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Original Article

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The Effects of Bit Wear on Respirable Silica Dust, Noise and Productivity: A Hammer Drill Bench Study

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Abstract

Objectives: Hammer drills are used extensively in commercial construction for drilling into concrete for tasks including rebar installation for structural upgrades and anchor bolt installation. This drilling task can expose workers to respirable silica dust and noise. The aim of this pilot study was to evaluate the effects of bit wear on respirable silica dust, noise, and drilling productivity.

Method: Test bits were worn to three states by drilling consecutive holes to different cumulative drilling depths: 0, 780, and 1560 cm. Each state of bit wear was evaluated by three trials (nine trials total). For each trial, an automated laboratory test bench system drilled 41 holes 1.3 cm diameter, and 10 cm deep into concrete block at a rate of one hole per minute using a commercially available hammer drill and masonry bits. During each trial, dust was continuously captured by two respirable and one inhalable sampling trains and noise was sampled with a noise dosimeter. The room was thoroughly cleaned between trials.

Results: When comparing results for the sharp (0 cm) versus dull bit (1560 cm), the mean respirable silica increased from 0.41 to 0.74 mg m^{-3} in sampler 1 ($P = 0.012$) and from 0.41 to 0.89 mg m^{-3} in sampler 2 ($P = 0.024$); levels above the NIOSH recommended exposure limit of 0.05 mg m^{-3}. Likewise, mean noise levels increased from 112.8 to 114.4 dBA ($P < 0.00001$). Drilling productivity declined with increasing wear from 10.16 to 7.76 mm s^{-1} ($P < 0.00001$).

Discussion: Increasing bit wear was associated with increasing respirable silica dust and noise and reduced drilling productivity. The levels of dust and noise produced by these experimental conditions would require dust capture, hearing protection, and possibly respiratory protection. The findings support the adoption of a bit replacement program by construction contractors.

Keywords: concrete drilling; dust concentration; masonry; noise level; tool wear

Introduction

Concrete drilling on construction sites can expose workers to silica dust and noise and, with repeated exposures, may cause chronic occupational diseases, such as silicosis and noise-induced hearing loss (Dement *et al.*, 2003, 2005). Concrete drilling is primarily performed by laborers, electricians, plumbers, and pipefitters for tasks including rebar installation for structural upgrades, earthquake preparedness, and setting anchor bolts. Structural upgrade jobs may require thousands of holes to be drilled; holes that may be up to 3 cm in diameter and 120 cm deep (Horton T. (2017) BART Earthquake Safety Program. Personal Communication). Exposure levels to silica dust and noise can be influenced by the type of concrete, drill size, drill power source, bit diameter, dust capture system, and surrounding environment. However, exposure levels due to other factors, such as bit wear, are unknown.

Crystalline silica is present in stone and concrete. When stone or concrete are cut, ground, chipped, or drilled, fine particles of silica are released into the air and, if of respirable size (i.e., <10 µm in aerodynamic diameter) are inhaled into the unciliated airways (ISO, 1995). Particles <2.5 µm in aerodynamic diameter deposit in the alveoli where they are phagocytosed by macrophages, triggering an acute inflammatory response. With chronic exposure, the inflammatory process can lead to the development of scar tissue in concentric layers around deposited dust particles, or silicotic nodules, in the lung. Small silicotic nodules are a hallmark of the early stages of the completely preventable disease, silicosis. When these small nodules coalesce into larger areas of lung fibrosis, silicosis can be disabling, and potentially fatal. According to Occupational Safety and Health Administration (OSHA) and the National Institute for Occupational Safety and Health (NIOSH), roughly 2 million US workers are exposed to dangerous levels of silica dust, and hundreds die each year from silicosis (NIOSH, 2002; OSHA, 2016). More than 80% of these silica-exposed workers are employed in construction (Steenland and Ward, 2014).

OSHA, NIOSH, and the ACGIH have published occupational exposure limits based on the respirable fraction of crystalline silica dust (NIOSH, 2002; OSHA, 2016; ACGIH, 2017). The ACGIH threshold limit value (TLV) is an 8-hour time-weighted average (TWA) of 0.025 mg m^{-3}. Occupational exposure limits set by OSHA and NIOSH coincide on the TWA dust concentration level of 0.05 mg m^{-3}, although the OSHA permissible exposure limit is not enforceable until mid-2017 for construction. The NIOSH recommended exposure limit (REL) is based on a 10-hour TWA, while OSHA and ACGIH use an 8-hour TWA limit.

