APPLIED STUDIES

The Effect of Local Exhaust Ventilation Controls on Dust Exposures During Concrete Cutting and Grinding Activities

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This study assessed the effectiveness of commercially available local exhaust ventilation (LEV) systems for controlling respirable dust and crystalline silica exposures during concrete cutting and grinding activities. Work activities were performed by union-sponsored apprentices and included tuck-point grinding, surface grinding, paver block and brick cutting (masonry saw), and concrete block cutting (hand-held saw). In a randomized block design, implemented under controlled field conditions, three ventilation rates (0, 30, and 75 cfm) were tested for each tool. Each ventilation treatment was replicated three times in random order for a total of nine 15-min work sessions per study subject. With the exception of the hand-held saw, the use of LEV resulted in a significant ($p < 0.05$) reduction in respirable dust exposure. Mean exposure levels for the 75 cfm treatments were less than that of the 30 cfm treatments; however, differences between these two treatments were only significant for paver block cutting ($p < 0.01$). Although exposure reduction was significant (70–90% at the low ventilation rate and 80–95% reduction at the high ventilation rate), personal respirable quartz exposures remained very high: 1.4–2.8 × PEL (permissible exposure limit) at the low ventilation rate and 0.9–1.7 × PEL at the high ventilation rate. Exposure levels found under actual field conditions would likely be lower due to the intermittent nature of most job tasks. Despite incomplete control, LEV has merit, as it would reduce the risk of workers developing disease, allow workers to use a lower level of respiratory protection, protect workers during short duration work episodes, reduce exposure to nearby workers, and reduce clean-up associated dust exposures.

Keywords: construction, local exhaust ventilation, masonry, silica, silica dust control

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Exposures to crystalline silica can result from construction activities in which dust is generated during the cutting, grinding, or drilling of concrete, brick, stone, and similar building materials. This occupational exposure can result in silicosis. Silica also has been recently classified as a Type 1 carcinogen by International Agency for Research on Cancer.(1) Effective treatments for silicosis are nonexistent, placing a high priority and importance on prevention through the reduction and elimination of respirable crystalline silica exposure.

There have been relatively few studies addressing the incidence or prevalence of silicosis among construction workers due to the transient nature of the industry,(2) lack of accurate silica exposure data,(3,4) and apparent underreporting of new cases.(5) Nevertheless, increased prevalence of silicosis and silica tuberculosis was observed in caisson construction workers from Hong Kong,(6) and construction workers in Finland were observed to have a standardized incidence ratio of 10.3 (95% confidence interval 1.3–37) for silicosis.(7) Construction workers from Hong Kong who died between 1979 and 1983 were found to have an elevated standardized mortality ratio for silicosis and tuberculosis mortality,(8) and the number of male construction worker deaths caused by silicosis was more

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than twice that of males (proportionate mortality rate = 210) employed in all industries.[9]

The duration and frequency of crystalline silica exposure to individual workers is highly variable due to the nature of construction work. Factors that affect worker exposure include type of work performed, work activity duration and frequency, construction material used, work location, and dust control measures.[10] Cutting, grinding, and drilling activities,[10] and dry sweeping[11] generate the highest respirable crystalline silica concentrations.

Exposure assessment and regulatory monitoring results indicate that crystalline silica exposure levels for a large number of construction workers are excessive. A Dutch field study examining 29 occupations within the construction industry found that 3.5% exceeded a respirable crystalline silica exposure level of 0.15 mg/m^3.[12] In another Dutch study, geometric mean respirable crystalline silica exposures for three different work activities at 30 different construction sites ranged from 0.04 mg/m^3 for inner wall constructors to 1.1 mg/m^3 for demolition workers.[10] An analysis of Occupational Safety and Health Administration (OSHA) inspection data revealed that nonresidential construction workers and masonry workers exceeded the OSHA permissible exposure limit (PEL) by factors of 13.0 and 15.6, respectively.[13] Compliance monitoring results from Washington State indicated 93% of 28 measurements taken from 1991 to 1993 exceeded the PEL of 0.1 mg/m^3.[14] Extrapolating the OSHA database to a national level, Linch et al.[15] estimated that 2.6% of masonry workers, 2.1% of heavy construction workers, and 1.3% of nonresidential construction workers—36,000 workers total—are exposed to at least twice the National Institute for Occupational Safety and Health (NIOSH) recommended exposure limit (REL) (0.05 mg/m^3) for crystalline silica. Despite the high crystalline silica exposure potential, the use of dust control measures is not common.[14]

Given the constraints and limited effectiveness of administrative, process, and PPE controls, engineering controls (water spray and local exhaust ventilation) provide the best means of reducing crystalline silica exposures. Water spray is considered to be a good method for reducing crystalline silica exposures, despite a lack of published data documenting its effectiveness. However, water source and disposal requirements, water damage potential, surface discoloration, material expansion, cleanup requirements, and cold weather issues (freezing, hypothermia, and slip hazards) make use of water problematic in many situations.

Previous studies demonstrated that water and local exhaust ventilation (LEV) systems can effectively reduce dust exposures, but not always to acceptable levels. In a controlled study, LEV was found to be most effective for concrete drilling, with crystalline silica exposures observed to be less than 0.1 mg/m^3 for 74% of the 53 evaluations conducted.[16] The LEV systems used for surface grinding and floor breaking were less effective, with only 26% of 23 and 7% of 30 evaluations resulting in crystalline silica exposures less than 0.1 mg/m^3, respectively. Thorpe et al.[17] found that in a field setting, water and LEV controls resulted in a 90% reduction in respirable dust exposures associated with the use of a portable saw. In a field evaluation of LEV used for tuck-point grinding, Nash and Williams[18] observed a mean crystalline silica exposure reduction of 94% (n = 1), although the exposure was still three times the OSHA PEL. The ventilation rates used for the LEV systems in these studies were not reported.

Despite the commercial availability of LEV systems for selected masonry tools, few studies have evaluated their effectiveness. Consequently, there is a need to assess the efficacy of engineering controls for reducing silica exposure under field conditions. The primary objective of this study was to assess the effectiveness of four tools (surface grinder, angle grinder, hand-held saw, and masonry saw) equipped with commercially available LEV systems for reducing respirable dust and crystalline silica exposure under controlled field conditions.

