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Experimental Evaluation of Respirable Dust and Crystalline Silica Controls during Simulated Performance of Stone Countertop Fabrication Tasks with Powered Hand Tools

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Abstract

Objectives—Workers who fabricate stone countertops using hand tools are at risk of silicosis from overexposure to respirable crystalline silica. This study explored the efficacy of simple engineering controls that can be used for dust suppression during use of hand tools by stone countertop fabricators.

Methods—Controlled experiments were conducted to measure whether wet methods and on-tool local exhaust ventilation (LEV) reduced respirable dust exposures during use of various powered hand tools on quartz-rich engineered stone. Respirable dust samples collected during edge grinding with a diamond cup wheel and a silicon carbide abrasive wheel were analyzed gravimetrically as well as by x-ray diffraction to determine silica content. A personal optical aerosol monitor was used simultaneously with the respirable dust samples and also for rapid assessment of controls for polishing, blade cutting, and core drilling.

Results—On-tool LEV and sheet-flow-wetting were effective in reducing exposures, especially when used in combination. Sheet-flow-wetting with LEV reduced geometric mean exposures by as much as 95%. However, typical water-spray-wetting on a grinding cup was less effective when combined with LEV than without LEV. Mean silica content of respirable dust samples from grinding operations was 53%, and respirable mass and silica mass were very highly correlated (r = 0.980). Optical concentration measures were moderately well correlated with gravimetric measures (r = 0.817), but on average the optical measures during a single trial using the factory calibration were only one-fifth the simultaneous gravimetric measures.

Conclusions—Sheet-flow-wetting combined with on-tool LEV is an effective engineering control for reducing respirable dust exposures during engineered stone edge grinding and blade

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cutting. On the other hand, addition of LEV to some water-spray-wetted tools may reduce the effectiveness of the wet method.

Keywords

crystalline silica; stone dust; dust suppression; local exhaust ventilation; engineering controls

INTRODUCTION

Respirable crystalline silica (RCS) exposure during stone countertop fabrication is a well-recognized respiratory disease hazard (OSHA/NIOSH 2015). Crystalline silica (SiO_2) has several polymorphs, including quartz, cristobalite, and tridymite (NIOSH 1975). Whereas natural stone countertop materials marketed as granite may contain 10 to 45% quartz (Simcox et al. 1999), “engineered” or “synthetic” stone may contain over 90% quartz by mass (OSHA/NIOSH 2015). Recent reports of silicosis among engineered stone fabricators in Spain (Garcia et al., 2011; Perez-Alonso et al. 2014), Israel (Kramer et al., 2012), Italy (Bartoli et al., 2012), and the United States (Friedman et al., 2015) suggest that countertop fabricators should be protected from RCS exposure when working with engineered as well as natural stone.

Time-weighted average exposures to RCS during countertop fabrication can exceed the current OSHA occupational exposure limit (OEL) of 0.050 mg/m^3 by as much as 80-fold unless some form of engineering control is used (Simcox et al. 1999; Phillips et al., 2013). Numerous studies, including those recently published by van Deurssen et al. (2014, 2015), have demonstrated the utility of both wet dust suppression methods and on-tool local exhaust ventilation (LEV) for controlling exposures to RCS in the construction trades. Data from the few countertop fabrication related studies published to date suggest that on-tool water spray and LEV systems can also provide effective suppression of respirable dust during countertop fabrication tasks such as cutting, edge profiling, and polishing, but concentrations may not be reduced below desired levels (Simcox et al., 1999; Cooper et al., 2015; Zwack et al., 2016; Qi and Echt 2016). Zwack et al. (2016) and Qi and Echt (2016) measured operator RCS exposures under field conditions for countertop edge grinding and polishing using hand tools under wet conditions but without LEV. On-tool water sprays were determined to be inadequate to control all exposures below 0.050 mg/m^3. Whether exposures would be adequately controlled when compared to higher OELs in other countries (which in Europe can range from 0.075 mg/m^3 in the Netherlands to 0.3 mg/m^3 in Poland), is unclear. The Qi and Echt report concluded that alternative engineering control approaches should be explored, especially for grinding.

LEV, particularly on-tool LEV, has proven effective in respirable dust control in concrete grinding and polishing (Akbar-Khanzadeh and Brillhart 2002; Akbar-Khanzadeh et al. 2007; Akbar-Khanzadeh et al. 2010; Healy et al. 2014; Croteau et al. 2004; Croteau et al. 2002; Echt and Sieber 2002; Flynn and Susi 2003), but the effectiveness of LEV in stone countertop fabrication with or without wet methods is largely uncharacterized. Cooper et al. (2015) reported that during engineered stone cutting using a hand-held worm-drive circular

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saw under controlled conditions, wet cutting with LEV was highly effective, reducing operator exposures by over 90% compared to the usual practice of wet cutting without LEV.

On-tool wetting is usually achieved using a water spray directed toward the point of contact with the stone. In the field and in controlled experiments we have observed that such sprays can be particularly messy during grinding with a segmented diamond cup wheel, and the effectiveness of the spray appears to be highly dependent on where it is directed. A dense droplet spray is ejected from the rapidly spinning grinding cup (7,000–10,000 revolutions per minute [rpm]). An alternative wetting strategy observed in a small number of shops is to flow water from a pipe or hose over the entire slab surface, but the effectiveness of this "sheet-flow-wetting" technique has not previously been evaluated.

The purpose of the present work was to explore the efficacy of on-tool LEV and alternative wetting methods in reducing operator exposures to respirable dust and RCS during simulations of common stoneworking tasks with handheld tools.