In studies at commercial construction sites, concrete drilling was associated with silica dust exposures above the NIOSH REL (Flanagan *et al.*, 2006; Sauvé *et al.*, 2013). Laborers performing tasks including drilling, chipping, and sanding had a median respirable silica exposure of 0.35 mg m^{-3}, seven times the 0.05 mg m^{-3} exposure limit (Rappaport *et al.*, 2003). In a scenario designed to represent an actual job site, use of a pneumatic rock drill with and without vacuum dust control resulted in mean respirable silica exposures of 0.30 mg m^{-3} and 0.04 mg m^{-3}, respectively (Cooper *et al.*, 2012). These high exposure levels highlight the importance of effective measures to reduce and control dust exposure during concrete drilling. The effectiveness of dust control systems has been documented for both hammer and rock drills; however, the widespread use of dust control systems for drilling may be limited by a lack of reliable equipment for dust control and cost of implementation (Shepherd *et al.*, 2009; Cooper *et al.*, 2012; Fan *et al.*, 2012; Echt and Mead, 2016).

Noise exposure during concrete drilling with pneumatic (rock) or electric hammer drills can lead to hearing loss, sleep disturbance, fatigue, and hypertension (Basner *et al.*, 2014). Construction worker noise exposure has been measured for a variety of construction tasks but there have been few measures of noise exposures focused on concrete drilling (Sinclair and Haflidson, 1995; Neitzel *et al.*, 1999; Schneider and Susie, 2016). A study comparing different power tools measured a noise level of 105 dBA when drilling with a hammer drill compared to 94 dBA when drilling with an ordinary drill (McClymont and Simpson, 1989).

For both construction and general industry, the OSHA permissible exposure limit for noise is 90 dBA (8-hour TWA with a 5-dB time-intensity exchange rate; 29 CFR 1926.52; 29 CFR 1910.95). Hearing conservation programs (HCPs) are required for overexposed workers but the HCP requirements for construction workers are not as protective as for general industry. For example, the construction regulation states, "ear protective devices inserted into the ear should be fitted or determined individually by competent persons." In contrast, the general industry regulation uses an action level of 85 dBA for initiating HCPs and gives specific requirements for noise exposure monitoring, audiometric testing and evaluation, hearing protection devices (HPDs), worker training and education, and record keeping. Both NIOSH and ACGIH recommend a more protective occupational exposure limit of 85 dBA with a 3-dB exchange rate. NIOSH estimates that 14% of workers exposed to noise levels of 85 dBA or higher, will develop hearing impairment and NIOSH's National Occupational Exposure Survey estimates that 421 000 construction workers are exposed to noise above 85 dBA (NIOSH, 1972; NIOSH, 2016).

Engineering interventions are the preferred method for reducing noise and silica dust exposures from power tools. Studies of the bit designs used for coal mining have found that increasing bit wear produces greater respirable dust levels (Organiscak *et al.*, 1996). Specific recommendations were made for bit replacement to minimize silica dust exposure. However, the designs of bits for coal drilling are different from masonry bits and there have been no comparable studies of the effects of masonry bit wear on respirable silica dust or noise generation.

The aim of this pilot study was to compare silica dust and noise exposures during concrete drilling using masonry bits with three states of wear: sharp, medium, and dull. Drilling was performed in a controlled laboratory setting using an automated bench system that repeatedly drilled holes into concrete blocks with a commercially available rotary hammer drill. A secondary aim was to determine how bit wear affected productivity (e.g., rate of penetration (ROP) of bit into concrete).

Methods

Test bench system

The automated test bench system for hammer drills has been previously validated and described in studies on bit wear and handle vibration (Antonucci *et al.*, 2017; Rempel *et al.*, 2017). The system can automatically drill multiple holes by driving an active drill under force and depth control into concrete block and advancing the concrete block after each hole is drilled (Fig. 1). A plastic mannequin, used for the placement of air and noise samplers, is mounted near the drill in the location where a worker would be while drilling.

The test bench is centered in a 100 m^3 test room with sealable doors to prevent dust leakage. Adjacent rooms house the computer control system and equipment for sample storage and gravimetric analysis. The test room contains an air cleaner (model DC AirCube 2000; Dustcontrol, Inc., Wilmington, NC) equipped with a class H filtration system (a 0.7 m^2 pre-filter and a 10 m^2 high-efficiency particulate air H13 filter; filtration efficiency >99.995 %; EN-60335-2-69) with a maximum volumetric flow rate of 1,800 m^3 h^{-1}. The measurement room contains an electronic balance (model CPA225D; Sartorius, Göttingen, Germany) with a sensitivity of 0.01 mg for dust mass measurements and a desiccator (SICCO Star-Desiccator V 1871-07; Bohlender GmbH, Grünsfeld, Germany) stocked with orange indicator silica gel desiccant and a hygrometer for maintaining a dry atmosphere.

