust shrouds and used as described in the next section, LEV2a. In addition, the Eibenstock Concrete Grinder, manufactured specifically for LEV concrete grinding with a dust collection shroud and ventilation port as an integral part of its design, was used as described in LEV2b.

LEV2a: HEPA-Tank Dust Control Method

Each of the three sizes of Metabo angle grinders was retrofitted with a heavy-duty urethane dust shroud and attached to the Eibenstock tank vacuum with HEPA filters for all testing by this method. The tank vacuum was operated continuously during task-specific grinding time for LEV2a. The auto filter cleaning function was utilized, and then the vacuum was turned off during the operator's rest times within each session. The HEPA filter was removed and cleaned on a regular basis.

LEV2b: Specifically Designed Concrete Grinder Control Method

The outlet of the Eibenstock concrete grinder was attached by vacuum hosing to the Eibenstock tank vacuum with HEPA filters for eight 45-min sessions in which 100-mm and 125-mm grinding cups were used. The vacuum was maintained, and sessions were managed as described in LEV2a.

LEV3: Shop-Vac Dust Control Method

Each of the three sizes of angle grinders was retrofitted with a heavy-duty urethane dust shroud and attached to a shop vacuum for all testing by this method. The shop vacuum was operated continuously during task-specific grinding time for LEV3 sessions. Filters were cleaned and repositioned during each rest time. The entire grinder set, including the vacuum motor, was cleaned, and a new filter was installed between each LEV3 grinding session.

Wet Grinding Dust Control Method

Equipment

Retrofitting each of the three sizes of angle grinders for wet grinding was accomplished by soldering a metal nipple into a small hole that was drilled into each of the metal blade guards provided with each angle grinder. Rubber hosing fitted with an in-line valve was connected to the nipple. The in-line valve allowed the operator or the researchers to regulate the flow of water that was delivered into the wheel guard over the grinding cups, subsequently wetting the concrete.

It was necessary to wrap the grinder housing with a rubber flanged cover to protect the air intake of each grinder motor from the wet concrete slurry that was produced during wet grinding. A ground fault interrupter (GFI) was also used to protect the operator from potential electric hazard that may arise from using retrofitted electrical equipment in a wet environment.

Operator-Adjusted Water Flow Rate

Prior to each of the operator-adjusted wet grinding sessions, the operator used the in-line valve to adjust the water flow, as he would in the field, to what he considered to be the optimum flow rate. This provided the appropriate amount of water to facilitate concrete grinding. Generally, water was observed spraying out of the metal guard at the operator-adjusted flow rate. The face shield of the operator's respirator required cleaning during his rest periods within each session because of splashing concrete slurry.

Researcher-Adjusted Water Flow Rate

The procedures for wet grinding flow rate were replicated, but the water flow was reduced by the researchers to a level where there was just enough water to produce a slurry, giving the appearance of controlled visible dust but not high enough to spray freely out of the metal guard.

Conventional Uncontrolled-Grinding Method

Each of the three sizes of angle grinders was used with the corresponding size of diamond grinding cup and the standard metal wheel guard attached, for the conventional uncontrolled grinding sessions.

Operator

An operator who was recruited from those working primarily in the concrete construction industry performed all the concrete grinding. The study was reviewed and approved by the Institutional Review Board of the researchers' institution. As required by this approval, the operator's participation in the study was voluntary, and he read and signed an informed consent form.

The operator was provided with all the necessary personal protective equipment (PPE). Prior to lab activities he was familiarized with the PPE and fitted for the respirator. The operator's PPE for all sessions included a powered air-purifying respirator (PureFlo ESM; Helmet Integrated Systems Ltd., Farnborough, U.K.), Tyvek coveralls, gloves, hearing protection, and safety shoes. The operator wore a vest adapted for the correct positioning of personal monitoring devices and the protection of air sampling pumps. For the wet grinding sessions, the operator also wore a rain suit with overalls and jacket, and rubber overboots. The type of gloves worn for each session, including anti-vibration gloves, was at the operator's discretion.

To simulate actual field activity, the operator's position during grinding, whether sitting or standing, was at his discretion, as were the grinding technique, the number and length of resting times within each session, the length of each break time between sessions, and the number of grinding sessions per day.

Maintenance and Cleaning

On a regular basis, the retrofitted shrouds, grinding cups, metal wheel guards, and general ventilation filter were cleaned and the entire lab was hosed down. During wet grinding, the lab's built-in catch basin was emptied regularly. General ventilation was run between each session to avoid carryover contamination from one session to the next. The face shield of the operator's respirator and his clothing were cleaned during rest periods within each session.

Air Monitoring and Sample Analysis

Air Monitoring Instruments

Air samples were collected using a portable personal pump (Airlite, model 110-100; SKC Inc., Covington, Ga.) connected to a 37-mm aluminum cyclone (model 225-01-02; SKC). Sampling media (37-mm PVC filter in 3-stage cassette) was provided by an accredited analytical laboratory. Air sampling pumps were calibrated prior to and at the end of each session using a primary flowmeter (DryCal DC-Lite; Bios International Corporation, Butler, N.J.). An air sample was removed from further data analysis if the sampling flow rate did not post-calibrate to $\leq$5% of pre-calibration value; no sample met this criterion of removal. A calibrated sling psychrometer (model 12-7012, Bacharach Inc., New Kensington, Pa.) was used to determine ambient temperature and relative humidity inside and outside the field lab.