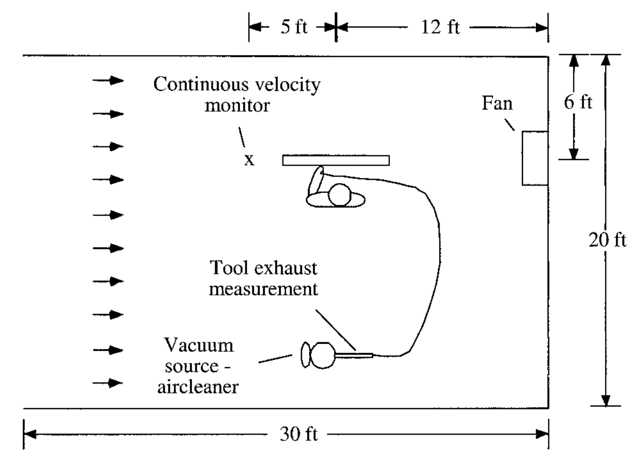

FIGURE 1. Schematic of LEV testing work area

MATERIALS AND METHODS

Study Location and Description

Dust control evaluations were conducted at the training site of the local brick and cement masons apprenticeship programs. Volunteers recruited for the study were apprentices who had been enrolled in either program for at least 4 weeks and had received training in using the tool studied. Personal protective equipment used by the study subjects included boots, gloves, earplugs, and a powered air-purifying respirator.

All tools were evaluated in a temporary structure (vinyl tent), which reduced the effects of wind and rain and prevented dust exposure to staff and apprentices working in the vicinity. The tent (Figure 1) had dimensions of 6.1 m (20 ft) wide by 9.1 m (30 ft) long and a volume of 149.2 m^3 (5267 ft^3). Vinyl walls were erected on three sides of the tent with the northeast wall left open. To prevent wind from entering cracks between walls, and walls and the ground, an inner wall of plastic sheeting that overlapped each wall interface was installed and secured to the ground using sandbags. Ventilation through the tent was provided by a 91 cm (36 inch) diameter fan (TPI, Johnson City, Tenn.) that was placed in a ground-level opening on the southwest wall. The fan had a measured flow of 111 m^3/min (3925 cfm), which produced an airflow velocity through the tent of approximately 12.2 m/min (40 ft/min) at the measurement location (Figure 1). Cross-sectional airflow measurements taken throughout the tent over several days prior to initiating the study indicated that the airflow through the tent was relatively uniform with the mean velocity ranging from 40 to 60 ft/min. Observations of smoke tests indicated that air was drawn only through the open end of the tent and moved toward the exhaust fan with a minimum of turbulence and swirling. These initial observations of the tent airflow characteristics were confirmed throughout the study by observing the airflow patterns of dust generated during the different work activities. During the study the airflow velocity through the tent was measured at the beginning, middle, and end of each work session using a thermo anemometer placed 5.2 m (17 ft) upwind of the exhaust fan at a height 1.25 m (49 inches). The study utilized a randomized block design, blocked by subject. Treatments were three levels of exhaust ventilation (0, 30, and 70 cfm) provided to each tool's LEV system. Each subject used a single tool over the course of a day. Each of the three treatments was replicated three times in random order for a total of nine 15-min work sessions per study subject. Depending on the work activity and amount of intersubject variability, one to five study subjects were used to evaluate each tool.

During initial experimentation, a flow rate of 30 cfm was observed to provide a reasonable level of dust control for the masonry saw and surface and angle grinders. Consequently, this airflow rate was selected as the low airflow treatment. The high airflow rate was selected based on the capacity of the vacuum (about 90 cfm) and meeting the American Conference of Governmental Industrial Hygienists (ACGIH) guidelines for concrete dust conveyance (3500 ft/min). The manufacturers did not have a recommended airflow rate for their shrouds.

Vacuum Source for Tool Ventilation

An industrial vacuum (Dust Control 3700c, Norsburg, Sweden; equipped with a 24-cm diameter cyclone and high-efficiency particulate air [HEPA] filter) was used to provide ventilation airflow for the tools evaluated. Air was conveyed from the tool to the industrial vacuum through a flexible, 5.2 m (17 ft) long, 5.1 cm (2 inch) diameter corrugated hose. Before and after each assessment, velocity was measured with a pitot tube (Dwyer, Michigan City, Ind.) and digital manometer (TSI, St. Paul, Minn.) using a six-point traverse. To counter airflow loss resulting from the increased resistance from dust loading on the HEPA filter, the built-in reverse airflow cleaning system was used four times at evenly spaced intervals during each 15-min work session. During each cleaning episode, which was approximately 3 to 5 sec in duration (1.3 to 2.2% of the 15-min work session), no airflow was provided to the tool.

Tools Evaluated and Work Activity Descriptions

Prior to initiating the study, the authors identified hand tools commonly used for tuck-point grinding, concrete surface grinding, and block and brick cutting that were marketed with LEV controls. The search included a review of Internet web sites and correspondence with tool manufacturers, local contractors, and equipment vendors. The masonry and hand-held saws used were the only LEV-equipped saws identified. Equipment selected for tuck-point and surface grinding was recommended by an equipment vendor, and the surface grinder was used by a local contractor. During each work session, observations regarding work practices were recorded. Face velocities presented for each LEV shroud were calculated based on the measured airflow rate and shroud area. The attributes of the four tools selected for evaluation are presented in Table I, with detailed descriptions provided as follows.

Angle Grinder

The hand-held, electric-powered angle grinder (Figure 2A) is commonly used in a restorative function to remove worn and dilapidated mortar in walls constructed of bricks, blocks, stones, or similar building materials. To complete the restoration process, new mortar is placed in the resulting groove in a process called "tuck-pointing." The angle grinder was equipped with a shroud that covered most of the grinding blade, with the portion protruding being equivalent to the grinding depth. For the no-ventilation treatment, the front piece of the angle grinder shroud was disconnected, allowing the remaining piece to act as a guard. Tuck-point grinding was performed on portable brick walls constructed by apprentices specifically for the study (Table I). During each session, study subjects maintained the same orientation to the wall (aligned lengthwise with the fan), with the exhaust fan to their right. The tool was set to a grinding depth of 1 cm for all work sessions. At the completion of each work session, the length of mortar joint removed was measured.

