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Case Study
Evaluation and Control of Respirable Silica Exposure During Lateral Drilling of Concrete

INTRODUCTION

Silica exists in both crystalline and noncrystalline forms, with crystalline silica being the hazard of concern. Silica, or silicon dioxide, exposure is associated with many occupations, including construction workers, laborers, miners, foundry workers, glassmakers, drywall finishers, bricklayers, and tuckpointers.(1) Crystalline silica occurs most commonly in the form of quartz, cristobalite, and tridymite, and occupational exposure limits (OELs) have been established for these three structures.(2,3) Quartz is the most common, both in the environment and industry, and is found in many natural materials, including granite, slate, limestone, sandstone, and manufactured materials such as concrete and masonry units (e.g., bricks, blocks, paving stones). Prolonged or repeated exposure to respirable (particles less than 10 μm in aerodynamic diameter) silica can result in silicosis or other silica-related diseases, including pulmonary tuberculosis, lung cancer, silicoproteinosis,(4) rheumatoid arthritis, sarcoidosis, and scleroderma. Silicosis is a fibrotic lung disease resulting from the deposition of crystalline silica in the alveolar region of the lungs. Symptoms associated with silicosis include shortness of breath, fatigue, chest pains, and susceptibility to infection. While preventable, silicosis can be a fatal lung disease.

The Occupational Safety and Health Administration (OSHA), National Institute for Occupational Safety and Health (NIOSH) and ACGIH® have published OELs (Table I) based on the respirable fraction of the silica aerosol, e.g., particles less than 10 μm in aerodynamic diameter.(2,5–7)

Several construction trades are exposed to silica dust through the cutting, grinding, chipping, and drilling of concrete. A number of studies have measured silica dust generated by construction tasks involving mechanical disturbance of concrete, and some have also evaluated various types of dust reduction methods.(8–12) However, few studies have evaluated exposures due to drilling. Studies sampling respirable silica exposure during vertical drilling into concrete with pneumatic rock drills found geometric mean concentration of 0.20 mg/m^3 (GSD = 5.2),(13,14) suggesting that drilling may lead to exposures above OELs when controls are not used. There were approximately 7.2 million workers employed in construction in 2008. The two segments of the industry most likely to utilize rock drills of the type used in this case study – (1) highway, street, and bridge construction; and (2) foundation, structure, and building exterior construction – employ 328,900 and 987,800 workers, respectively.(15)

Exposure to dust can be reduced through one or more of the following methods: reduced dust generation or dispersion, dilution, isolation from the worker, and control or capture. Of these, the preferred method is reduction of dust generation followed by dust control or capture. The primary means of dust exposure reduction methods used in construction are source dust collection and/or wet dust suppression. Source

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TABLE I. Occupational Exposure Limits for Crystalline Silica

Organization or Agency	Form of Crystalline Silica	Limit (mg/m^3)
NIOSH[A]	Quartz	REL = 0.05 10-hr TWA during a 40-hour workweek
	Cristobalite	REL = 0.05 10-hr TWA during a 40-hour workweek
	Tridymite	REL = 0.05 10-hr TWA during a 40-hour workweek
OSHA[B]	Quartz	PEL = 250 mppcf ÷ (% Quartz + 5)
	Cristobalite	PEL = $\frac{1}{2}$ (250 mppcf) ÷ (% Cristobalite + 5)
	Tridymite	PEL = $\frac{1}{2}$ (250 mppcf) ÷ (% Tridymite + 5)
ACGIH	Crystalline silica	TLV = 0.025
	Quartz	2006-Combined into one TLV, Crystalline Silica
	Cristobalite	2006-Combined into one TLV, Crystalline Silica
	Tridymite	2005-Withdrawn due to insufficient data