This test bench system differs from the design of test bench designs specified in European standards (EN 50632-1, EN 50632-2-6, and EN 1093-3, and TNO 2014 R10615) on several factors: the room

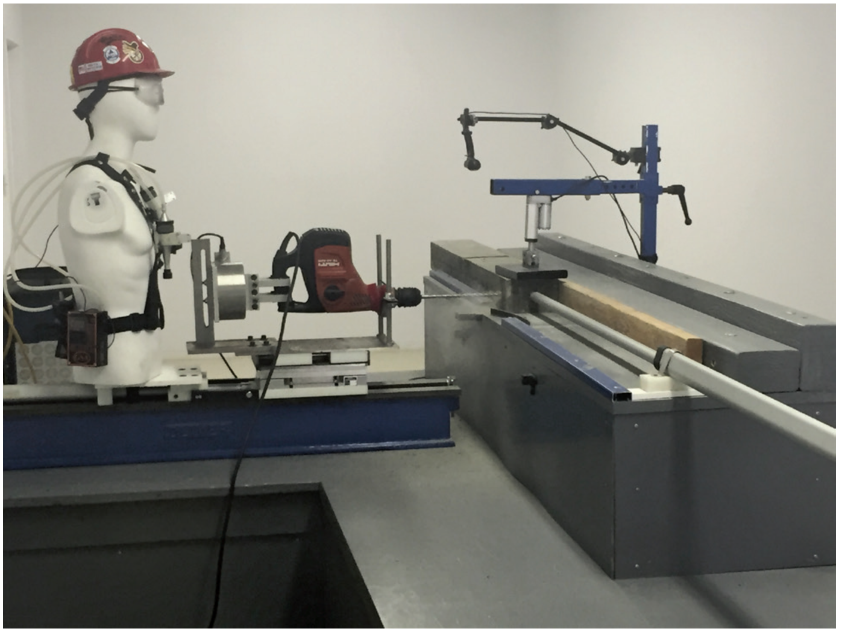

Figure 1. Drill test bench with an active hammer drill drilling into concrete—dust is visible. After each hole is drilled, the concrete block is advanced, the block is secured, and the next hole is drilled. The mannequin is instrumented for dust and noise sampling.

volume was half that of the EN standard; the drilling was performed automatically rather than by a human; and the number of holes tested per condition was 41 rather than 60.

Concrete blocks

Non-reinforced concrete blocks (8.9 × 30 × 30 cm) were prepared on site to meet the quality and consistency standards for reinforced concrete used in structural settings (slump 80 mm; ISO, 2009; CEN, 2013). The blocks cured for at least 28 days.

Drill and bit wear

The automated test bench repeatedly drove an activated hammer drill horizontally into a concrete block. The drill (model TE40; Hilti, Liechtenstein) was equipped with a 1.3 cm diameter carbide-tipped masonry bit (model 5439, DeWalt, Baltimore, MD). The drill and bit studied are representative of those used by commercial contractors. Bits in three states of wear were tested: sharp, medium, and dull (Fig. 2). These states of bit wear were based on practical bit use (i.e., total depth of concrete drilled by bit before testing). Sharp bits had never been used. Medium and dull bits were prepared by drilling 780 cm (i.e., 78 holes each 10 cm deep) and 1560 cm (i.e., 156 holes each 10 cm deep) of cumulative drilling depth into concrete, respectively.

Dust monitoring and gravimetric analysis

During drilling, three dust samples were simultaneously collected in the mannequin's breathing zone, e.g., within 30 cm of the nose or mouth (Fig. 3). Both respirable dust (defined above) and inhalable dust were measured. Total inhalable dust is the fraction of airborne material that enters the nose and mouth during breathing. The particle sizes of total inhalable dust are up to 100 µm.

Three size-selective sampling trains were used for each sampling session: two identical respirable dust samplers and one inhalable dust sampler. Cyclone samplers (model FSP-10; GSA Messgerätebau GmbH, Ratingen, Germany) with cellulose nitrate membrane filters (Sartorius Type 11301037; Sartorius AG) were used for the two respirable dust samplers (4 µm median cut point). A cone sampler (model GSP-10; GSA Messgerätebau GmbH) with glass fibrous filters (MN 85/90 BF 37 mm, PR 0.5 µm, Macherey-Nagel) was used for the inhalable dust sampler (100 µm median cut point).