Surface Grinder

This hand-held electric-powered tool (Figure 2B) is used to produce a smooth finish on poured concrete surfaces. The surface grinder shroud covered the grinding cup completely, allowing for a seal between the working surface and the shroud. Air entered the shroud through twenty-two 0.5 cm holes positioned concentrically on the shroud periphery. The shroud was completely removed for the no-ventilation treatment. Surface grinding was performed on concrete walls of varying length that were used by apprentices for instructional purposes (Table I). A 0.88 m^2 (9.5 ft^2) area on each wall was marked off for each 15-min work session. Apprentices were instructed to work for 11.5 min on the wall, 1 min on the 4-inch wide horizontal top section, 2 min putting a 45° chamfer on a vertical side edge, and 0.5 min putting a 45° chamfer on a horizontal edge. The latter three exercises were included to mimic real working situations in which there is no seal between the shroud and working surface, and dust capture is compromised. During each work session study subjects maintained the same orientation to the wall (aligned lengthwise with the fan), with the exhaust fan to their left. A piece of plastic sheeting was hung down from the tent ceiling to the top of the wall to simulate a continuous wall.

Masonry Saw

The gasoline-powered masonry saw (Figure 2C) was specifically designed for cutting pavers, 5–10 cm thick blocks used in the construction of walkways, patios, and similar surfaces. Cuts are made by pushing the object on a sliding tray into a fixed blade. The saw's LEV system[19] consisted of a 2.5 cm (1 inch) square tube running the length of the saw immediately below the blade. Exhaust ventilation was connected to the open end of the tube located at the rear of the saw, and dust was captured through a slot in the tube near the point of contact between the blade and material being cut. The LEV performed as a push/pull system, with air currents generated by the blade pushing dust into the slot and the exhaust system pulling the dust away. Airflow measurements taken in the dust collection tube while the saw was being operated (but not while actually cutting), indicated that the rotating blade generated an airflow of about 10 cfm into the dust collection tube. The masonry saw's exhaust ventilation was disconnected and the exhaust take-off was sealed for the no-ventilation treatment. The saw was positioned so that the bottom of the blade was 102 cm (40 inches) from ground level. Paver blocks and clay bricks were used to test the masonry saw. During each session, study subjects maintained the same orientation, with the exhaust fan to their backs and the saw blade aligned with the exhaust fan. The total number of cuts was recorded to determine a work rate.

TABLE I. Attributes of Tools and Construction Materials Used in Study

Tool Attribute	Work Activity: Tuck Point Grinding	Surface Grinding	Block and Brick Cutting	Block Cutting
Tool	angle grinder	flat grinder	masonry saw	hand-held saw
Make	Flex (Porter Cable)	Flex (Porter Cable)	EDCO	Partner
Model	F1509 FR	LD 1509 FR	GMS-10	K650 Active
Power source	electric	electric	gasoline	gasoline
Weight	4.1 kg (9.1 lbs)	2.9 kg (6.4 lbs)	53 kg (116 lbs)	9.4 kg (20.7 lbs)
Dimensions[A]	37 × 18 × 18 cm 15 × 7 × 7 in	36 × 11 × 18 cm 14 × 5 × 7 in	104 × 64 × 48 cm 41 × 25 × 19 in	76 × 30 × 30 cm 25 × 10 × 10 in
Power (watts)	1200	1200	3000	
Operating RPMs	10,000	10,000	5500	3600
Blade type	diamond	diamond cup	diamond, dry cut	diamond
Make	Concut	Dimas	EDCO	Concut
Diameter (cm)	11.4	13.5	24.0	30.5
Tip speed (ft/min)	3750	4430	2830	5500
Ventilation shroud				
Face dimensions (cm)	12.3 × 4.0[B]	17.8[C]	17.5 × 0.8[B]	38.1 × 317.5
Face area (cm^2)	49.2	248.8	13.9	121.0
Face velocity (ft/min)	555/1401[D]	110/277	1971/4973	225/570
Construction material	Brick walls with Type S mortar: 70% sand 20% sand 10% hydrated lime	concrete walls	paver blocks bricks with three 3.8-cm (1 in) holes	concrete blocks (C-90)
Dimensions (length × height × width)	1.8 × 1.4 × 0.15 m 6.0 × 4.6 × 0.5 ft 1-cm wide mortar joints	variable length 1.2 × 0.10 m 4.0 × 0.33 ft	paver blocks 29.5 × 29.5 × 5.7 cm $11\frac{5}{8} \times 11\frac{5}{8} \times 2\frac{1}{4}$ in Bricks 19.4 × 6.4 × 9.4 cm $7\frac{5}{8} \times 2\frac{1}{2} \times 3\frac{11}{16}$ in	30.5 × 20.3 × 20.3 cm 12 × 8 × 8 in

[A]Length by height by width.
[B]Length by width.
[C]Diameter.
[D]Face velocity at ventilation airflow rates of 29.4 and 74.2 cfm, respectively (overall average ventilation rate for low and high treatments).

Hand-Held Saw

The gasoline-powered hand-held saw's (Figure 2D) configuration and operation is similar to that of a chain saw, with the engine and controls located near the operator. This tool has numerous applications in the construction industry due to its high power, portability, and ability to cut a variety of different materials. Dust control for the hand-held saw was facilitated by a port near the back end of the guard to which the exhaust ventilation was connected. The exhaust ventilation was disconnected from the hand-held saw for the no-ventilation treatment. Standard C-90 cement blocks were placed on a base so that the top of the block was 80 cm (32 inches) above ground level. Otherwise, the hand-held saw was tested in a manner similar to that of masonry saw.

Exposure Monitoring

Dust control effectiveness was assessed by collecting personal and "downstream" respirable dust samples during each work session following NIOSH Method 0600.[20] A portable air sampling pump (Gilian, St. Petersburg, Fla.) pulled air through a nylon cyclone (MSA, Pittsburgh, Pa.) at a rate of 1.7 L/min. Personal exposure samples were taken on each subject's left lapel and "downstream" samples were collected 107 cm (42 inches) upwind of the exhaust fan. Air sampling trains were calibrated pre- and postsampling using a primary standard (Gilian).

The respirable dust emission rate (ER) was estimated by taking the product of the air concentration upwind of the exhaust fan and the building exhaust ventilation rate (Equation 1).

$$ER = C * Q_{tent} \tag{1}$$

where ER is the respirable dust emission rate in grams per second, C is the respirable dust concentration (mg/m^3), and Q_{tent} is the tent exhaust ventilation rate (1.85 m^3/sec). Emission rate calculations assume that the exhaust rate is constant, the point sample represents the average respirable dust concentration, and all of the respirable dust released from the tool does not settle, remains airborne, and exits the tent through the exhaust fan. Dust settling calculations, which assumed that the maximum settling velocity was 0.6 cm/sec (10 μm diameter, 2.7×10^3 kg/m^3 density particulate), dust was generated a maximum distance of 4.3 m from the fan, and the minimum (5th percentile) wind velocity was 0.11 m/sec, theoretically confirm that respirable quartz particulates would not settle prior to reaching the exhaust fan.