[A]NIOSH Publication No. 2005–151.
[B]The PEL for silica in OSHA's Safety and Health Regulations for Construction, 29 CFR 1926.55(a), is an 8-hr TWA expressed in terms of millions of particles per cubic foot (mppcf) instead of milligrams per cubic meter (mg/m^3). The construction PEL units were derived from an obsolete particle count sampling method, which has been replaced with respirable particulate sampling methods that provide results in units of mg/m^3. The OSHA National Emphasis Program (NEP) Crystalline Silica adopted a conversion factor of 0.1 mg/m^3 per mppcf for use in converting the construction PEL to units of mg/m^3 for comparison to laboratory results.

dust collection uses local exhaust ventilation (LEV) to move dust from the source to a point of collection. Vacuum systems are utilized with shrouds, ductwork, and often filtration in dust collection systems to control silica and other particulates. This case study describes our evaluation of LEV for collection and capture of dust generated by lateral concrete drilling.

While studies have documented respirable silica exposures associated with vertical drilling, exposures associated with horizontal drilling have not been characterized. Horizontal drilling into concrete, e.g., dowel and rod drilling, is used for structural upgrades to bridges, highway sound walls, buildings, and other structures. Typically, the holes are 1 in. (25.4 mm) in diameter and 1 to 2 ft (30.5 to 61 cm) deep. Rebar is inserted into the holes and secured with epoxy, and then concrete is poured into an adjacent form connecting the newly formed concrete with the original structure. An upgrade may involve drilling thousands of holes. The drilling is usually done manually by laborers who use 30- to 45-lb (13.6 to 20.4 kg) pneumatic rock drills.

The Ergonomics Program at the University of California at San Francisco (UCSF) is developing a jig to support the rock drill. This work is funded through a cooperative agreement between CPWR - The Center for Construction Research and Training, and NIOSH and is part of a larger study that is focused primarily on the design and evaluation of tools and equipment that minimize upper body strain among construction workers. The primary purpose of the jig we evaluated for this case study is to support the weight and the applied forces of the drill and, thereby, to reduce musculoskeletal injuries.

However, due to increased interest in reducing silica exposure among construction contractors, driven in part by a relatively new Cal/OSHA silica standard, UCSF has incorporated additional components to the original jig aimed at reducing silica and noise exposure during rock drilling. The jig evaluated as part of this case study is still in development and is not commercially available. It is being developed in partnership with regional contractors and unions so that the resulting prototype will have been field tested and evaluated for its feasibility for routine use in the construction industry. Because the jig is not yet commercially manufactured, cost information is not available. The LEV system (vacuum and drill bit shroud) used in combination with the jig to reduce silica dust exposure is commercially available for approximately $2100.

The primary objective of this case study was to compare silica exposure during lateral concrete drilling using (1) the usual, manual method with a pneumatic rock drill (Figure 1); (2) a movable jig that supports a pneumatic rock drill and increases the distance between the operator and the point of dust generation (Figure 2); and (3) the same jig equipped with a dust shroud and LEV system (Figure 3). A secondary objective was to determine whether use of the jig reduced noise exposure to the drill operator due to the increased distance created by the jig between the point of noise generation and the worker. Future studies will evaluate the ergonomic impact of the jig.

Drilling was performed under "experimental conditions" intended to mimic those experienced by laborers on actual job sites. Test conditions were designed so that the independent variables were the use, or lack of use, of the vacuum dust control system, and use, or lack of use, of the jig. A single experienced laborer operated the tested equipment during all experimental trials.

METHODS

This case study was conducted at the Northern California "Terence J. O'Sullivan" Laborers Training Center in San Ramon, California. All trials occurred on April 22 and 23, 2010. The laborer participating in these trials used personal protective equipment, including gloves, hearing protection,

FIGURE 1. APT Model 137 pneumatic rock drill.

FIGURE 2. Pneumatic drill with support jig (vacuum is not used).

FIGURE 3. Dust capture shroud functioning while drilling. The locks were added to provide weight to the shroud so that it would slide toward the hole while drilling.

and a powered air-purifying respirator (PAPR). The case study was approved by the UCSF Institutional Review Board.