Portable battery-powered pumps (model SG 10–2; GSA Messgerätebau GmbH, Neuss, Germany) were used to draw air through the samplers. These maintain a constant volumetric flow rate in the presence of varying flow resistance; the SG 10–2 pumps are designed to achieve a flow rate of 10 dm^3 min^{-1} (±5%) and meet the requirements of European Standard EN 12919 (CEN, 1999). The flow rates of the pumps were calibrated to 10 dm^3 min^{-1} before each session and verified after each sampling session with a digital volumetric flow meter (model 4146 primary calibrator; TSI, Incorporated, Shoreview, MN).

Due to sensitivity to atmospheric moisture content, filters for the samplers were conditioned for a minimum of 48 hours in a desiccator at constant relative humidity (28% ± 2) and temperature (17°C ± 5) prior to weight measurements. Weighing of filters was performed with an anti-static weighing pan to minimize static charge buildup. Filters with stainless steel support screens were assembled in two-piece plastic cassettes before being placed into the samplers.

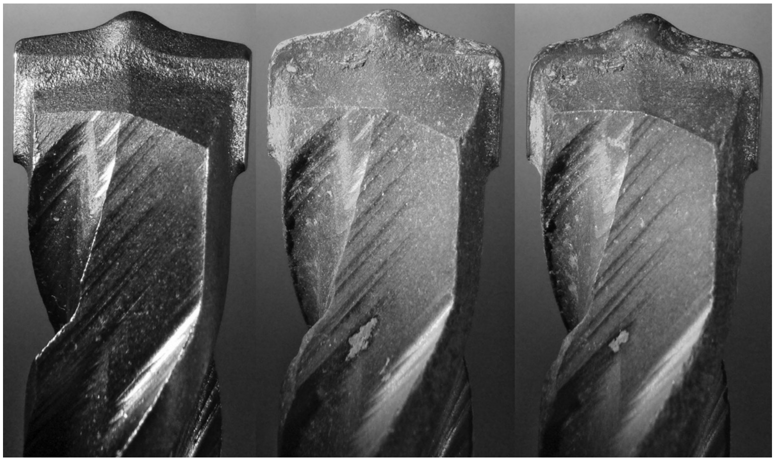

Figure 2. Three conditions of bit wear: sharp, medium, and dull, correspond to cumulative drilling depths of 0, 780, and 1560 cm.

Figure 3. Samplers and dosimeter microphone attached to mannequin.

Noise sampling

Noise samples were collected using a Type 2 personal noise dosimeter (Model 706RC; Larson Davis, Depew, NY) and analyzed using Blaze software (Larson Davis v 6.0.1). The microphone was clipped to the mannequin's harness on the middle-top of the left shoulder within 0.1 m of the ear (Fig. 3), pointing towards the drill bit as per the American National Standards Institute S12.19 standard (ANSI, 2001). The dosimeter was calibrated at sound pressure levels of 94 dB and 114 dB before and after each sampling session (Model CAL150; Larson Davis).

Unlike dust sampling, where an entire 41-hole sampling session was considered a 'sample,' for noise, each hole drilled was considered a sample. Noise measurements were made following the NIOSH and ACGIH TLV criteria: time-intensity exchange rate, 3 dB; threshold level, 80 dBA; criterion level, 85 dBA as an 8 hour TWA; criterion duration, 8 hours, A weighting, slow response, range 70–140 dB, and datalogging interval of 1 s (NIOSH, 1998; ACGIH, 2017). Noise measurements made near the edges of each concrete block were excluded due to consistently producing louder (outlier) sounds, most likely owing to the block edges being set in vibration during drilling.

Noise data were analyzed on the basis of the A-weighted equivalent-continuous sound pressure level ($L_{Aeq,T}$), the sound level of a hypothetical steady-state sound containing the same energy as the actual sound over the same measurement period. $L_{Aeq,T}$ levels were calculated for each sample using equation (1):

$$L_{Aeq,T} = 10\log\left(\frac{1}{T}\int_{T_1}^{T_2}\frac{P_A^2(t)}{P_0^2}\right)dB(A), \quad P_0 = 20\mu Pa \quad (1)$$

where $L_{Aeq,T}$ = A-weighted equivalent-continuous sound pressure level (dBA) over measurement period (T in s) required to drill one hole; P_0 = standard reference pressure (Pa); and $P_A(t)$ = instantaneous, A frequency-weighted sound pressure signal (Pa) (Earshen, 2000). However, because the durations of drilling a hole varied within and between test conditions, the total noise energy associated with drilling each hole was summed using the sound exposure level (L_{AE}), normalized to a reference duration of 1-s duration (T_0), using equation (2) (Earshen, 2000).