The respirable dust mass of each sample was determined gravimetrically using NIOSH Method 0600.[20] After dust mass was

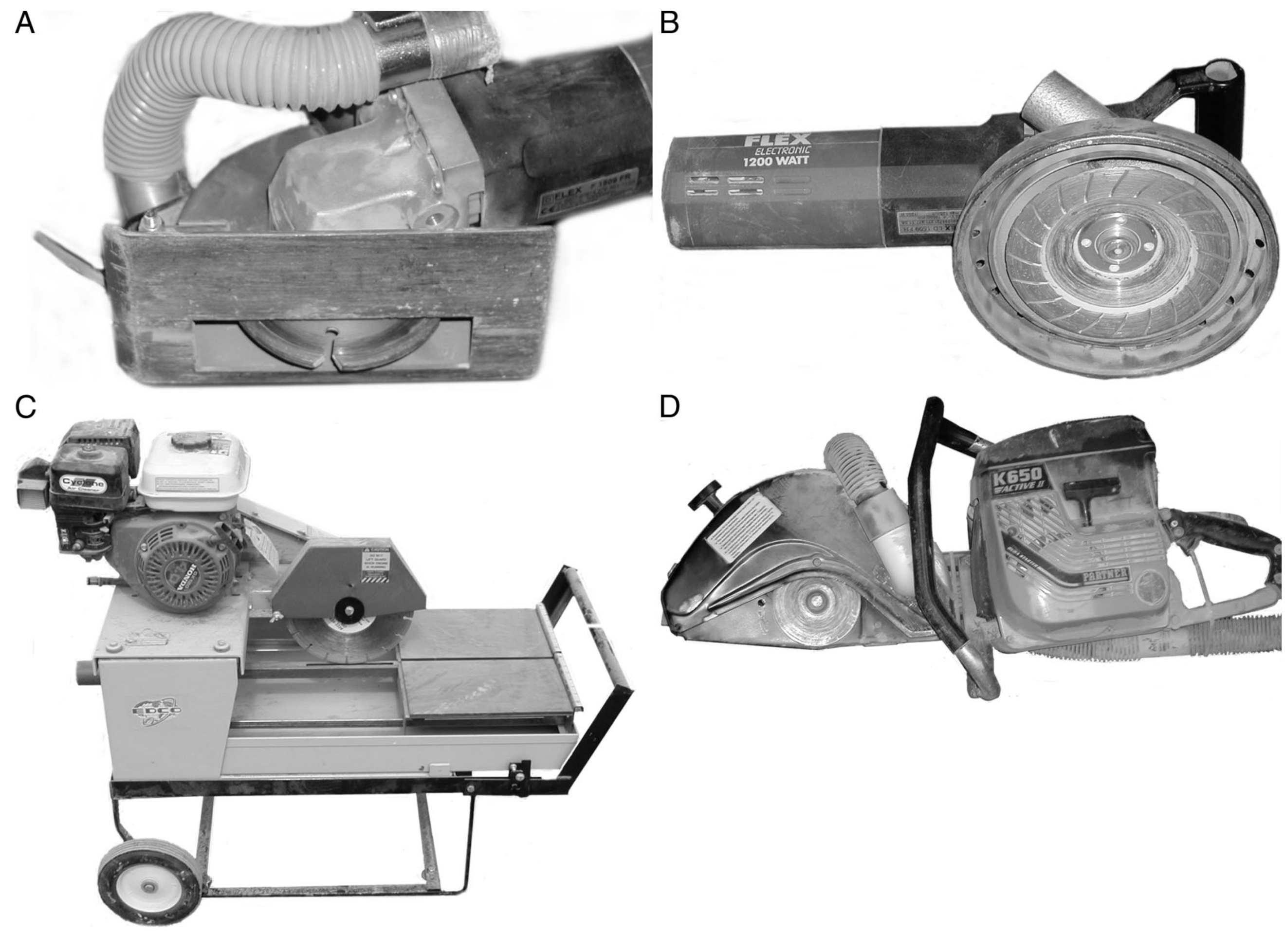

FIGURE 2. (A) Tuck-point grinder; (B). surface grinder; (C) masonry saw; (D) hand-held saw

determined, replicate filters were placed together in a crucible and ashed. These composite samples were subsequently analyzed for quartz and cristobalite by infrared spectrometry using NIOSH Method 7602.[21] Laboratory quality was assessed by the collection and analysis of field blanks at a rate of 10%. For quartz analysis a standard was analyzed twice for every 10 samples, and variation was found to be less than 5%.

Data Analysis

Analytical results found to be less than the limit of detection (LOD) were entered into the analysis as 50% of the LOD, which was 5 μg for gravimetric analysis and 5.5 μg for quartz analysis. Linear statistical models were developed with ventilation rate included as a discrete variable. Model development was an iterative process whereby predictors (tool ventilation rate, study subject, interaction of tool ventilation rate and study subject, wind velocity through tent, and work rate) were added and their effect on the overall model was considered. Pairwise comparisons between treatments were made using t-tests. Effectiveness of the LEV systems for controlling dust was based on comparisons of personal respirable dust and quartz exposures to the OSHA 8-hour time-weighted average (TWA)-PELs and reduction in respirable dust exposure (Equation 2):

$$\% \text{ Reduction} = [(NV_{gm} - V_{gm})/NV_{gm}] * 100 \qquad (2)$$

where NV_{gm} is the geometric mean respirable dust exposure for a study subject under the no-ventilation treatment and V_{gm} is the geometric mean respirable dust exposure for a study subject under ventilation treatment.