MATERIALS AND METHODS

Seven experiments assessing different tools and dust suppression methods were conducted as summarized in Table 1. The tools used are shown in Figure 1. Experiment 1 was intended to assess LEV for respirable dust (RD) and RCS control during steel cup edge wet grinding and edge wet polishing, using on-tool wetting systems, and to compare grinding and polishing exposures. Experiment 2 assessed LEV for RD control during steel cup wet edge grinding, and compared wetting by on-tool spray with wetting by a sheet water flow over the slab edge (as shown in Figure 2). Experiment 3 assessed LEV for RD and RCS control during steel cup wet edge grinding and SiC wheel wet edge grinding, where wetting was provided by a sheet water flow. Experiment 4 supplemented the Experiment 3 data with SiC wheel grinding under dry conditions, with and without LEV. Experiment 5 revisited edge polishing to compare exposures with on-tool center feed wetting to those with sheet flow wetting, with and without LEV. Experiment 6 assessed LEV during wet and dry blade cutting, where wetting was provided by a sheet water flow. Finally, Experiment 7 assessed the effectiveness of LEV during dry hole drilling, and compared dry drilling exposure measures to exposures when using a simple water immersion technique. To obtain quantifiable gravimetric measurements, it was necessary to perform stoneworking tasks continuously for 20 minutes or more per replicate trial, which placed high physical demands on the tool operator. Direct-reading instruments alone were used in some experiments for more rapid assessment of dust controls.

Experimental setting

All experiments except for Experiment 2 were conducted in the enclosed environment of a portable shelter 305 centimeter (cm) by 305 cm in plan with 215 cm high zippered side panels and peaked top (EZ Up Inc., Stockholm, WI, USA). The unventilated shelter was erected outdoors on a slightly sloped concrete surface to promote water drainage away from the work space. An engineered stone slab was placed on two saw horses in the center of the shelter (Figure 2). Between trials the shelter was opened to allow airborne dust to dissipate, and deposited dust was removed from the slab by hosing, vacuuming, or wet wiping.

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Experiment 2 was conducted just outside the enclosure, on a calm day with mild breezes less than 16 kilometers per hour as reported by the local weather service. This experiment was conducted outside the enclosure in order to minimize any potential effect of accumulated water mist to act as a dust scavenger.

A single individual, experienced in the tasks required, performed all of the stonework activities. A ground fault circuit interrupter (GFCI) was used in each power circuit to protect against shock, and the tool operator wore hearing protection, steel-toed rubber boots, a Tyvek coverall, and a hood-type powered air purifying respirator (PAPR) (Optimair 6a, MSA Inc., Cranberry Township, PA, USA) with HEPA cartridge filters (MSA Type H Optifilter) with an assigned protection factor of 25. The number of trials per day were limited so that anticipated exposure with respiratory protection would not exceed an 8-hour time-weighted average of 0.050 mg/m^3. The University of Oklahoma Health Science Center Institutional Review Board (IRB) reviewed the study protocol and determined that it did not constitute human subjects research.

Stone substrate

Pieces of 2 cm thick, 122 cm long, 60 cm wide quartz-rich (>85%) engineered stone from a single manufacturer were used as the test material. Experiments 1–4 were performed on pieces from one slab and Experiments 5–7 were performed on pieces from a different slab.

Tools, dust suppression equipment, and task design

Suction for LEV shrouds was provided by a HEPA-filtered vacuum (RIDGID ShopVac Model 9662611, Emerson Electric Co., Elyria, OH, USA), preceded by a water pre-separator made from a 5-gallon plastic jerrican. The vacuum's flow rate was measured by placing the tool with shroud inside a box that was sealed on one end to a balometer (ALNOR capture hood ABT711). The hose connecting the shroud to the vacuum passed through a sealed hole on the other end of the box. The flow rate was approximately 85 cubic meters per hour with the tools in place.

In Experiments 2, 3, 5, and 6, sheet-flow-wetting was provided by a simple "purpose-built" distribution manifold (Figure 2) similar to that seen in an Oklahoma City countertop fabrication shop. The manifold was made from a 122 cm long section of 3.2 cm (inner diameter) polyvinyl chloride pipe in which 6.5-millimeter (mm) diameter holes were drilled every 15 cm along its length. One end was plugged and the other was connected to a water hose via a garden hose valve. The pipe was clamped in place on top of the slab with the holes directed toward the work edge. The slab was leveled in the left-right direction relative to the operator position and slightly tilted toward the work edge to promote a uniform sheet-flow-wetting and cascade over the work edge. The water flow rate was measured to be 5.5 liters per minute (L min^{-1}).

The rotation rates for tools were measured with a stroboscope (Novastrobe Model 6203−.011, Monarch Instrument, Amherst, NH, USA).

Edge grinding with diamond cup wheel—Cup wheel grinding was performed with a 10-cm diameter diamond cup wheel (Cyclone Model CW40 Coarse Turbo, Diamax

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Industries, Atlanta, GA, USA). In Experiment 1, an electric angle grinder (Makita Model 9564CV, La Mirada, CA, USA) was used, fitted with a third-party shroud with add-on water spray for water-only trials (Alpha Wet Blade Cutting Kit, Alpha Professional Tools, Oakland, NJ, USA) and a different third-party vacuum shroud (Model MK-IXL 5” vacuum shroud, MK Diamond Products Inc., San Francisco, CA, USA), modified to incorporate a water spray, for water-spray-wetting-with-LEV trials. In Experiment 2, the Makita grinder with the modified vacuum shroud was used for trials with and without LEV. In Experiment 3, an electric Ryobi Model AG542 angle grinder (One World Technologies, Anderson, SC, USA) was used with the modified vacuum shroud for trials with and without LEV. In all experiments, the slab was ground at an angle to create a 45-degree beveled edge across its full 122-cm width. The grinder rotation rate was approximately 10,000 rpm. When the on-tool water-spray-wetting was used, flow was approximately 6.0–6.5 L min^{-1}. In Experiment 1, the operator was free to vary the position of the grinder as needed to reduce fatigue. In Experiments 2 and 3, the tool orientation was standardized so that the long axis of the grinder was horizontal and the LEV take-off was on top.

Edge polishing—Polishing was performed using an electric wet polisher with integrated center-feed-wetting (Makita Model PW5001C) with a 10-cm diameter 50-grit polishing pad (#50 Grit Wet Diamond Polishing Pad, Archer USA, Sunland Park, NM, USA). The wet polisher was fitted with an LEV shroud (Dust Shroud Kit Dry Grinding Dust Cover for Angle Grinder Hand Grinder 4”/5”, various vendors, imported from Hong Kong). The optional center-feed water spray emanated from two holes in the center of the polisher head at a flow rate of 5.8–6.0 L min^{-1}. The polisher was operated at a rotation rate of 4,000 rpm. Polishing was performed on a 45-degree beveled edge. In Experiment 1, the operator was free to vary the position of the polisher, but in Experiment 5 the tool orientation was standardized so that the long axis of the polisher was horizontal and the LEV take-off was on top.