Air Monitoring Procedure

Personal, area, and background air samples were collected during all grinding sessions to monitor for respirable crystalline silica dust and RSP. Two sampling pump trains, with the filter and cyclone attached at the shoulders (right and left), were worn to collect replicate personal air samples. Area air samples were collected within the lab, approximately 2 m (6.6 ft) away from the operator, not in direct line between the operator and the general ventilation inlet. Sampling pumps for personal and area samples were operated for the entire length of each session regardless of whether the operator was grinding or resting, or inside or outside the lab. The task-specific grinding time was documented for each session. Outdoor air samples, used for background and quality assurance purposes, were collected each day for the entire work shift. The field blank samples, collected each day, were treated as active samples except that no air was passed through the filters.

Air Sample Collection and Analysis Methods

National Institute for Occupational Safety and Health (NIOSH) method 7500 was used to collect and analyze crystalline silica (air and bulk) samples by X-ray diffraction, and NIOSH method 0600 was used to measure RSP.(18) Air sampling filters were provided and analyzed by an accredited analytical lab.

Dust Reduction (Efficiency) Calculation

Percent dust reduction (efficiency) was calculated as "100 $[(C_{nc} - C_c)/C_{nc}]$," where C_{nc} = concentration of dust with no local dust control, and C_c = concentration of dust with local dust control.

Statistical Data Analysis

Data were compiled and analyzed using SPSS Statistical Package (version 15; SPSS Inc., Chicago, Ill.). Descriptive statistics were used to summarize and tabulate data. A t-test (or Mann-Whitney U test in nonparametric cases) was used to examine the differences between two variables. Analysis of variance (or Kruskal-Wallis test in nonparametric cases) was used to examine the differences among three or more variables; this analysis was followed by post-hoc tests. Regression analysis was used to examine the relation between certain variables. Analysis of variance (ANOVA) was performed to examine the relationships of outcomes (respirable silica dust and RSP) and existing factors.

RESULTS AND DISCUSSION

Influence of Major Factors of Concrete Grinding on Dust Exposure Levels

The main effects and significant interaction of factors (e.g., GV) vs. outcomes (e.g., RSP), as determined by using four-way ANOVA, are presented in Table I. Both respirable silica dust and RSP were significantly ($p < 0.001$) influenced by GV, grinder diameter, and dust control method and their interactions but not by the grinding surface position. All other interaction terms (not shown in the table) were not significant. Although both models were highly significant ($p < 0.001$), higher prediction was obtained in the model for RSP than in the model for respirable silica dust; almost 83% ($r^2 = 0.826$) of the variability in RSP could be explained by these factors as compared with only 73% ($r^2 = 0.735$) of the variability in respirable silica dust. Relationships between factors and outcomes are further discussed in the upcoming sections.

Air Sampling and Break Times

The session lengths (air sampling times), predetermined for each session by the researchers depending on the dust control method used, ranged from 5–90 min. Frequency and duration of breaks within each session were at the operator's discretion, simulating common practices in actual concrete grinding activities. Break times within each session ranged from 0–39 min. The task-specific (actual grinding) time within each session ranged from 5–69 min. On average, each air

TABLE I. Influence of Major Factors of Concrete Grinding on Dust Exposure Levels Using Four-Way ANOVA

Outcome	Factors	F	p
Respirable silica dust	General ventilation[A]	5.27	<0.05
	Diameter (of grinder)[B]	3.83	<0.05
	Grinding position[C]	0.97	>0.05
	Control method[D]	26.3	<0.001
	General ventilation*Control method	8.71	<0.001
	Diameter*Control method	3.21	<0.005
Respirable particulate matter (RSP)	General ventilation[A]	9.88	<0.005
	Diameter (of grinder)[B]	7.60	<0.001
	Grinding position[C]	1.40	>0.05
	Control method[D]	45.4	<0.001
	General ventilation*Control method	14.1	<0.001
	Diameter*Control method	6.13	<0.001
	General ventilation*Diameter*Control method	2.05	<0.05

[A]General ventilation: on, off.
[B]Grinder diameter: 4, 5, or 7 in.
[C]Grinding (surface) position: horizontal, vertical.
[D]Control methods: HEPA-cyclone, HEPA-tank special, HEPA-tank retrofit, wet grinding operator-adjusted, wet grinding researcher-adjusted, uncontrolled grinding.

sampling session included 76.3% actual concrete grinding time inside the lab and 23.7% rest time. Rest time occurred in noncontaminated areas outside the lab or sometimes inside the lab, with no grinding activity and with the GV on. During each data collection day, the operator worked for an approximate 7- to 9-hr work shift that, on the average, included 57.4 % time on grinding activities and 42.6% time on other related activities, such as cleaning and organizing the lab, maintaining tools, and taking major breaks.

Climatic Conditions

On average, the ambient temperature within the lab was approximately 14°C (57°F) with relative humidity of approximately 47%, with little variation during each day.

Bulk Samples

Analysis of 12 bulk samples for the nine concrete slabs had a mean (SD) of 29% (9.4%) crystalline silica (quartz) ranging from 11–43%.