RESULTS

Experimental Conditions

Effects of wind velocity across the work area, ventilation airflow rate, work rate, and respirable crystalline silica content of the construction materials were analyzed to assess the significance of their effects on personal exposures.[22] Wind velocity (n = 91, mean = 11.5 m/min, standard deviation [SD] = 3.7) was not a significant predictor of personal respirable dust exposure or emission rate and is not discussed further. Precise control of LEV rate was achieved as demonstrated by the fact that the overall mean (±SD) for the low (29.4±1.5) and high (74.2±5.2) ventilation treatments did not vary considerably from the targets of 30 and 75 cfm, respectively. Ventilation rate change over the duration of each experiment was minimal (1.6%±7.4). The overall mean (±SD) work rates (feet cut/hour) were 118.6 (±41.9) for tuck-point grinding; 267.6 (±16.5) for concrete block cutting; 79.3 (±12.5) for paver block cutting; and 86.4 (±14.9) for brick cutting. No means of

TABLE II. Geometric Mean (GSD) Personal Respirable Dust and Quartz Exposure Levels (mg/m³)

Work Activity	Study Subject	No Ventilation		Low Ventilation		High Ventilation	
		Dust	Quartz	Dust	Quartz	Dust	Quartz
Tuck-point grinding		(n = 14)		(n = 14)		(n = 13)	
	all	22.17 (2.4)	3.04 (1.98)	6.11 (1.9)[A]	1.02 (1.76)	3.01 (3.3)[C]	0.47 (3.27)
	1	35.80 (1.1)	4.98 (1.01)	6.70 (1.4)[A]	0.81 (1.40)	3.06 (8.2)	0.59 (8.53)
	2	6.59 (1.9)	1.34 (1.91)	3.56 (2.4)	0.58 (2.37)	3.56 (2.2)	0.66 (2.19)
	3	55.17 (1.1)	5.17 (1.06)	9.93 (1.2)[A]	1.47 (1.20)	4.29 (2.2)[C]	0.49 (2.22)
	4	27.15 (1.6)	3.54 (1.57)	8.55 (1.3)[B]	1.34 (1.32)	3.53 (2.0)	0.47 (2.01)
	5	12.54 (2.1)[F]	1.77 (2.10)[F]	3.50 (1.9)[F]	1.23 (1.90)[F]	0.37[G]	0.07[G]
Surface grinding		(n = 5)		(n = 6)		(n = 5)	
	all	165.34 (1.2)	29.16 (1.24)	11.15 (1.7)[A]	2.36 (1.72)	8.00 (1.4)[C]	1.70 (1.34)
	1	181.17 (1.1)	32.10 (1.13)	10.12 (2.3)[A]	2.16 (2.31)	8.66 (1.3)[C]	1.83 (1.34)
	2	144.16 (1.4)[D]	25.24 (1.35)[D]	12.28 (1.1)[A]	2.57 (1.10)	7.11 (1.4)[D,F]	1.52 (1.44)[F]
Paver block cutting[H]		(n = 6)		(n = 6)		(n = 6)	
	all	89.85 (1.4)	22.52 (1.48)	13.12 (1.4)[A]	3.32 (1.44)	4.31 (1.5)[C,E]	0.95 (1.44)
	1	71.05 (1.2)	16.91 (1.22)	12.82 (1.2)[A]	3.18 (1.23)	4.96 (1.7)[C,E]	0.92 (1.65)
	2	113.62 (1.4)	29.98 (1.38)	13.42 (1.7)[A]	3.46 (1.70)	3.74 (1.3)[C,E]	0.97 (1.32)
Brick cutting[H]	1	26.69 (1.6)	4.24 (1.64)	7.27 (1.2)[B]	1.04 (1.18)	3.67 (2.0)[D]	0.60 (2.03)
Block cutting[I]	1	2.35 (1.6)				2.44 (1.6)	

Note: n = 3 per study subject/treatment unless otherwise noted (see footnotes F and G).
Comparison (t-test) of low ventilation to no ventilation.
[A] $p < 0.01$.
[B] $p < 0.05$.
Comparison (t-test) of high ventilation to no ventilation.
[C] $p < 0.01$.
[D] $p < 0.05$.
[E] $p < 0.05$, comparison (t-test) of low and high ventilation rates, all other "low vs. high" comparisons $p > 0.05$.
[F] N = 2.
[G] N = 1.
[H] Masonry saw.
[I] Hand-held saw.

measuring work rate for surface grinding was available. The percentage respirable quartz content of the five different materials used ranged from 15 to 24% and did not vary appreciably (CV < 20%).[22]

Personal Dust Exposure Results

Personal respirable dust measurements were used to assess the efficacy of the LEV systems (Table II). The exposure data were approximately lognormally distributed and were log transformed prior to analysis. For the hand-held saw, personal respirable dust exposures for the high-ventilation rate treatment (GM = 2.44 mg/m³) and the no-ventilation treatment (GM = 2.35 mg/m³) were not significantly different ($p > 0.05$). As demonstrated in Table II and Figures 3A–3C, the other three LEV-equipped tools significantly reduced personal respirable dust exposure for both the low- and high-ventilation rates tested as compared with the no-ventilation treatment ($p<0.05$). For these three tools the mean exposure level for the high-ventilation rate was nonsignificantly ($p>0.05$) less than that of the low-ventilation rate. Considerably greater intersubject variability was noted for tuck-point grinding, (Figure 3A) compared with that observed for surface grinding (Figure 3B) of block and brick cutting (Figure 3C). This is probably the result of observed differences in work technique among subjects who tested the tuck-point grinder.

The effectiveness of LEV in reducing personal dust exposure levels is demonstrated in Figure 4, which shows the average and SD of exposure reduction for the tuck-point grinder, surface grinder, and paver block cutter. Despite the very large reduction in respirable dust exposures (70–90% at the low-ventilation rate and 80–95% reduction at the high-ventilation rate), personal respirable dust exposures remained very high: 1.4–2.8 × PEL at the low-ventilation rate and 0.9 to 1.7 × PEL at the high-ventilation rate (Figure 5A). Note that these comparisons assume the concentrations observed during the 15-min work sessions would be maintained for an 8-hour period.

Without LEV, mean personal respirable dust exposures ranged from 2.35 to 165.34 mg/m³ (0.5 to 33 times the PEL). LEV at the high-ventilation rate reduced average respirable dust exposure levels to just below the PEL for tuck-point grinding, and paver block and brick cutting. Surface grinding achieved the highest overall reduction in dust exposure levels, but the average still exceeded the respirable dust PEL by a factor of 1.6 even at the high-ventilation rate. Figure 5B shows these same data in comparison with the respirable crystalline silica PEL. Silica exposure levels associated with the no-ventilation treatment were remarkably high, ranging from 4.4 to almost 360 times the PEL. The application of LEV reduced exposures considerably; however, even at the high-ventilation rate the respirable quartz PEL was exceeded by a factor of 5 to 20 for all tools.