The pneumatic rock drill used for drilling concrete was an APT Model 137 (American Pneumatic Tool, Inc., Santa Fe Springs, Calif.). The 30-pound (13.6 kg) drill was equipped with a 20 in. (50.8 cm) hexagonal bit with a 7/8 in. (2.2 cm) diameter cutting tip. Compressed air was supplied to the drill by a compressor regulated to a constant pressure, and the drill motor was generally operated at full throttle.

The vacuum (model 2800c, Dustcontrol, Inc., Wilmington, N.C.) was tested in combination with a cylindrical shroud (part 6001, Dustcontrol), which surrounded the bit (Figure 3). The vacuum is specified to provide a flow rate of 114 cubic feet of air per minute (194 cubic meters per hour) and 84 inches of water (20.9 kPa) lift. It has an inertial separator, or cyclone, to remove the largest particles, followed by a fine filter rated to remove 99.9% of particles, and finally, a high efficiency particle air (HEPA) filter rated to remove at least 99.97% of 0.3 micron particles. The vacuum also features a "reverse air pulse cleaning system" to prevent the buildup of dust on the fine filter, which could reduce the flow rate. The shroud, which resembles a cylinder, is 3.9 in. (9.9 cm) in height, has a 2 in. (5.1 cm) diameter hose connection and a 1–1/4 in. (3.2 cm) diameter hole for the bit.

Personal air samples were collected from the breathing zone of the laborer during each trial. The samples were collected using a personal air monitoring pump (GilAir-5, Sensidyne, Inc., Clearwater, Fla.) to draw 4.2 L of air per minute through a GK2.69 Respirable Cyclone (BGI Inc., Waltham, Mass.) equipped with a pre-weighed, 37 mm diameter, 5-micron pore size polyvinyl chloride (PVC) filter positioned on the operator's lapel. The flow rates of the sampling pumps were calibrated at the beginning and measured at the end of each workday using a primary flow meter (Defender 510M, Bios International Corporation, Butler, N.J.). Samples were analyzed using NIOSH Method 0600 to determine the total mass of respirable dust (R.J. Lee Group, Inc., Monroeville, Pa.). The same samples were also analyzed using X-ray diffraction, NIOSH method 7500, to determine quartz, cristobalite, and tridymite concentration in the respirable mass. Concentrations of total respirable dust, quartz, cristobalite, and tridymite were calculated using laboratory reported sample masses and air sample volumes collected in the field.

Sound pressure levels were measured as near as possible to the operator's ears during drilling to approximate noise exposure without interfering with use of the drill (2800M Quest Technologies, Oconomowoc, Wisc.). The sound level meter was calibrated by the manufacturer in April 2010 and the calibration was verified in the field (Quest QC-10 calibrator).

The case study included 12 trials of the following three drilling conditions:

1. drilling with jig and dust control
2. drilling with jig and without dust control
3. drilling without jig and without dust control.

Each test condition was performed four times and the order of each test condition was randomized across all trials to minimize bias that might be introduced due to variation associated with operator fatigue and other temporal or environmental effects. Drilling was performed for approximately 50 min per trial with the vacuum dust control and for approximately 25 min when the dust control was not used. These times were selected based on the minimum duration of sample time needed to achieve an analytical limit of quantification of 0.05 mg/m^3 (the NIOSH recommended exposure limit [REL] for respirable silica). The operator was instructed to drill holes at approximately the same rate for all three drilling conditions. The mean number of holes drilled across all three conditions was 0.6 holes per minute and there was no significant difference between methods.