Samples with Values Below the Detection Limit

Of the total 336 combined personal samples collected on the right ($n = 201$) and left ($n = 135$) shoulders of the operator, 100 (29.8%) were below detection limit for respirable crystalline silica dust, and 2 (0.6%) were below the detection limit for RSP. For samples collected during LEV, wet, and uncontrolled grinding, the number of samples below the detection limit for crystalline silica dust was 91 of 178 (51%), 8 of 82 (9.8%), and 1 of 76 (1.3%), respectively. The one below the detection limit silica sample for uncontrolled grinding was obtained for a 5-min session with general ventilation on. Each day one outdoor background sample was also collected. All background samples were below the detection limit for silica dust. Limit of detection (LOD) for either silica or RSP was 10 μg/sample. A nondetect value for a silica dust sample should not be considered as missing value or zero (since silica dust is almost everywhere); it is an unknown concentration with a value less than the analytical LOD. Each sample below the LOD was treated according to recommendations of Hornung and Reed[19] by giving a value of $10/\sqrt{2} = 7$ μg/sample. When the level of censoring is relatively high, as is the case for some measures in this study, the substitution of a fixed value (e.g., 7 μg/sample) may result in bias in the estimated mean and standard deviation.[20,21]

Replicate Samples

Statistical analysis of 135 replicate samples showed that the levels of silica dust and RSP were not significantly different between the replicate samples collected on both shoulders of a right-handed operator during LEV grinding or wet grinding. However, during uncontrolled grinding, silica dust and RSP levels were significantly ($p < 0.05$) higher for samples collected on the right shoulder than those collected on the left shoulder. For data analysis, silica dust and RSP concentrations of personal replicate samples were averaged and reported as the personal exposure values. In cases where no replicate samples were analyzed (56 for LEV grinding and 10 for wet grinding), the values of those samples collected on the right shoulder were included in the data analysis.

Area Samples vs. Personal Samples

Concentrations of silica dust and RSP of a total of 177 area samples were lower than, and significantly ($p < 0.001$) correlated with, those of the concurrently collected personal samples. The regression line between the concentrations of personal samples (PS) and area samples (AS) for silica dust was PS = 0.871 + 1.50 AS ($r^2 = 0.556$), and for RSP was PS = 2.75 + 1.62 AS ($r^2 = 0.645$). This finding indicates that the concentration of personal samples might be estimated by determining the concentration of area samples in a closed and relatively small space.

General Ventilation vs. No General Ventilation

Task-specific GM concentrations of silica dust during personal monitoring were significantly ($p < 0.005$) lower when GV was on (66.0%) than when GV was off. Task-specific GM concentrations of RSP were also significantly ($p < 0.005$) lower when GV was on (70.2%) than when GV was off.

Concrete Slab Position/Surface Orientation (Horizontal vs. Inclined Grinding)

The mean concentrations of silica dust and RSP were generally higher in the 99 samples that were collected when grinding was performed on a concrete surface in the inclined position (to simulate wall grinding) as compared with those of the 102 samples collected when grinding was performed on a concrete surface in the horizontal position (to simulate floor grinding) under the same conditions. The differences were not statistically significant; therefore, no distinction was made between concrete slab positions in the reporting of concentrations. Grinding on a surface in the inclined position was more demanding and presented greater ergonomic challenges. To overcome this problem, it was necessary to counterbalance the 180-mm grinder by using a flexible rubber support during inclined grinding sessions.

Influence of Session Times

Statistical analysis using one-way ANOVA showed no significant difference in silica dust and RSP levels in the samples obtained during short, medium, or long monitoring sessions. Therefore, all 201 sampling sessions were included in the dataset, each as an independent case, and no distinction was made between sampling times in the reporting of concentrations.

Influence of Angle Grinder and Grinding Cup Size

Grinding Cup Rotation Rate and Grinding Surface Area

The amount of dust generated by concrete surface grinding was expected to be proportional to the amount of concrete removed while grinding. This amount could be obtained by multiplying the contact surface area between the grinding media and the concrete by the rotation per minute (rpm) of the grinding cup by the depth of concrete removed in a rotation. The surface area of the grinding media would depend on the diameter of the grinding cup and the shape, width, and spacing of the grinding cup media. For this reason, all grinding cups were chosen to be of a similar double row, segmented style to limit the differences in contact area to a factor of the cup diameter. The no load rpm for each grinder varied with size: 11000 rpm for the 115-mm grinder, 9000 rpm for the 150-mm grinder, and 8500 rpm for the 180-mm grinder. The rpm varies depending on the load imposed on the grinder during its operation. Any calculation of the actual surface area per unit time would be unreliable, making it an unsuitable factor in comparing the dust generation of differently sized grinding cups. Sizes of the hand-held angle grinders were different, by necessity, to accommodate the different sizes of grinding cups. The angle grinders were chosen to be as similar as feasible in other aspects, such as manufacturer and features. Therefore, for the purpose of size comparison, diameters of the grinding cups have been used throughout this report to distinguish the three different size combinations of angle grinders and grinding cups.