Edge grinding with silicon carbide abrasive grinding wheel—Abrasive wheel grinding was performed with a 10 cm diameter by 5 cm thick, 80 grit silicon carbide (SiC) grinding wheel (Black Crow 80 grit Green Silicon Carbide Grinding Wheel, Hornytoad Tools, Dallas, TX, USA) using the Makita polisher previously described. The tool was operated at 4,000 rpm in order to maintain a rotation rate well under the 6,495 rpm maximum allowed for the abrasive wheel. The integral water feed on the tool was not used. The LEV shroud for the polisher was modified by cutting away a portion to allow the wheel edge to contact the work, and by replacing the short brush apron with a longer apron, fabricated from semi-rigid plastic, that extended to within approximately 0.7 cm of the wheel’s edge. Grinding was conducted on a vertical edge (90-degree angle) for ease of tool handling. The tool axis was horizontal with the LEV take-off on top.

Blade cutting—Blade cutting was performed with a flat 12.5-cm diameter “turbo” diamond cutting blade (Makita Model A-94605) using the Makita angle grinder described above. The grinder was fitted with an LEV shroud (Makita Model 195236-5 Dust Collecting Wheel Guard) from which the detachable portion was removed to expose approximately 2 cm of the blade radius. Straight vertical cuts of depth totaling approximately 1 cm after 2–3

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passes were made in the slab with the blade. All trials were conducted with the same shroud in place. The tool was operated at 10,000 rpm.

Core drilling—Drilling of simulated faucet holes was performed with a 1–3/8 inch (3.49 cm) diamond core bit (Diteq Model D66205, Lenexa, KS, USA) used on the Makita polisher at a speed of approximately 3000 rpm. LEV trials were conducted using a dust shroud ("BitBuddie", Dustless Technologies, Price, UT, USA) that fit around the core bit and rested on the stone surface. LEV was not tested in combination with wet methods because the LEV shroud would have sucked in large amounts of water. For wet trials, the desired location of the hole was covered with a shallow pool of water contained in a ring of plumber's putty (Oatey, Cleveland, OH, USA) about 12 cm in diameter affixed to the stone surface, as shown in Figure 1. This improvised "water ring" is a common method for wet core drilling. Each trial consisted of drilling one hole through the 2-cm thick slab, which took 1–3 minutes depending on the pressure applied by the tool operator.

Exposure measurement and sample analysis

Aerosol concentrations in the operator's breathing zone were measured in all experiments using a compact laser aerosol photometer (SidePak Model AM510, TSI Inc., Shoreville, MN, USA) fitted with a Dorr-Oliver 10-mm nylon cyclone pre-separator that was clipped to the tool operator's collar. The SidePak aerosol monitor's flow was adjusted to 1.7 L min^{-1} as required for selective sampling of respirable dust. The monitor was factory calibrated to the respirable fraction of ISO 12103-1, A1 Test Dust. During Experiments 5 and 7, in which 2-minute average aerosol concentrations during polishing and core drilling were observed to be low, 3–4 background readings of ambient aerosol were interspersed between experimental trials. Two-minute average background concentrations were measured within the closed shelter after the dust from the preceding trial was allowed to dissipate as described above.

Personal breathing zone respirable dust samples were collected in Experiment 1 using a GS-3 cyclone respirable dust sampler (Catalog number 225.1, SKC Inc., Eighty Four, PA, USA) with pre-weighed 5-micrometer (μm) pore size polyvinyl chloride (PVC) filters (SKC 225-8-01) in 37-mm diameter 3-piece cassettes (SKC 225–8202). The cyclone was clipped to the coverall collar and connected by 6.5 mm ID tubing to an air sampling pump (SKC Universal PCXR4 or PCXR8). The cyclone sampling train was calibrated to 2.75 L min^{-1} flow, for sampled volumes of approximately 55 and 82.5 liters for grinding trials and polishing trials, respectively. Two field blanks were collected per day of measurements, with a total of 6 field blanks collected over three days of sampling.

Following Qi et al. (2016) and Echt and Mead (2016), to ensure more consistently quantifiable filter samples than proved feasible in Experiment 1 using the GS-3 cyclone during task simulations, in Experiments 3 and 4 personal breathing zone respirable dust samples were collected using a GK4.162 (RASCAL) respirable cyclone (Mesa Labs, Butler, NJ, USA) with a Leland Legacy air sampling pump (SKC) operating at 9.0 L min^{-1} flow rate, for a sample volume of approximately 180 liters. This sampler uses 47 mm diameter 5-μm pore size PVC filters (SKC 225-5-47) in 3-piece conductive cassettes (SKC 225–8497).

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Air sampling trains and the aerosol monitor flow were calibrated using a frictionless piston calibrator (BIOS DC-Lite, Mesa Labs, Butler, NJ, USA). Three or four field blanks were collected on each of the 3 days of sampling, for a total of 11 field blanks.

During simultaneous aerosol monitoring and respirable dust collection, the collar positions of the two samplers were alternated between trials to avoid bias due to sampler location. When measurement was conducted using the SidePak aerosol monitor only, the cyclone pre-separator was mounted on the operator's dominant (right) side collar.

Collected respirable dust was analyzed gravimetrically in-house for respirable mass according to NIOSH Method 0600 (NIOSH 2003). The limit of detection (LOD) and limit of quantification (LOQ) for the gravimetric analysis were estimated as recommended in ASTM International Method D6552-06 (ASTM 2011). The LOD for gravimetric analysis in Experiment 1 was 0.057 mg and the LOQ was 0.190 mg. In Experiments 3 and 4, the gravimetric LOD and LOQ were 0.015 mg and 0.051 mg, respectively.

After gravimetric analysis, the filters were sent to a certified laboratory for analysis of silica content by x-ray diffraction according to NIOSH Method 7500 (NIOSH 2003). The LOD and LOQ for silica, cristobalite, and tridymite mass, as reported by the laboratory, were 0.004 and 0.013 mg, 0.005 and 0.016 mg, and 0.010 and 0.013 mg, respectively.