These data were also analyzed with linear regression to determine the possible effects of other work condition variables in addition to ventilation rate. These models used log of personal dust exposure as the dependent variable and ventilation rate (coded as dummy variables for low versus no and high versus no ventilation), subject, wind velocity, workrate, and the interaction of subject and ventilation rate as potential independent variables. Nonsignificant variables were removed from the final models, which are shown in Table III. The resulting r^2 values indicate that ventilation rate and subject are good predictors of personal respirable dust exposure for all tasks except block cutting.

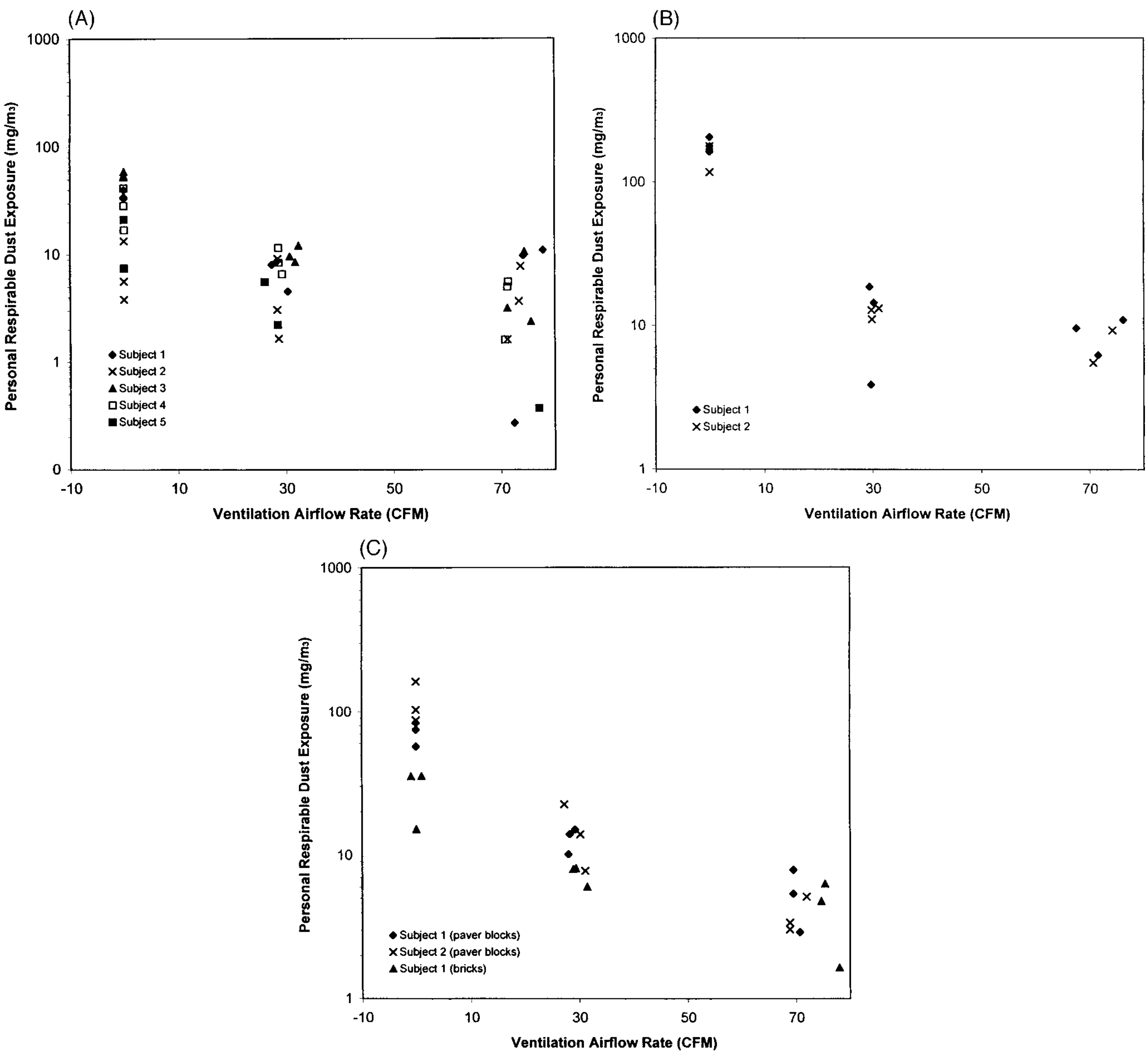

FIGURE 3. (A) Personal respirable dust exposures (mg/m^3) resulting from tuck-point grinding work activity as a function of ventilation airflow rate (cfm); (B) personal respirable dust exposures (mg/m^3) resulting from surface grinding work activity as a function of ventilation airflow rate (cfm); (C) personal respirable dust exposures (mg/m^3) resulting from paver block and brick cutting work activities as a function of ventilation airflow rate (cfm)

Respirable Dust Emission Rate

Respirable dust emission rate data were used to assess LEV system effectiveness in reducing area dust concentrations (Table IV). Emission rate results were similar to those observed for personal exposure. These data were approximately lognormally distributed and were log transformed prior to analysis. The use of LEV resulted in a significant ($p < 0.05$) reduction in emission rate for all tools except the hand-held saw. For all tools the emission rates for the high- and low-ventilation rates were not significantly different ($p < 0.05$). Linear regression results indicated a high level of association between emission rate and personal exposure for surface grinding ($r^2 = 0.718$) and paver block cutting ($r^2 = 0.748$), but not for tuck-point grinding ($r^2 = 0.488$) or brick cutting ($r^2 = 0.488$).

DISCUSSION

The use of LEV significantly ($p < 0.05$) reduced occupational dust exposures for all tools evaluated, with the exception of the hand-held saw (Table II). Despite the large reduction in personal dust exposure levels, some respirable dust exposures and all respirable quartz exposures exceeded the OSHA 8-hour TWA-PEL by more than an order of magnitude, even at the highest ventilation rate tested. Although the LEV systems evaluated did not reduce crystalline silica exposures below the PEL under the conditions present in this study, this dust control alternative reduces the risk of workers developing disease. In addition, reducing emission rates should reduce exposures to nearby workers. Finally, dust exposures resulting from clean-up activities would be reduced substantially.