Grinding Cup Size

The mean concentration of silica dust was higher when using grinders with 180-mm grinding cups than with 100 or 125 mm diameter grinding cups, but the differences did not reach the significance level ($p < 0.1$). The mean concentration of RSP was significantly ($p < 0.05$) higher when using grinders with 180-mm grinding cups than with 100 or 125 mm diameter grinding cups. The grinder with a diameter of 115 mm was not included in this data analysis because of its very small sample size; the number of samples collected using 100, 115, 125 and 180 mm diameter grinding cups was 70, 4, 64, and 63, respectively.

Since the concentrations of silica dust and RSP were not significantly different when using grinders with 100, 115, or 125 mm diameter grinding cups, for further data analysis, these three cup sizes were combined in category 100 to 125 mm and compared with those using grinder cups with 180 mm diameter.

Comparisons Among the LEV Methods

Angle Grinder Retrofitted for LEV vs. Concrete Grinder Designed for LEV

The mean concentrations of silica dust and RSP were not significantly different between the Metabo angle grinders (angle grinder retrofitted for LEV; LEV2a, n = 24) and those for the Eibenstock grinder (concrete grinder designed for LEV; LEV2b, n = 8) when used with comparably sized grinding cups. Both grinding setups were attached to the Eibenstock tank vacuum equipped with HEPA filters (HEPA-Tank).

Although the operator reported that the Eibenstock concrete grinder with vacuum (LEV2b) was much more comfortable than the Metabo angle grinder, results indicated that the effectiveness of the two setups was not statistically different. Therefore, for further statistical data analysis and reporting, the two LEV control methods, LEV2a and LEV2b, were combined into one category: LEV2: HEPA-Tank.

Comparison Between HEPA-Cyclone, HEPA-Tank, and Shop-Vac Dust Control Methods

With the GV off, the mean concentrations of silica dust and RSP collected during LEV3 (Shop-vac) grinding were significantly ($p < 0.05$) higher than those collected during either LEV1 (HEPA-Cyclone) grinding or LEV2 (HEPA-Tank) grinding. The mean concentration of silica dust and

TABLE II. Task-Specific Respirable Crystalline Silica Dust and Total Respirable Suspended Particulate (RSP) Concentrations During Surface Concrete Grinding

GV	Dust Control Method	Grinding Cup Size (mm)	N[A]	Silica Dust (mg/m^3)		RSP (mg/m^3)	
				Mean	SD	Mean	SD
Off	LEV: HEPA-cyclone and HEPA-tank	100–125	28	0.17	0.12	1.67	1.53
		180	12	0.54	0.47	5.09	3.86
	Shop vacuum	100–125	11	0.92	1.69	10.0	15.3
		180	6	1.90	1.00	22.2	11.5
	Wet grinding	100–125	17	0.96	1.50	7.79	11.1
		180	8	8.83	6.68	58.7	37.2
	Uncontrolled grinding	100–125	14	23.6	21.8	142	108
		180	6	55.3	27.7	359	126
On	LEV: HEPA-cyclone and HEPA-tank	100–125	29	0.11	0.14	0.67	0.59
		180	12	0.20	0.29	2.52	4.16
	Shop vacuum	100–12.5	13	0.12	0.08	1.19	0.90
		180	6	0.14	0.06	2.14	0.86
	Wet grinding	100–125	14	0.27	0.16	2.70	1.34
		180	7	2.08	1.32	14.0	6.86
	Uncontrolled grinding	100–125	12	5.78	3.87	39.2	22.6
		180	6	15.1	5.24	99.7	31.7

[A]N = number of samples.

RSP collected during LEV1 (HEPA-Cyclone) grinding was generally higher than those collected during LEV2 (HEPA-Tank) grinding; no statistically significant difference was observed between the two dust control methods. With the GV on, there were no significant differences in the silica dust and RSP between the three LEV control methods. Thus, the results of the samples collected during LEV1 (HEPA-Cyclone) grinding and LEV2 (HEPA-Tank) grinding were combined and reported as one control method "HEPA (Cyclone & Tank)."

Vacuum Endurance

One each of the DC 2800c Dustcontrol vacuum and accessories (HEPA-Cyclone) and the Eibenstock 1500 vacuum and accessories (HEPA-Tank) performed in all the scheduled sessions with minimal maintenance, such as clearing/changing filters between sessions and emptying the bags when full. However, the Shop-vac had to be completely cleaned between each session, the filters dislocated without moving the vacuums. Many sessions showed no dust accumulation in the tank and three sets of Shop-vacs burned out during the related grinding sessions.

Wet Grinding Water Flow Rate

According to the operator, grinding at the reduced flow rate (researcher-adjusted) was more difficult than grinding at the operator-adjusted water flow rate, and the operator stated that researcher-adjusted flow rates were not representative of field practice. Therefore, after performing 9 of the 36 intended sessions, further testing with the researcher-adjusted flow rate method was discontinued.

On average, the concentrations of silica dust and RSP were lower when the wet grinding was performed at the higher, operator-adjusted water flow rate ($n = 37$) than when it was performed at a reduced, researcher-adjusted water flow rate ($n = 9$). However, the differences were not statistically significant. For further data analysis and reporting, the two versions of wet grinding were combined and reported as "wet grinding."