Replicates and randomization

Except as noted, each experiment was conducted in multiple blocks, where each block consisted of one trial each per experimental condition. The number of replicates of each condition was thus generally equal to the number of blocks. The order of conditions was randomized in each block. The exceptions were Experiment 1, where grinding trials were always followed by polishing trials but the order of LEV or no-LEV trials was random, and Experiment 2, where trials of a single condition were replicated 2–3 times consecutively and the order of conditions was not randomized. In Experiment 3, one SiC wheel trial with LEV and one SiC wheel trial without LEV were repeated due to failed optical measures in one block; however, in another block a SiC without LEV trial was inadvertently substituted for a SiC with LEV trial, resulting in unequal numbers of replicates for the different conditions and exposure measures.

RESULTS

Edge grinding with diamond cup wheel

The results of gravimetric analysis, silica analysis, and aerosol photometer monitoring during wet grinding with the diamond cup wheel are summarized in Table 2. Normal equivalent deviations (NED) plots (Johnson, 2017, pp. 38–41) of the logarithms of the gravimetric results and silica results revealed these data to be log-normally distributed, and an NED plot of the aerosol monitor results revealed these to be normally distributed. One gravimetric result was below the LOD. All three measures in Experiment 1 showed the counterintuitive outcome that exposure for water-spray-wetted grinding with LEV was higher than that for water-spray-wetted grinding without LEV. Two-sample *t*-tests on the logarithms of the collected dust measures in Excel indicated a statistically significant

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difference in the geometric mean concentrations for both the with-LEV vs. without-LEV gravimetric results ($p = 0.0003$) and the with-LEV vs. without-LEV RCS results ($p \ll 0.0001$), though the differences were opposite in direction to what might be expected (concentrations were higher with LEV than without); the differences measured by aerosol monitor were not statistically significant.

The aerosol monitor results in Experiment 2 were consistent with the counterintuitive result from Experiment 1, though not statistically significant. Due to this anomalous result and the unequal number of observations at different conditions (i.e. the data set was unbalanced), two-way ANOVA was not conducted; instead, selected contrasts were performed in Excel using two-sample *t*-tests. In the open air, sheet-flow-wetting provided superior dust control compared to water-spray-wetting for the measures pooled over LEV condition ($p = 0.0003$). LEV significantly reduced exposures during sheet-flow-wetting grinding ($p = 0.0006$).

The gravimetric and silica results Experiment 3 appeared to be log-normally distributed. Due to the unbalanced data set and log-normal data distributions, statistical analyses of the gravimetric and silica data were conveniently conducted using the GLIMMIX procedure in SAS, specifying a log-normal distribution and designating wetting and LEV condition as fixed effects. No random effects were included. For the gravimetric respirable dust data, the main effects of grinder type and LEV condition as well as their interaction were significant ($p = 0.0082$,$p < 0.0001$, and $p < 0.0021$, respectively). Similar results were obtained for the respirable silica data ($p < 0.0021$, $p < 0.0001$, and $p < 0.0012$). For the aerosol monitor data, only the LEV condition was significant ($p < 0.0039$). Sheet-flow-wetting combined with LEV reduced exposures during cup wheel grinding by nearly 50% compared to sheet-flow-wetting alone, as determined by the geometric mean of gravimetric measures, the geometric mean of RCS measures, and aerosol monitor mean concentrations.

Quartz was the only form of silica detected during grinding with the cup wheel. The silica mass and respirable mass were highly correlated ($r = 0.95$). The percent silica content of the respirable dust calculated from the paired respirable dust and RCS mass for each sample was not significantly affected by LEV or flow type. The mean silica fraction was 52.0% (range 9.6 – 76.2%).

Edge grinding with silicon carbide abrasive grinding wheel

Wet SiC grinding trials in Experiment 3 and dry trials in Experiment 4 were conducted under identical conditions except that all of the Experiment 3 trials used sheet flow wetting and all of the Experiment 4 trials were dry. The results of wet and dry trials were therefore aggregated for analysis. While not optimal from an experimental design perspective, it seemed unlikely that an unknown factor could be present that would confound the analysis. . The gravimetric results and silica results were log-normally distributed with similar variances, whereas the aerosol monitor results were normally distributed with dissimilar variances. The GLIMMIX procedure was again employed for the gravimetric respirable dust data The analysis indicated a significant main effect for LEV condition ($p < 0.0001$) but not wetting condition, though the wetting approached significance ($p = 0.0523$); the interaction was not significant.. The small number of replicate trials in Experiment 4 (the dry trials) no doubt limited the power of the analysis to detect a main effect for wetting condition. For the

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respirable silica data, both wetting condition and LEV condition were significant (p = 0.0251 and p < 0.0001, respectively), and the interaction was again non-significant.

Compared to the baseline condition of dry SiC grinding without LEV, the geometric mean exposures, measured as respirable dust concentration or as RCS concentration, were reduced by about 50% by use of sheet-flow-wetting alone and about 85% by the use of LEV alone. Use of LEV in addition to sheet-flow-wetting reduced exposure by about 95% compared to baseline. LEV appeared to be more effective as an adjuvant to sheet-flow-wetting with the SiC wheel than it was for sheet-flow-wetting with the cup wheel.

Aerosol monitor concentration data, as averages over the 20-minute trial duration, were approximately normally distributed and variances were dissimilar. Analysis was again conducted with the SAS GLIMMIX procedure, specifying wetting condition and LEV condition as fixed effects. The results indicated a non-significant interaction of wetting condition and LEV condition but significant main effects for both wetting condition (p = 0.0098) and LEV condition (p = 0.0059). The exposure reductions calculated from the aerosol monitor results for wetting and LEV conditions were similar to the reductions noted above for the gravimetric and silica results.

Three of the SiC wheel wet grinding samples and two of the SiC wheel dry grinding samples were positive for cristobalite, but cristobalite did not exceed 2% of the total silica mass in any sample. The RCS mass and respirable dust mass were very highly correlated (r = 0.980). The mean silica fraction among samples from SiC grinding was 54.1% (range 44.3 – 62.2%), which was not significantly different from the mean silica fraction for the cup grinding samples.

Edge polishing

The gravimetric results for edge polishing were severely censored, with 4 of the 6 wet-polishing-with-LEV masses and 5 of the 6 wet-polishing-without-LEV masses below the LOD, preventing statistical comparison of the two polishing conditions using these data. The silica results for polishing were mostly above the LOD, but all were below the LOQ (~0.16 mg/m^3), providing insufficient basis for determining the effect of LEV in combination with wetting. Only quartz was detected. It was not determined whether the aerosol monitor readings were above background.