We used a reduction from baseline exposures measured with no controls to less than the NIOSH REL of 0.05 mg/m^3 as our criteria for determining whether or not a control was considered effective. These methods and test criteria are similar to those used by NIOSH in an evaluation of dust controls for tuckpointing(11) and by CPWR in a similar evaluation of dust controls for multiple masonry tasks.(16)

Given the small sample sizes and the associated uncertainty as to the normality of the data, a non-parametric test, the Wilcoxon rank sum test for small independent samples, was used to compare results from each test condition. A single, left-tailed test at the 5% significance level was used because it was assumed controls would result in either no change or a reduction in exposure. The alternative hypotheses stated that exposure levels in controlled settings were lower than tools with no control.

RESULTS

A summary of the personal air monitoring results for silica exposure associated with the three test conditions appears in Table II. Drilling lateral holes into concrete without using the jig and dust control resulted in an average exposure to respirable silica that was 14 times the REL. Using the jig with the drill produced a 55% reduction in silica exposure compared to drilling without the jig but still resulted in exposures six times the REL. Drilling holes while using the jig and dust control resulted in a 94% reduction in respirable silica compared to drilling without the jig, and brought the average exposure to less than the REL.

The silica concentrations associated with drilling with the jig alone and drilling with the jig and dust control were both shown to be less than silica concentrations measured while drilling without the jig and dust control (Wilcoxon, $p < 0.025$). The respirable silica concentrations when drilling with the jig and dust control were lower than those associated with just the jig (Wilcoxon, $p < 0.025$).

The mass of dust collected in two bags on the first day was measured and used with total vacuum run times to derive a rate of dust collection. During these three trials with the vacuum, totaling 143 min, approximately 78 lbs (35.4 kg) of dust was collected, resulting in a collection rate of 0.55 lbs of dust per minute.

The background noise level from nearby construction equipment, measured near the operator, was approximately 80 decibels on an A-weighted scale (dBA). The source of the noise was an electrical power generator approximately 8 ft from the operator and an air compressor about 10 to 12 ft from the operator. When drilling with the rock drill alone, the sound level near the operator ranged from 111 to 116 dBA. When drilling with the rock drill mounted in the jig, the sound level ranged from 108 to 111 dBA. When drilling with the rock drill mounted in the jig and the vacuum operating, the sound level near the operator ranged from 108 to 110 dBA. Sound pressure level was typically 2 to 3 decibels higher on the exhaust side of the rock drill.

DISCUSSION

Based on our task time-weighted average (TWA) sampling results, the mean respirable silica exposure concentrations were greatest for drilling with the usual, manual method (e.g., without the jig and vacuum) with levels 14 times the NIOSH REL of 0.05 mg/m^3. Use of the jig without the vacuum reduced levels to six times the REL. Drilling with the jig and vacuum system resulted in exposure levels below the NIOSH REL. Drilling with the jig and without a vacuum would require use of a respirator with an assigned protection factor (APR) of 10, assuming that the tasks sampled were performed continuously over a work shift. However, based on these data, a respirator with an APR of 10 would offer

TABLE II. Respirable Silica While Drilling Concrete with a Pneumatic Rock Drill

	Mean mg/m^3 (range)	Standard Deviation	Percent Reduction^A	Hazard Ratio^B
Drilling with jig and dust control	0.04 (<0.02–0.05)	0.01	94.3	0.80
Drilling with jig and without dust control	0.30 (0.09–0.64)	0.24	55.3	6.0
Drilling without jig and without dust control	0.68 (0.42–0.84)	0.19	NA	14

^{A}Compared to drilling without the jig or the dust control.
^{B}Silica hazard ratio equals mean exposure divided by 0.05 mg/m^3, the NIOSH REL.

inadequate protection when drilling without the jig or vacuum. However, both the concentration of quartz in building materials and the environmental conditions vary on construction sites. In addition, the NIOSH REL is based on a 10-hr TWA exposure, and workers may not perform these tasks continuously over the entire work shift. Therefore, collection of representative exposure data during field operations should be used to determine the adequacy of controls in use.