Crystalline Silica Dust and RSP Concentrations

Table II and Figures 2 and 3 summarize task-specific silica dust and RSP concentrations by dust control methods, general ventilation, and grinding cup diameter sizes.

Dust Control Methods Efficiency

Overall, compared with the conventional *uncontrolled grinding*: (1) LEV (HEPA-Cyclone or HEPA-Tank) grinding reduced GM concentrations of silica dust 99.0% ($p < 0.001$) and RSP 98.9% ($p < 0.001$); (2) LEV (Shop-vac) grinding reduced GM concentrations of silica dust 98.1% ($p < 0.001$) and RSP 96.9% ($p < 0.001$); and, (3) wet grinding reduced GM concentrations of silica dust 94.4% ($p < 0.001$) and RSP 92.6% ($p < 0.001$). Compared with *wet grinding*: (1) LEV (HEPA-Cyclone or HEPA-Tank) grinding reduced GM concentrations of silica dust 83.1% ($p < 0.001$) and RSP 84.8% ($p < 0.001$); and (2) LEV (Shop-vac) grinding reduced GM concentrations of silica dust 67.2% ($p < 0.01$) and RSP 57.9% ($p < 0.01$). Compared with *LEV (Shop-vac) grinding*, the LEV (Cyclone + Tank) reduced GM concentrations of silica dust 48.4% ($p < 0.01$) and RSP 63.8% ($p < 0.001$).

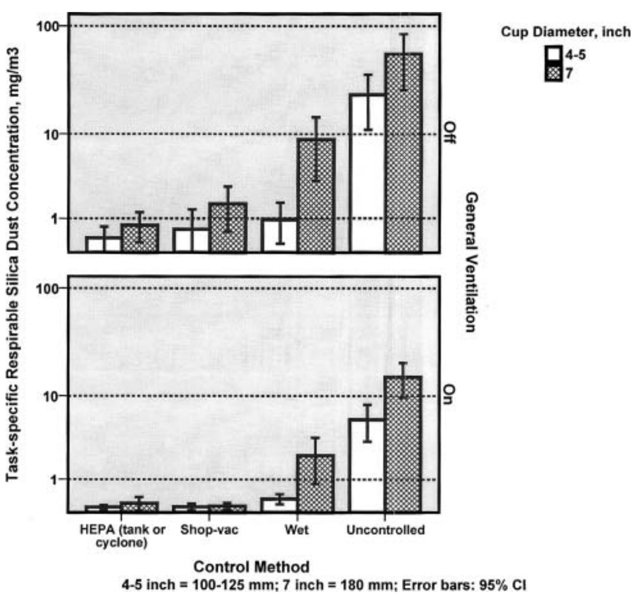

FIGURE 2. Task-specific respirable silica dust exposure levels by general ventilation, dust control method, and grinder cup diameter size; note the logarithmic scale.

Exposure Assessment

The findings of this study reveal that the application of GV, LEV grinding, or wet grinding methods can considerably reduce the concentrations of respirable crystalline silica dust and RSP generated during concrete surface grinding. However, examination of the silica dust data indicates that even minimum levels of respirable silica dust generated during grinding were still above the ACGIH[22] threshold limit value (TLV®) of 0.025 mg/m^3.

Using the ACGIH TLV as an exposure criterion and assuming that the operator's exposure lasted for an entire 8-hr shift, hand-held concrete surface grinding in enclosed workspaces (similar to our lab) would require the use of a respirator or the application of suitable administrative control regardless of GV, position of concrete surface, size of angle grinder or grinding cup, or control method applied. However, LEV-HEPA grinding with a 100- to 125-mm grinding cup may require only the use of a respirator with an assigned protection factor of 10. In agreement with our study, Nij et al.[23] concluded that to control silica dust in construction [with current technology], "the combined use of more than one dust control measure will lower the chance of over exposure."[(p.218)])

The U.S. Occupational Safety and Health Administration (OSHA) has set a permissible exposure limit (PEL) for silica dust evaluation that is defined by the equation: $PEL = (10\ mg/m^3)/(\%Si + 2)$, where %Si is the percentage of crystalline silica dust in the sample. In view of the mandated OSHA PEL, the mean concentrations of silica dust have been evaluated to determine the potential silica dust exposure for four different work-rest regimens. The compliance statuses, which OSHA mandates, are presented in Table III by general ventilation (on or off), dust control method, grinding cup diameter size, and work-rest regimen.

Comparison With Other Similar Studies

This study concluded that the efficiencies of the silica dust control methods were as follow: 66.0% for GV, 99.0% for LEV:HEPA grinding, 98.1% for LEV:Shop-vac grinding, or 94.4% for wet grinding. This study also concluded that the current control methods do not reduce silica dust to below the ACGIH-recommended silica dust exposure criteria of 0.025 mg/m^3,[22] requiring further refinement in the engineering control options.