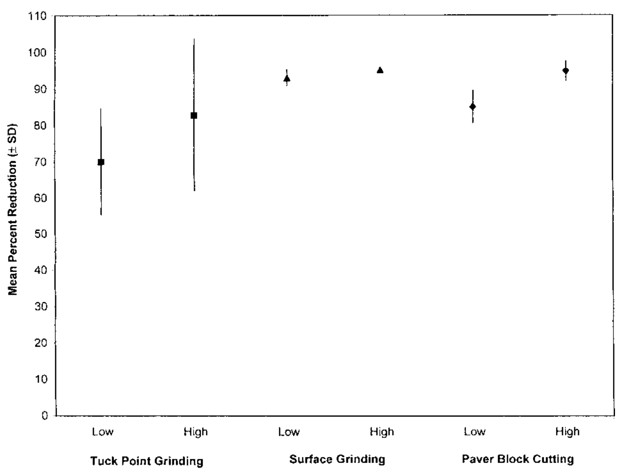

FIGURE 4. Mean personal respirable dust exposure reduction (%) of low- and high-ventilation rate treatments as compared with no-ventilation rate treatment for tuck-point grinding, surface grinding, and paver block cutting work activities

Silica exposure levels associated with the non-LEV treatments in this study are considerably greater than those observed in actual construction industry exposure assessment studies. For example, the mean uncontrolled silica exposure associated with surface grinding (29.2 mg/m^3) in this study is approximately 20 to 60 times greater than that observed in field-based exposure assessment studies.[14,23,24] Consequently, the use of LEV in an actual construction setting could reduce silica exposures to levels well below the PEL, if LEV provides a level of silica exposure reduction similar to that observed in this study (80 to 95% at the high ventilation rate). The high silica exposure levels observed in this study are probably a result of the continuous work sessions during which the study subjects worked at a very high rate. Additionally, the wind velocity and corresponding rate of dust removal in this study were considerably lower than what would be expected at most construction sites.

Intersubject and interreplicate variability in personal dust exposure was minimal for cutting and surface grinding. However, considerable variability was noted for tuck-point grinding, suggesting the importance of worker technique for maximizing dust capture.

Increasing the ventilation rate from 30 to 75 cfm improved dust capture and reduced personal exposure levels. A comparison of the low- and high-ventilation rate treatments (Table II) indicated a significant ($p < 0.05$) reduction in respirable dust exposure for the paver block cutting work activity and a nonsignificant decrease in personal exposure for tuck-point grinding and surface grinding. Compared with the low-ventilation rate, the high-ventilation rate reduced respirable dust exposures an additional 12.8% for tuck-point grinding, 2.2% for surface grinding, 9.8% for paver block cutting, and 13.6% for brick cutting. Note that the higher level of dust control afforded by the high-ventilation rate reduced respirable dust exposures below the OSHA TWA-PEL for tuck-point grinding and paver block and brick cutting, but not for surface grinding (Figure 5A).

The rate of dust settling in the ventilation conveyance hoses is another factor that needs to be considered in the determination of a minimum ventilation rate. Observations made during the study indicate that after each work session, substantially more dust was deposited in the conveyance hose at the low-ventilation rate compared with the high-ventilation rate. For industrial ventilation systems a minimum transport velocity of 3500 to 4000 ft/min is recommended to limit the settling of concrete dust in the conveyance system.[25] Based on this recommended dust conveyance velocity, 30 cfm (1375 ft/min) is inadequate and a ventilation rate of 75 cfm (3440 ft/min) should be considered the minimum ventilation rate for the system tested (2-inch hose).

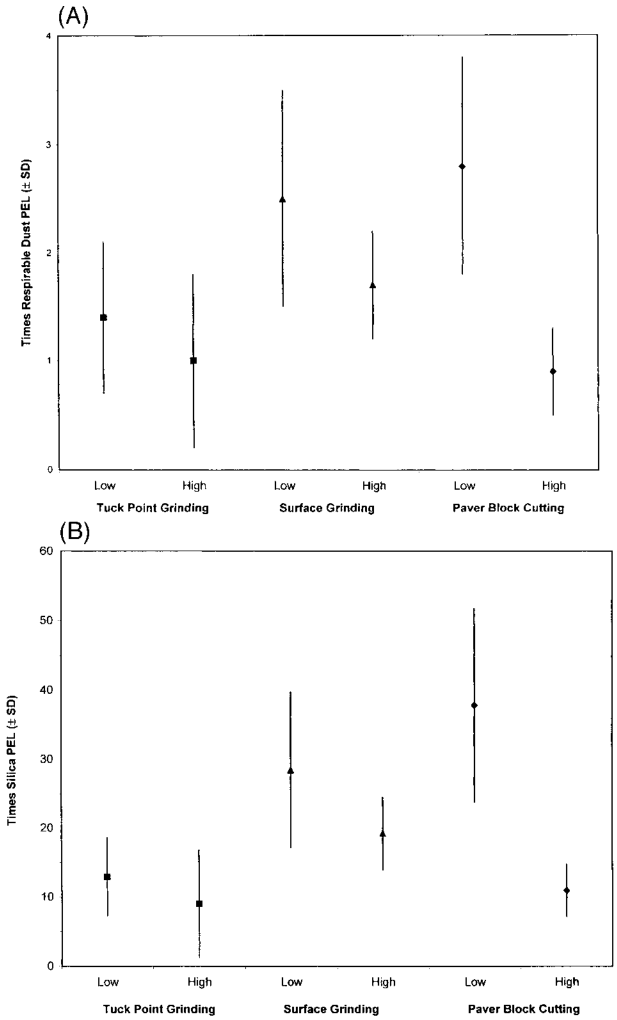

FIGURE 5. (A) Comparison of mean personal respirable dust exposure levels with OSHA 8-hour TWA-PEL (5 mg/m^3); (B) comparison of mean personal respirable quartz exposure levels with OSHA 8-hour TWA-PEL (PEL = 10 mg/m^3/(% respirable quartz + 2)

The effectiveness of an LEV system for capturing dust is dependent on the proximity of the contaminant source to the shroud (L_x), face velocity (V_f), and the magnitude and direction of competing air currents (wind). These factors provide insight as to the relative effectiveness of the LEV systems tested. The surface grinder shroud performed like an enclosing hood (L_x = 0 cm) when it was flush against a surface and very little dust was observed to be escaping. In contrast, considerably more dust was observed to be escaping when the seal between the shroud and surface was compromised while putting a 45° chamfer on a side edge (L_x = 2.5 cm). Under this operational condition, dust capture in an actual construction setting would likely be further compromised as a result of higher wind velocities than those of the controlled field