In Experiment 5, aerosol monitoring was repeated during wet polishing with center-feed-wetting with and without LEV, as well as sheet-flow-wetting with and without LEV. The exposures, measured as two-minute average concentrations, were not significantly elevated above background (~0.073 mg/m^3) for any of the control conditions.

Blade cutting

Aerosol monitoring results during blade cutting are shown in Table 4. Unlike the previous SidePak measures, the data in Experiment 6 were approximately log-normally distributed. The logarithms of the data had similar variances as indicated by Levene's test (α = 0.05) (Levene, 1960). Two-way ANOVA on the logarithms of the data values indicated both wetting condition and LEV condition to be significant factors (p = 0.0003 and p = 0.045,

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respectively). Their interaction was non-significant. Compared to dry cutting without LEV, LEV alone provided a 26% reduction in respirable dust exposures, sheet-flow-wetting alone provided a 52% reduction, and LEV combined with sheet-flow-wetting provided a 72% reduction.

Core drilling

Even though visible dust was generated during core drilling, the elevation of the exposure measures above background (~ 0.063 mg/m^3), as 2-minute average concentrations measured by the SidePak aerosol monitor, was not statistically significant for any condition.

DISCUSSION

The purpose of this study was to make comparisons between dust control conditions rather than to characterize actual work exposures for comparison to occupational exposure limits. Tasks were of intentionally long duration under confined conditions in order to ensure the collection of quantifiable respirable dust masses, so that the measured exposures should not be taken to represent those that might typically be seen in a countertop fabrication shop.

Comparison of gravimetric measures and optical measures

Paired measures of respirable dust were made in Experiments 1, 3, and 4 using gravimetric methods and the TSI SidePak optical aerosol monitor. Although the SidePak reported results in units of mg/m^3, these values were only relative because the instrument was not calibrated for the aerosol being measured. Particle concentration measurement by light scattering methods is influenced by the size distribution and refractive index of the aerosol particles, so that the measurement is only accurate when the measured aerosol is identical to the calibration aerosol (Hinds, 1999, p. 370). Omitting gravimetric results that were below the LOQ, scatter plots (Figure 3) indicated a linear association between the SidePak optical measures and the gravimetric measures from the GS-3 and GK4.162 cyclones with a correlation coefficient of 0.817. Simple linear regression of the SidePak measures on the gravimetric measures indicated a non-significant intercept. Regression using a zero intercept resulted in a coefficient of 0.196 with $R^2 = 0.85$. Thus on average the optical monitor with factory calibration reported a concentration only about one-fifth of the true respirable dust mass concentration when measuring individual dust samples from grinding engineered stone.

The scatter plot in Figure 3 suggests that even if a suitable calibration factor were applied, an optical measure (averaged over task duration) would not be a reliable indicator of the respirable dust mass concentration during a single performance of a grinding task. For measures aggregated across replicate trials, regression of the means of the optical measures on the geometric means of the corresponding gravimetric measures for seven different tool/control configurations yielded a coefficient of 0.247 with a zero intercept ($R^2 = 0.942$). The aggregated measures are also plotted in Figure 3. The good correlation between aggregated optical measures and aggregated gravimetric measures supports the use of aerosol monitoring for rapid exposure measurement during replicate trials to screen for efficacy of dust controls. In addition, when conducting RCS measures using a respirable cyclone,

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parallel sampling with an optical instrument could provide additional time-concentration information useful in correlating exposures with stone working specific tasks. However, analytical results presented for Experiment 3, in which the aerosol monitor results failed to identify statistically significant main effects demonstrated with the gravimetric and silica results, suggest that the monitor results may not provide sufficient power in statistical tests.

Efficacy of wet methods and LEV for respirable dust suppression

Both wet methods and LEV were shown to be individually effective in reducing respirable dust exposures during SiC wheel edge grinding (Experiments 3 and 4) and blade cutting (Experiment 6). LEV in combination with on-tool water-spray-wetting was unexpectedly found to be less effective than water-spray-wetting alone during cup grinding (Experiments 1 and 2). We conjecture that there are two major mechanisms of capturing dust by wet methods: 1) the emitted dust particles impinge on the wet surface and are captured, and 2) water droplets thrown into the air scavenge airborne respirable dust particles. It was observed that the cup wheel threw off a dense cloud of droplets during water-spray-wetting, especially under no-LEV conditions. When LEV was applied, it captured many of the droplets due to the proximity between the LEV port on the vacuum shroud and the water spray nozzle, resulting in a visibly less dense droplet cloud, which may reduce the efficacy of droplet scavenging. Grinding with sheet-flow-wetting (Experiments 2 and 3) did not throw off a dense droplet cloud, and LEV was found to further reduce the respirable dust concentration. Sheet-flow-wetting may produce fewer airborne droplets to scavenge dust compared to water-spray-wetting. However, the continuous and gentle sheet-flow-wetting might capture more dust by the impingement mechanism than water-spray-wetting as it was used in this work. Furthermore, the LEV applied with sheet-flow-wetting may more effectively capture airborne dust as evidenced by the further reduced respirable dust concentration.

The results from Experiments 1 and 3 for cup wheel grinding were not obtained under identical conditions because different cyclones and different angle grinders (but each fitted with the same shroud) were used; nevertheless, the measured exposures provide some basis for comparing the control conditions. The gravimetric and silica measures for sheet-flow-wetting with LEV in Experiment 3 did not indicate lower exposures than were found during water-spray-wetting without LEV in Experiment 1. Since the water sheet covered the whole slab, only a portion of the water made contact with the tool at any given time. Assuming all water flowed over the 122-cm wide work edge in a uniform manner, the water flow to the actual contact zone of a 10-cm diameter grinding wheel was approximately 0.45 L min^{-1}, much less than the 6 L min^{-1} flow from the water-spray-wetting. Both Experiments 1 and 3 were conducted in the enclosed environment, which may affect the relative performance of the two wetting methods with different effective flow rates because airborne droplets were contained inside, a condition favorable to the droplet scavenging mechanism. In an open air condition, which is closer to the real condition in stone countertop shops, the effect of different flow rates may be less influential because water droplets and moisture can rapidly dissipate. In the open air test in Experiment 2, sheet-flow-wetting provided superior dust control compared to water-spray-wetting, especially when combined with LEV.