The results of the current study confirmed and complemented the findings of our previous study.[2] The report of our pilot study in 2007 (apparently the last publication on the subject) showed 99.8% LEV and 99.2% LEV/GV efficiencies and compared its findings with five other (known to the authors) related studies published during 2002–2004.[5–7,24,25] The majority of these studies have focused on LEV grinding combined with either natural or general ventilation. Akbar-Khanzadeh and Brillhart[6] evaluated task-specific silica dust concentration during actual manual concrete grinding. Approximately 31% of the subjects used LEV grinding with an average efficiency of 73.1%. In 69% of the samples, the levels of silica dust exceeded the criteria. Echt and Sieber[24] reported on an LEV system that included a concrete grinder equipped with a ventilated shroud and demonstrated its effectiveness in reducing silica dust levels. Croteau et al.[7] studied the performance of LEV application with three ventilation airflow rates during concrete surface grinding

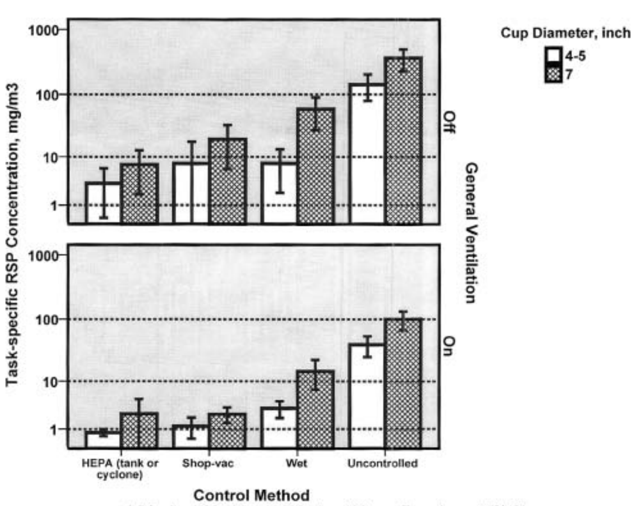

FIGURE 3. Task-specific total respirable suspended particulate (RSP) exposure levels by general ventilation, dust control method, and grinder cup diameter size; note the logarithmic scale.

TABLE III. Crystalline Silica Dust Exposure Assessment Results, Based on OSHA PEL Criteria

GV	Dust Control Method	Grinding Cup Size (mm)	N[A]	Work-Rest Regimens: 100–0 (not realistic)	50–50 (realistic, practical)	25–75 (realistic, not practical)	10–90 (realistic, practical)
Off	LEV: HEPA-cyclone and	100–125	28	○	○	○	○
	HEPA-tank	180	12	•	•	○	○
	Shop vacuum	100–125	11	•	•	○	○
		180	6	•	•	○	○
	Wet grinding	100–125	17	•	•	•	•
		180	8	••	••	•	•
	Uncontrolled grinding	100–125	14	•••	•••	••	••
		180	6	•••	•••	••	••
On	LEV: HEPA-cyclone and	100–125	29	○	○	○	○
	HEPA-tank	180	12	○	○	○	○
	Shop vacuum	100–125	13	•	○	○	○
		180	6	•	○	○	○
	Wet grinding	100–125	14	•	○	○	○
		180	7	•	•	•	○
	Uncontrolled grinding	100–125	12	••	••	•	•
		180	6	••	••	••	•

Notes: Respirator requirements: ○ = no respirator, • = half-mask respirator, •• = full face respirator, ••• powered air-purifying respirator.
[A]N = number of samples.

and reported a significant reduction in silica dust exposure. They reported 91.9% efficiency for LEV and 94.2% for the combination of LEV and GV. Flanagan et al.,[(5)] using a box-fan, vacuum, and shroud, showed dust reductions of 57, 50, and 71%, respectively. Croteau et al.[(25)] collected air samples during concrete LEV grinding and three varieties of dust collection shroud configurations. The application of LEV resulted in dust reduction up to 86.4%. Twenty-six percent of samples in their study exceeded the permissible criteria.

Both our current study and the one published in 2007 were performed in a controlled enclosed field laboratory to simulate concrete grinding in enclosed spaces (e.g., the basements of residential and commercial buildings), whereas the other related studies were performed at various construction sites. Both our studies used diamond grinding cups, as did three of the other studies.[(4–6)] In general, diamond grinding cups are applied when more aggressive rough grinding is needed; abrasive grinding is used for finer finishing work.[(5)] Diamond cups are currently preferred for concrete surface grinding. One study reported that using an abrasive grinding cup may generate up to 60% less dust than the diamond grinding cup.[(5)] In our study, four diameter sizes of grinding cups of 100, 115, 125, and 180 mm were used, all in the range of diameters of grinders used in the three other studies.[(5,6,25)] The grinding wheel speed (rotation rate) in our studies was estimated at 6000–10000 rpm, which was within the range of those estimated in the other four studies.[(5–7,25)]

Although both our current and pilot[(2)] studies showed that wet grinding can reduce GM concentration of silica dust 94.4% and 98.2%, respectively, they seem to be the only studies in the application of the wet method during concrete grinding. Nevertheless, application of the wet dust reduction technique used in other construction activities such as during cutoff sawing have reduced respirable silica dust at least 75%[(26)] and generally reduced silica dust up to 67%.[(16)] A Meeker et al.[(27)] report showed the portable LEV unit reduced silica dust by 96% for block cutting and 91% for brick cutting. Stationary wet saws reduced the silica dust by 91%. However, use of water may not be a feasible dust control method for many interior work situations or in cold environments.[(28)]

CONCLUSIONS

- The equipment, engineering controls, and grinding methods chosen for this study represent those that are readily available and in current use for manual concrete surface grinding.
- Overall, GV reduced GM concentration of silica dust by 66.0% and RSP by 70.2% compared with no general ventilation.
- Overall, compared with conventional uncontrolled grinding: (1) LEV (HEPA-Cyclone or HEPA-Tank) grinding reduced GM concentrations of silica dust 99.0% ($p < 0.001$) and RSP 98.9% ($p < 0.001$); (2) LEV (Shop-vac) grinding reduced

GM concentrations of silica dust 98.1% ($p < 0.001$) and RSP 96.9% ($p < 0.001$); and (3) wet grinding reduced GM concentrations of silica dust 94.4% ($p < 0.001$) and RSP 92.6% ($p < 0.001$).