Sound levels near the operator ranged from 108 to 116 dBA depending on the configuration of the drill. Levels were slightly higher when neither the jig nor vacuum was used. However, the sound levels were unacceptably high under all three test conditions. Based on OSHA PELs, workers without hearing protection would be overexposed to noise in less than 30 minutes.[17] The more protective occupational exposure limits published by NIOSH and ACGIH would be exceeded after a few minutes of drilling concrete without hearing protection. The use of LEV does not appear to increase noise levels.

Based on the measured sound levels, hearing protection must be worn when drilling into concrete with pneumatic drills. Double hearing protection – earmuffs worn over earplugs – is recommended to achieve maximum noise reductions. However, use of quieter equipment (e.g., electric drills and muffled generators and compressors) should be considered for noise reduction, since even the most protective combination of earplugs and earmuffs does not provide sufficient protection when exposed to sound levels greater than 110 dBA for 8 or more hours per day. In addition, substitution and engineering controls are preferred means of controlling occupational health hazards and should be implemented prior to personal protective equipment (PPE). Significant noise sources for this task, in addition to the drill, were an electrical power generator and air compressors. In addition to selecting equipment with the lowest noise ratings, loud equipment should be placed as far as possible from the operator, and noise barriers should be placed between the equipment and the operator. When using a pneumatic rock drill, the drill's exhaust port should be facing away from the operator.

While the vacuum system provided large reductions in respirable silica exposure during drilling, exposure during cleaning and maintenance should also be considered. The operator should wear his or her respirator while changing vacuum bags and filters and while cleaning tools, dust control equipment, and the work area. Compressed air should not be used to remove dust from the worker's clothing or work area.

Several limitations should be considered when interpreting these data. The number of trials per condition – four – was small; however, the variance in measures was small to moderate (coefficient of variation ranges from 0.28 to 0.78), indicating that a small number of samples may be representative of the actual exposure distribution. The exposures were measured in settings where work was simulated. During real work, local conditions, weather, and drilling rates may significantly alter exposure. For example, interior work may involve larger silica exposures than those measured here.

CONCLUSIONS

Use of the tested vacuum dust collection system during lateral drilling reduced the operator's exposure to 80% of the NIOSH REL for respirable silica based on task time-weighted averages (TWAs). Use of the jig without the vacuum system resulted in a reduction in the concentration of respirable silica by approximately half, but the exposures still exceeded the NIOSH REL. The laborer who operated the tool during these trials indicated that drilling with the jig was easier on his back and much more desirable compared to drilling without the use of the jig. The worker acceptance of the jig combined with the reduction in respirable silica indicates that the combined use of the jig and vacuum system is a promising means for reducing multiple occupational health risks associated with concrete drilling tasks.

RECOMMENDATIONS

This case study demonstrated that a drill jig and vacuum system can be effective in reducing respirable silica exposure to less than the NIOSH REL. Further evaluation of this equipment is needed on job sites to demonstrate that the results of this case study are transferable to real-world conditions. Testing the jig and vacuum system on job sites will provide additional input from workers and contractors regarding typical use, barriers to use, and design improvements, which may not be noted in the setting of this case study. While beyond the scope of this case study, future work will assess the ergonomic effects of the jig and changes in productivity and cost associated with using the system.

When possible, the use of PPE should be avoided in favor of engineering controls or substitution as a means of controlling hazards. PPE, including respirators, is prone to failure and depends on the knowledge and diligence of workers and their employers for proper use, creating the potential for failure and thus occupational exposure to hazardous agents such as respirable quartz. When respirators are used, they must be used as part of a comprehensive respiratory protection program, which includes medical evaluation, fit testing, training, maintenance, and cleaning. In addition, PPE does nothing to reduce contaminant generation or exposure risks to other workers and bystanders in the vicinity.

Vacuums that utilize a cyclonic separator, such as the one tested in this survey, should be given priority when selecting vacuums for further testing or use on job sites. These vacuums use inertial impaction to remove the larger particles and the majority of the mass from the airstream before it passes through the filter, which is designed to remove the remaining small particles.

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