TABLE III. Linear Models [β (SE)] Describing Log Respirable Dust (mg/m³) Exposure Levels

Variable	Tuck Point Grinding	Surface Grinding	Paver Block Cutting (Masonry Saw)	Brick Cutting (Masonry Saw)	Block Cutting (Hand-Held Saw)
n	41	16	18	9	6
Subjects	5	2	2	1	1
Intercept	2.24 (0.40)[C]	5.07 (0.22)[C]	4.54 (0.18)[C]	3.28 (0.29)[C]	0.85 (0.27)[D]
Ventilation rate[A]					
Low airflow	−1.29 (0.31)[C]	−2.69 (0.26)[C]	−1.92 (0.22)[C]	−1.30 (0.41)[C]	
High airflow	−2.06 (0.31)[C]	−3.03 (0.25)[C]	−3.04 (0.22)[C]	−1.99 (0.41)[C]	0.04 (0.39)
Subject[B]					
1	1.08 (0.45)[D]	0.06 (0.21)	−0.08 (0.18)		
2	0.35 (0.45)				
3	1.46 (0.45)[C]				
4	1.11 (0.45)[D]				
Model r^2	0.633	0.934	0.934	0.799	0.002

[A]Reference: no ventilation provided.
[B]Reference: Nth subject where N = total number of subjects.
[C]$p < 0.01$.
[D]$p < 0.05$.

study. However, if a tight seal is maintained between the shroud and the working surface, wind probably has a negligible effect on dust capture.

The angle grinder LEV system also operates as both an enclosing and capturing hood. As the angle grinder blade is being pushed into the mortar joint, the shroud is transitioning from the capturing hood to the enclosing hood mode. Dust capture was observed to be most effective when the angle grinder blade was pushed completely into the mortar joint and there was an effective seal between the shroud and the working surface.

These factors also explain the difference in performance between the hand-held and masonry saws. For the masonry saw a small slot opening results in a very high V_f (4970 feet/min at 75 cfm), the slot is positioned very near the point of dust generation (L_x = 8 cm), and the air currents generated by the blade (velocity = 2830 ft/min) are directed into the LEV slot. In direct contrast, the hand-held saw had a lower V_f (570 ft/min at 75 cfm), greater L_x (25 cm), and more substantial blade velocity (5500 feet/min) directed away from the ventilation exhaust. Careful consideration of these design parameters may help in developing more effective LEV systems.

The airflow rates used in this study are considerably less than the 25 to 60 cfm per inch of blade or grinding wheel diameter that is recommended by ACGIH.[25] Under the high airflow treatment, the surface grinder, angle grinder, masonry saw, and hand-held saw, had airflow rates of 13.2, 15.6, 7.1, and 5.8 cfm per inch blade diameter, respectively. To meet the minimum ACGIH airflow rate guideline of 25 cfm per inch blade diameter, airflow rates of 113, 133, 236, and 300 cfm are needed for the surface grinder, angle grinder, masonry saw, and hand-held saw, respectively. Given the high level of dust control observed in this study and the relatively small reduction in dust exposure provided by the high-airflow treatment as compared with that of the low airflow treatment, it appears that the ACGIH recommendation may be excessively high and in some situations, both economically and technically unfeasible. Airflow rate recommendations for this LEV application should perhaps be based on a more conventional approach that considers shroud area, distance to dust generation point, enclosing versus capture hood, and competing air currents.

During the study the performance of the tools, LEV systems, and vacuum source was assessed through observations and comments solicited from the study subjects. Both the hand-held saw and masonry saw performed their intended tasks as expected and no comments were made regarding their performance. However, study subjects indicated that the angle and surface grinder shrouds completely obstructed their view of the working surface and the

TABLE IV. Respirable Dust Emission Rate (mg/sec)

Work Activity	Study Subjects	No Ventilation GM (GSD)[A]	n	Low Ventilation GM (GSD)	n	High Ventilation GM (GSD)	n
Tuck point grinding	5	23.62 (1.76)	13	0.96 (3.28)[B]	14	0.50 (4.16)[D]	13
Surface grinding	2	79.37 (1.19)	6	4.38 (2.32)[B]	6	3.06 (2.02)[D]	6
Paver block cutting	2	20.68 (1.20)	6	2.79 (1.35)[B]	6	2.45 (1.97)[D]	6
Brick cutting	1	8.03 (1.52)	3	0.64 (2.55)[C]	3	1.14 (4.93)	3
Block cutting	1	106.50 (1.36)	3			79.50 (1.54)	3

Note: Emission rate (mg/sec) = concentration (mg/m³) * tent ventilation rate (1.853 m³/sec).
[A]Geometric mean and geometric standard deviation.
Comparison of low ventilation to no ventilation.
[B]$p < 0.01$.
[C]$p < 0.05$.
Comparison of high ventilation to no ventilation.
[D]$p < 0.01$.

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vacuum line restricted their mobility. Other operational issues of note regarding the angle grinder was the build-up of dust within the shroud resulting from the small 2.5 cm (1 inch) diameter exhaust port and the 90° bend in the exhaust port take-off.

Industrial vacuum performance was contingent on maintaining the filter. As the filter became loaded with dust and static pressure increased, there was a corresponding decrease in ventilation rate. Initial experimentation indicated airflow could decrease as much as 20% after a 15-min work session. To maintain a relatively constant airflow throughout the work session, the reverse flow cleaning system was used four times at evenly spaced intervals during each 15-min work session. At a maximum the filter cleaning procedure took about 20 sec per 15-min work session. Although the filter cleaning procedure only assumed 2.2% of a 15-min work session, this practice could increase personal exposure levels by as much as 20% if an LEV control resulted in a 10-fold exposure reduction. In an actual field implementation, cleaning would be conducted much less frequently, perhaps several times per day.

CONCLUSIONS

This study demonstrated that LEV can substantially reduce respirable dust and crystalline silica exposures during concrete cutting and grinding activities in a controlled field setting. Due to the variable conditions encountered at construction sites, further research is needed to address LEV effectiveness under actual field conditions. Successful implementation of this engineering control in the field will require diligence on the part of the operator to ensure an adequate tool ventilation rate is provided and that the LEV system is operating as intended. To this end, manufacturers of industrial vacuums and LEV systems need to provide operating and maintenance guidelines. Manufacturers should also engage in product testing to provide the user with information regarding exposure reduction potential and minimum tool ventilation rates. This testing would best be conducted using a standard procedure, the basis for which is provided in this study.

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