- Compared with wet grinding: (1) LEV (HEPA-Cyclone or HEPA-Tank) grinding reduced GM concentrations of silica dust 83.1% ($p < 0.001$) and RSP 84.8% ($p < 0.001$); and (2) LEV (Shop-vac) grinding reduced GM concentrations of silica dust 67.2% ($p < 0.005$) and RSP 57.9% ($p < 0.01$).
- Compared with LEV (Shop-vac) grinding, the LEV (Cyclone + Tank) reduced GM concentrations of silica dust 48.4% ($p < 0.005$) and RSP 63.8% ($p < 0.001$).
- Concentrations of silica dust and RSP collected by personal sampling were significantly ($p < 0.05$) higher than those (1) collected by area sampling; (2) on the right side of the (right-handed) operator during uncontrolled grinding (where the dust was physically thrown by the grinding wheel) than on the left side; and (3) when using the 180-mm grinding cup rather than the 100–125 mm cup.
- With all other conditions the same, the concentrations of silica dust and RSP collected by personal sampling were not significantly different: (1) among 100, 115, and 125 mm diameter grinding cups; (2) during grinding of a surface in the horizontal position compared with an inclined position; (3) by water flow rates for wet grinding adjusted by the researcher or by the grinding operator; and (4) for different task-specific sampling periods for each dust control method (e.g., 5-, 15-, 25-min sampling periods for uncontrolled grinding).
- At the levels of exposure reported herein and assuming that the exposure lasts for an entire 8-hr work shift, the current dust control methods do not reduce silica dust to below the ACGIH-recommended[22] silica dust exposure criterion of 0.025 mg/m^3. This strongly suggests the need for further refinement in the engineering control options and additional administrative controls or the use of respirators.
- Angle grinders retrofitted with the LEV equipment utilized in this study provided similar silica reductions as the concrete grinder with LEV built in. However, the latter was the operator's ergonomic preference.

RECOMMENDATIONS

When concrete grinding is performed in an enclosed workplace:

1. Install and use general ventilation to supplement engineering controls applied at the source of dust generation.
2. Use grinders equipped with local exhaust ventilation (LEV grinding) or with a water attachment (wet grinding).
3. Use grinders and accessories designed specifically for concrete grinding, if available and practical.
4. Until appropriate higher-efficiency dust control methods are devised and used, use air-purifying respirators with protection of at least 10 (e.g., half-mask) with LEV grinding, 100 (e.g., full-face) with wet grinding, and 200 (e.g., powered air-purifying respirator) with uncontrolled grinding.
5. Use appropriate personal protective equipment, such as coverall, face and eye protection, anti-vibration gloves, and hearing protectors.
6. Observe electrical safety during wet grinding.
7. Use an appropriate work-rest regimen (e.g., 25–75%).
8. Use a smaller size grinder, which helps eliminate ergonomics problems created by bulky, heavy hand tools.

There is an urgent need for uniform guidelines for the manufacture and selection of equipment appropriate for manual concrete grinding, the assembly of retrofitted dust control apparatuses, and the maintenance of hand-held angle grinders and the accessories that are commonly used for concrete grinding.

ACKNOWLEDGMENTS

This research project was funded by the National Institute for Occupational Safety and Health, the Centers for Disease Control and Prevention (Grant # 1 R01OH009271-01); however, the findings in this report do not necessarily reflect the views of these agencies and no official endorsement should be inferred. Robert Funa, Joshua Otiso, and Amie Anschutz assisted with field data collection and data entry and verification. Bureau Veritas North America provided and analyzed the air sample filters. Duffey Concrete Cutting Inc. (Toledo, Ohio) provided the field lab space, concrete grinding operator, and field technical assistance.