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Individually, LEV alone was more effective than sheet-flow-wetting alone during SiC wheel grinding, whereas sheet-flow-wetting was more effective than LEV during blade cutting. The relatively poorer performance of LEV during blade cutting compared to SiC grinding was perhaps attributable to the 3-fold difference in dust ejection velocity as determined by the tool rotation rate (4000 rpm for SiC grinding vs. 10,000 rpm for blade cutting) as well as the diameter of the wheel or blade (10 cm for the SiC wheel vs. 12.5 cm for the cutting blade). The effectiveness of the LEV for all operations could likely be improved with exhaust ventilation rates higher than the relatively low 85 cubic meters per hour used in this work.

RCS exposures during core drilling and wet polishing were too low for the efficacy of dust controls to be evaluated using the direct-reading aerosol monitor. The relatively low exposures during dry core drilling were surprising; though low-speed dry drilling resulted in a heap of settled dust surrounding the newly drilled hole, it is possible that it did not generate much respirable aerosol.

RCS exposures during grinding and polishing

Respirable quartz was measured in all of the samples from grinding operations and detected in most of the samples from wet polishing. Cristobalite was found in about one-third of the SiC wheel grinding samples, constituting no more than 2% of the silica mass in those samples. No cristobalite was found in the cup grinding or polishing samples. Cristobalite is known to be formed at high temperature in the Acheson furnace SiC production process (Foreland et al., 2008), so it seems likely that dust abraded from the grinding wheel was the source of the cristobalite.

RCS as a fraction of total respirable mass averaged 53% overall (range 9.3–76.2%). These values were similar to the 42.5% mean and 25.0 – 78.3% range seen by Qi and Echt (2016) and the 14–67% range found by Phillips et al. (2013) in bulk dust samples from engineered stone.

Respirable mass and RCS measures were very highly correlated ($r = 0.98$). Thus, for a sampling campaign involving a single type of stone, only a limited number of respirable dust samples might need to be analyzed for silica to obtain a reliable percent silica factor for application to the remainder of the respirable dust mass samples.

As previously noted, the silica exposures measured in this study were not necessarily representative of real-life fabrication conditions. In particular, the prolonged (20–30 minutes) performance of a single task within a small enclosure was designed to optimize the potential for collecting quantifiable amounts of dust for a single task; the purpose was to make comparisons between dust control conditions, not to compare exposures to occupational exposure limits. That said, these results suggest that the interventions explored in this work have the potential to substantially reduced RCS exposures under real working conditions.

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SUMMARY AND CONCLUSIONS

Controlled experiments were conducted to assess the efficacy of wet methods and on-tool LEV during diamond cup wheel edge grinding, SiC wheel edge grinding, edge polishing, blade cutting, and core drilling on engineered stone. Sheet-flow-wetting and LEV in combination were more effective than either dust suppression method alone during grinding and cutting. On the other hand, addition of LEV to some water-spray-wetted tools may reduce the effectiveness of the wetting.

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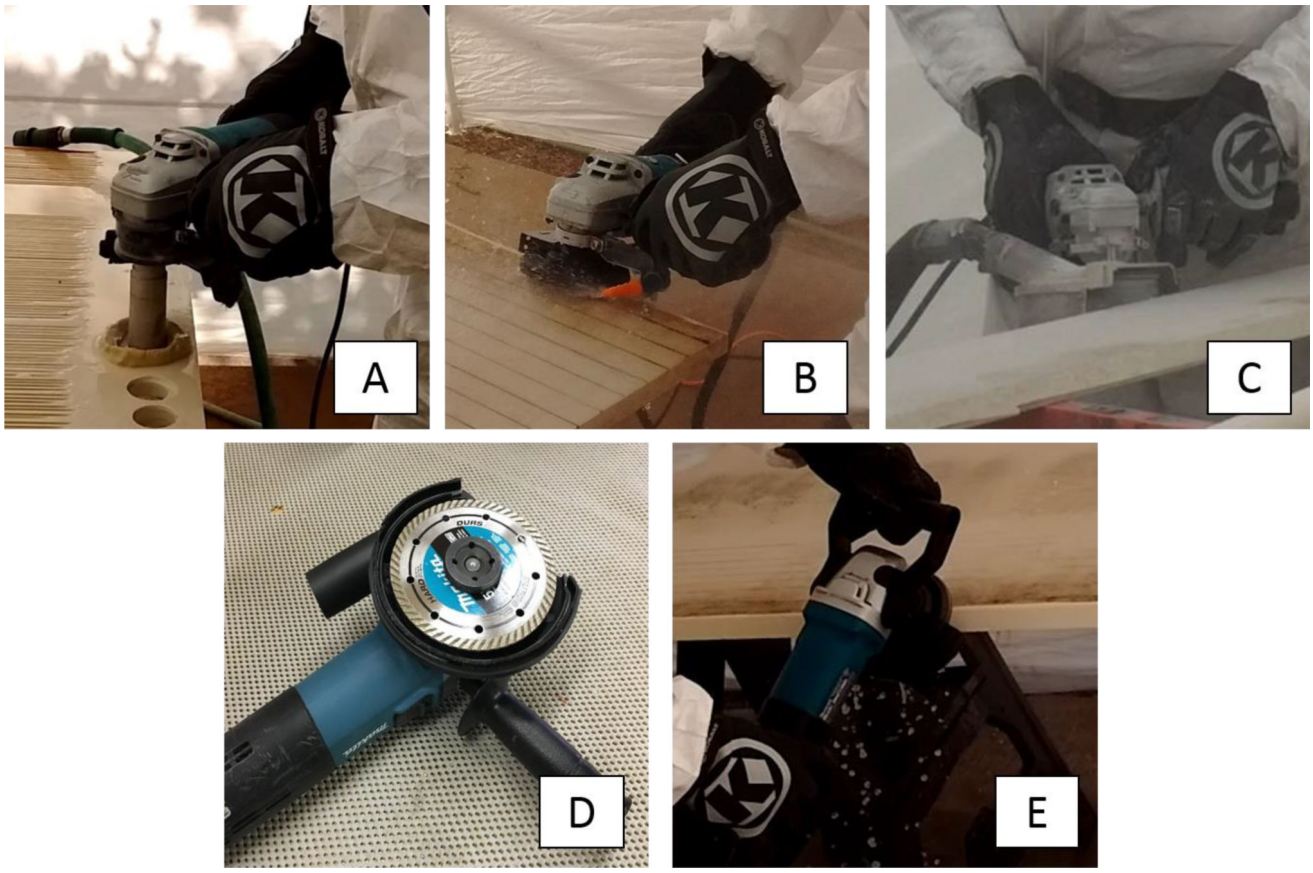

Figure 1.