REFERENCES

1. "Occupational Employment and Wages, May 2008, 47-2051 Cement Masons and Concrete Finishers." [Online] Available at http://www.bls.gov/oes/current/oes472051.htm#nat (Accessed June 3, 2010).
2. **Akbar-Khanzadeh, F., S.A. Milz, A. Ames, et al.:** Crystalline silica dust and respirable particulate matter during indoor concrete grinding—Wet grinding and ventilated grinding compared with uncontrolled conventional grinding. *J. Occup. Environ. Hyg. 4*:770–779 (2007).
3. **Flanagan, M.E., N. Seixas, P. Becker, et al.:** Silica exposure on construction sites: Results of an exposure monitoring data compilation project. *J. Occup. Environ. Hyg. 3*:144–152 (2006).
4. **Rappaport, S.M., M. Goldberg, P. Susi, et al.:** Excessive exposure to silica in the U.S. construction industry. *Ann. Occup. Hyg. 47*:111–122 (2003).
5. **Flanagan, M.E., N. Seixas, M. Major, et al.:** Silica dust exposure during selected construction activities. *Am. Ind. Hyg. Assoc. J. 64*:319–328 (2003).
6. **Akbar-Khanzadeh, F., and R.L. Brillhart:** Respirable crystalline silica dust exposure during concrete finishing (grinding) using hand-held grinders in the construction industry. *Ann. Occup. Hyg. 46*:341–346 (2002).
7. **Croteau, G.A., S.E. Guffey, M.E. Flanagan, et al.:** The effects of local ventilation controls on dust exposure during concrete cutting and grinding activities. *Am. Ind. Hyg. J. 63*:458–467 (2002).

8. **Lumens, M., and T. Spee:** Determinants of exposure to respirable quartz dust in the construction industry. *Ann. Occup. Hyg. 45*:585–595 (2001).
9. **Linch, K., W.E. Miller, R.B. Althouse, et al.:** Surveillance of respirable crystalline silica dust using OSHA compliance data (1979–1995). *Am. J. Ind. Med. 34*:547–558 (1998).
10. **Yassin, A., F. Yebesi, and R. Tingle:** Occupational exposure to crystalline silica dust in the United States, 1988–2003. *Environ. Health Perspect. 113*:255–260 (2005).
11. **Centers for Disease Control and Prevention (CDC):** Silicosis mortality, prevention, and control —United States, 1968–2002. *Morbidity and Mortality Weekly Report 54*:401–405 (2005).
12. **Steenland, K.:** One agent, many diseases: Exposure-response data and comparative risks of different outcomes following silica exposure. *Am. J. Ind. Med. 48*:16–23 (2005).
13. **Linch, K.:** Respirable concrete dust—Silicosis hazard in the construction industry. *Appl. Occup. Environ. Hyg. 17*:209–211 (2002).
14. **National Institute for Occupational Safety and Health (NIOSH):** *Request for Assistance in Preventing Silicosis and Deaths in Construction Workers*, Pub. No. 96-112. Washington, D.C.: NIOSH, 1996. pp. 2–3.
15. **Freeman, C.S., and E.A. Grossman:** Silica exposures in workplace in the United States between 1980 and 1992. *Scand. J. Work, Environ. Health 2(Suppl. 2)*:47–49 (1995).
16. **National Institute for Occupational Safety and Health (NIOSH**): *Hazard Review: Health Effects of Occupational Exposure to Respirable Crystalline Silica*, DHHS (NIOSH) Pub. No. 2002-129. Washington, D.C.: NIOSH, 2002. pp. 67–79.
17. **ACGIH:** *Industrial Ventilation, A Manual of Recommended Practice*, 25th ed. Cincinnati, Ohio: ACGIH, 2004. p. 9–9.
18. **National Institute for Occupational Safety and Health (NIOSH):** *NIOSH Manual of Analytical Methods* (Methods 0600 and 7500). P.M. Eller and M.E. Cassinelli (eds.). 4th ed., DHHS (NIOSH) Pub. No. 94–113. Washington, D.C.: NIOSH, 1998.
19. **Hornung, R.W., and L.D. Reed:** Estimations of average concentration in the presence of non-detectable values. *Appl. Occup. Environ. Hyg. 5*:46–51 (1990).
20. **Helsel, D.:** Much ado about next to nothing: Incorporating nondetects in science. *Ann. Occup. Hyg. 54*:257–262 (2010).
21. **Flynn, M.R.:** Analysis of censored exposure data by constrained maximization of the Shapiro-Wilk W statistic. *Ann. Occup. Hyg. 54*:263–271 (2010).
22. **ACGIH:** *Threshold Limit Values and Biological Exposure Indices.* Cincinnati, Ohio: ACGIH, 2009. p. 51.
23. **Nij, E., S. Hilhorst, T. Spee, et al.:** Dust control measures in the construction industry. *Ann. Occup. Hyg. 47*:211–218 (2003).
24. **Echt, A., and W.K. Sieber:** Control of silica exposure from hand tools in construction: Grinding concrete. *Appl. Occup. Environ. Hyg. 17*:457–461 (2002).
25. **Croteau, G., M. Flanagan, J. Camp, et al.:** The efficacy of local exhaust ventilation for controlling dust exposures during concrete surface grinding. *Ann. Occup. Hyg. 38*:509–518 (2004).
26. **Thorpe, A., A.S. Ritchie, M.J. Gibson, et al.:** Measurements of the effectiveness of dust control on cut-off saws used in the construction industry. *Ann. Occup. Hyg. 43*:443–456 (1999).
27. **Meeker, J.D., M.R. Cooper, D. Lefkowitz, et al.:** Engineering control technologies to reduce occupational silica exposures in masonry cutting and tuckpointing. *Pub. Health Rep. (Suppl. 1)124*:101–111 (2009).
28. **Lahiri, S., C. Levenstein, D.I. Nelson, et al.:** The cost effectiveness of occupational health interventions: prevention of silicosis. *Am. J Ind. Med. 48*:503–514 (2005).