Tools used in the experiments. A: drilling with a core bit using a “water ring” made of plumber’s putty; B: steel cup edge grinding with jet spray; C: SiC dry edge grinding; D: grinder fitted with a cutting blade; E: edge polishing.

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Figure 2.
Experimental setup for wet operations using sheet flow wetting via a perforated water distribution manifold.

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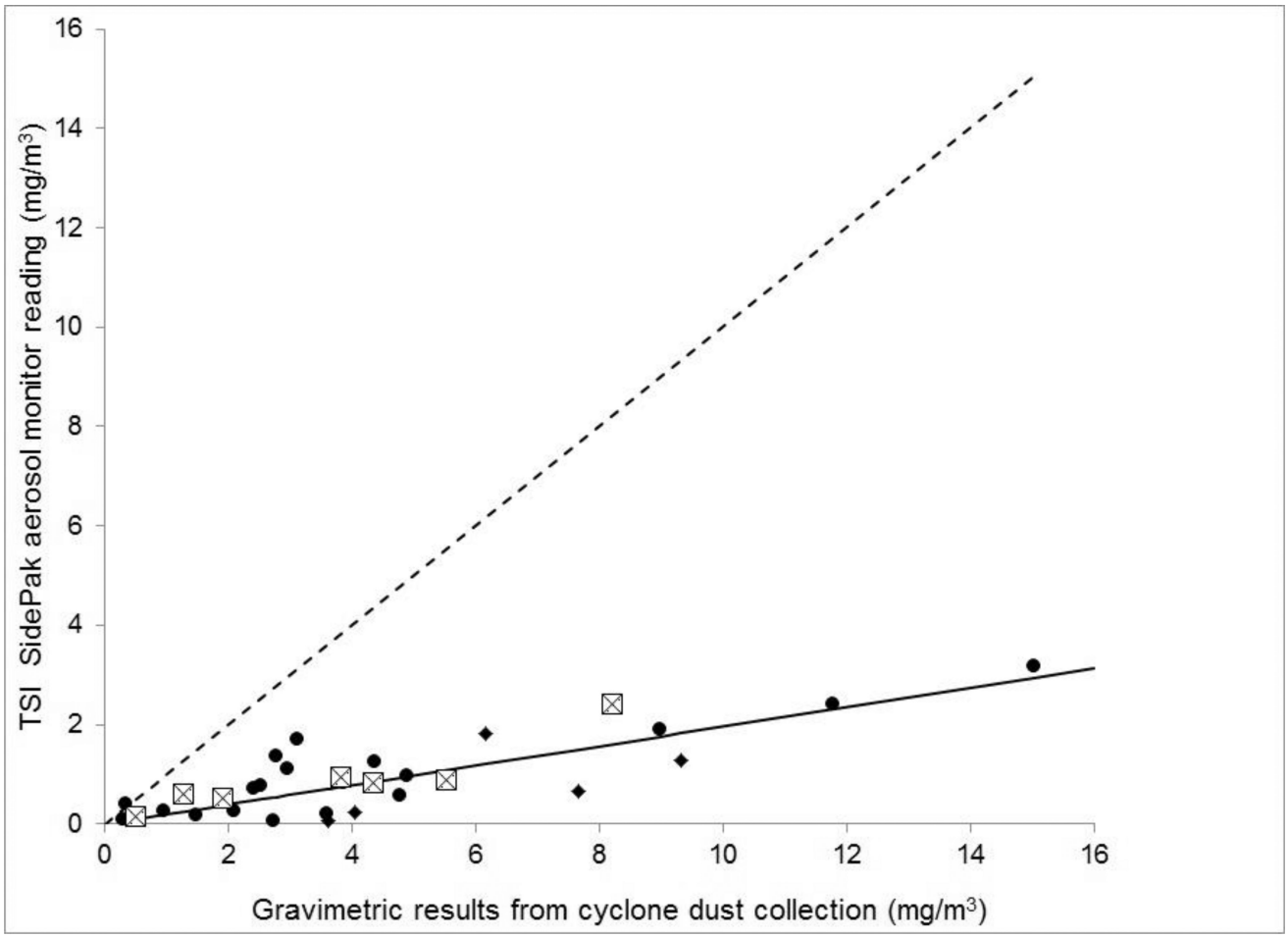

Figure 3.

Scatter plot of paired data from the TSI SidePak optical aerosol monitor with Dorr-Oliver cyclone and gravimetric analysis of respirable dust > LOQ collected using cyclone samplers. Solid circles: GK4.162 cyclone samples; solid diamonds: GS-3 cyclone samples. The solid line represents the least-squares fit with zero intercept. A dotted line with unit slope is provided for comparison. The squares with crosses represent the mean of the replicated aerosol monitor measures for a given tool/condition plotted against the corresponding geometric mean of the replicated gravimetric measures.

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Table 1

Summary of simulated stoneworking experiments

Experiment	Tasks and control conditions*	Exposure measures	Blocks of trials[a]	Trial duration (minutes)
1	Cup grinding, water-spray-wetting, LEV Cup grinding, water-spray-wetting, no LEV Polishing, center-feed-wetting, LEV Polishing, center-feed-wetting, no LEV	RD (GS-3 cyclone) RCS (GS-3 cyclone) RD (aerosol monitor)	6	20 (grinding) 30 (polishing)
2[b]	Cup grinding, water-spray-wetting, LEV Cup grinding, water-spray-wetting, no LEV Cup grinding, sheet-flow-wetting, LEV Cup grinding, sheet-flow-wetting, no LEV	RD (aerosol monitor)	–[c]	2
3	Cup grinding, sheet-flow-wetting, LEV Cup grinding, sheet-flow-wetting, no LEV SiC wheel grinding, sheet-flow-wetting, LEV SiC wheel grinding, sheet-flow-wetting, no LEV	RD (GK4 cyclone) RCS (GK4 cyclone) RD (aerosol monitor)	4[d]	20
4	SiC wheel grinding, dry, LEV SiC wheel grinding, dry, no LEV	RD (GK4 cyclone) RCS (GK4 cyclone) RD (aerosol monitor)	3	20
5	Polishing, center-feed-wetting, LEV Polishing, center-feed-wetting, no LEV Polishing, sheet-flow-wetting, LEV Polishing, sheet-flow-wetting, no LEV	RD (aerosol monitor)	6	2
6	Blade cutting, sheet-flow-wetting, LEV Blade cutting, sheet-flow-wetting, no LEV Blade cutting, dry, LEV Blade cutting, dry, no LEV	RD (aerosol monitor)	6	2
7	Core drilling, with water ring Core drilling, dry, LEV Core drilling, dry, no LEV	RD (aerosol monitor)	6	1–3

*SiC = silicon carbide; RCS = respirable crystalline silica; RD = respirable dust

[a]Each block consisted of one trial per condition, generally in random order.

[b]Conducted in open air; all the other experiments were conducted in an enclosed tent.

[c]5 replicates of each condition were performed, but were not randomized in blocks.

[d]Two additional SiC wheel trials were performed due to failure of the aerosol monitor during one block.

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Table 2

Effect of on-tool LEV and water flow configurations during wet edge beveling with diamond cup grinding wheel.

	Cup grinding, water-spray-wetting, with LEV	**Cup grinding, water-spray-wetting, no LEV**	**Cup grinding, sheet-flow-wetting, with LEV**	**Cup grinding, sheet-flow-wetting, no LEV**
	Respirable dust concentrations (20-minute average, Experiment 1)		Respirable dust concentrations (20-minute average, Experiment 3)	
Replicates	6	6	4	4
Range (mg/m^3)	2.933[a] - 9.306	< LOD - 2.708[a]	1.467 – 2.521	2.763 – 4.890
GM (mg/m^3)	5.158	1.238[a]	1.900	3.812
GSD	1.578	1.772	1.248	1.284
	Respirable silica concentrations (20-minute average, Experiment 1)		Respirable silica concentrations (20-minute average, Experiment 3)	
Replicates	6	6	4	4
Range (mg/m^3)	2.084 – 6.223	0.261 – .571	0.907 – 1.484	1.520 – 2.621
GM (mg/m^3)	2.988	0.434	1.128	2.115
GSD	1.584	1.399	1.226	1.283
	Aerosol monitor respirable concentrations[b] (20-minute average, Experiment 1)		Aerosol monitor respirable concentrations[b] (20-minute average, Experiment 3)	
Replicates	6	6	4	4
Range (mg/m^3)	0.071 – 1.830	0.182 – 1.152	0.187 – 0.770	0.202 – 1.375
Mean (mg/m^3)	0.898	0.627	0.505	0.949
Variance (mg/m^3)^2	0.477	0.147	0.0585	0.2761
	Aerosol monitor respirable concentrations[b] in open air (2-minute average, Experiment 2)			
Replicates	5	5	5	5
Range (mg/m^3)	0.026 – 0.390	0.010 – 0.066	0.008 – 0.022	0.019 – 0.044
Mean (mg/m^3)	0.058	0.038	0.013	0.028
Variance (mg/m^3)^2	0.00051	0.00025	0.00003	0.00007

GM = geometric mean (mg/m^3), GSD = geometric standard deviation

[a] < LOQ

[b] Not calibrated for stone dust

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Table 3

Effect on exposure of on-tool LEV and sheet-flow-wetting during edge grinding with a silicon carbide (SiC) abrasive wheel.

	SiC wheel grinding, sheet-flow-wetting, with LEV	**SiC wheel grinding, sheet-flow-wetting, no LEV**	**SiC wheel grinding, dry, with LEV**	**SiC wheel grinding, dry, no LEV**
	Respirable dust concentrations (20-minute average, Experiment 3)		Respirable dust concentrations (20-minute average, Experiment 4)	
Replicates	4	6	3	3
Range (mg/m^3)	0.302 – 0.963	2.403 – 8.969	0.332 – 2.954	3.119 – 15.012
GM (mg/m^3)	0.505	4.347	1.269	8.201
GSD	1.621	1.650	3.238	2.330
	Respirable silica concentrations (20-minute average, Experiment 3)		Respirable silica concentrations (20-minute average, Experiment 4)	
Replicates	4	6	3	3
Range (mg/m^3)	0.160 – 0.496	1.161 – 4.436	0.198 – 1.830	1.749 – 8.738
GM (mg/m^3)	0.248	2.249	0.767	4.819
GSD	1.639	1.664	3.286	2.417
	Aerosol monitor respirable concentrations[a] (20-minute average, Experiment 3)		Aerosol monitor respirable concentrations[a] (20-minute average, Experiment 4)	
Replicates	3	5	3	3
Range (mg/m^3)	0.088 – 0.251	0.053 – 1.906	0.254 – 1.119	1.693 – 3.165
Mean (mg/m^3)	0.158	0.822	0.593	2.423
Variance (mg/m^3)^2	0.007	0.458	0.2131	0.5418

GM = geometric mean (mg/m^3), GSD = geometric standard deviation;

[a]Not calibrated for stone dust

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Table 4

Effect of on-tool LEV and sheet-flow-wetting on exposures during blade cutting, as respirable concentrations by aerosol monitor[a] (2-minute averages, Experiment 6)

	Blade cutting, sheet-flow-wetting, with LEV	Blade cutting, sheet-flow-wetting, no LEV	Blade cutting, dry, with LEV	Blade cutting, dry, no LEV
Replicates	6	6	6	6
Range (mg/m^3)	0.525 – 2.408	0.968 – 5.904	1.951 – 6.722	3.415 – 6.240
GM (mg/m^3)	1.212	2.075	3.203	4.332
GSD	1.688	1.893	1.551	1.242

GM = geometric mean (mg/m^3), GSD = geometric standard deviation

[a]Not calibrated for stone dust