$$L_{AE} = L_{Aeq,T} + 10\log\left(\frac{T}{T_0}\right) \quad (2)$$

Using equation 2, it becomes apparent that the maximum L_{AE} acceptable under the NIOSH and ACGIH occupational exposure limits for noise in a 28 800-s (i.e., 8-hour) workshift is 129.6 dBA.

In addition, for each noise sample an allowable time (T_A) was calculated for exposure to the L_{EQ} (equation 3; Earshen, 2000). The allowable time is the maximum length of time that the task of drilling a hole could be undertaken before reaching the recommended NIOSH or ACGIH 8-hour TWA.

$$T_A = \frac{480 \text{ min}}{2^{(L-85)/3}} \quad (3)$$

where T_A = maximum allowable duration in minutes, L = A-weighted sound pressure level, 85 = REL or TLV (dBA), and 3 = exchange rate (dB).

Productivity: rate of penetration

Drilling productivity per hole (10 cm depth) is expressed as ROP and calculated as the hole depth divided by drilling time (mm s^{-1}). The computer clock was used to time from the moment of bit contact, based on load cell output, to reaching the target drilling depth. The drill rotational speed was constant and was not influenced by hole depth or bit wear state.

Experimental design

The study consisted of three trials for each of the three drilling conditions: sharp, medium, and dull bit, or nine trials total. For each trial, the test bench was programmed to drill approximately one hole per minute for 41 min. Each hole was drilled to a depth of 10 cm and the target force-on-bit (e.g., drilling force) was 100 N. After each trial, the test room was cleaned with a vacuum and wiped down. The air cleaner was operated until the respirable dust concentration returned to the levels before the start of the trial.

A minimum sample time of 41 min was selected based on the estimated minimum duration to achieve an analytical limit of quantification <0.05 mg m^{-3}, the NIOSH REL for respirable silica. The measurement sensitivity depends on the volume of air drawn through the filter and weighing resolution of the analytical balance. The following calculation was used to determine the minimum concentration that can be measured (C_{min}) during a 41-min sampling session (Wabeke, 2013):

$$C_{min} = \frac{1000 \times m_{min}}{t \times f} = \frac{1000 \times 0.01\,\mathrm{mg}}{41\,\mathrm{min} \times 10\,\frac{dm^3}{min}} = 0.024\,\frac{mg}{m^3} \quad (4)$$

where m_{min} is the 'analytical sensitivity' or the smallest mass that can be reliably measured with the balance in mg (0.01 mg for the Sartorius analytical balance), f is the sample flow rate in dm^3 min^{-1}, and t is the length of time of sampling in minutes. The minimum concentration of dust that can be detected from an air sample collected under the conditions described is 0.024 mg m^{-3}. For example, assuming that 20% of the respirable dust measured is silica, this method can estimate respirable silica concentrations as low as 0.005 mg m^{-3}, which is 10% of the NIOSH REL of 0.05 mg m^{-3}.

Direct-reading dust monitor

A direct-reading aerosol monitor (DustTrak II Model 8530; TSI, Inc., Shoreview, MN) was also used in the test room for personal monitoring of respirable dust levels in real time. This provided feedback to researchers on dust concentrations before they reoccupied the test room. A size-selective impactor with a 4.0 µm 50% cut point was attached to the inlet of the monitor to remove larger particles and allow measurement of the respirable fraction. The inlet of the 1-m long conductive tubing was attached over the mannequin's left shoulder in the breathing zone (see Fig. 3). The flow rate of the internal pump was calibrated before and after each sampling session (TSI 4146 flow meter).

Silica dust analysis

One air sample was collected in the direct-reading monitor, across all three trials, for each test condition (e.g., one sample each for sharp, medium, and dull bits). The samples were analyzed by an accredited analytical laboratory (R.J. Lee Group, Inc., Monroeville, PA) using NIOSH method 0600 to determine the respirable mass and NIOSH method 7500 to determine percent crystalline silica (quartz, cristobalite, and tridymite by X-ray diffraction) in the respirable mass.

Statistical analysis

Differences in outcomes between the three bit wear test conditions were compared using one-way analysis of variance. If significant, pair-wise comparisons were performed using the Tukey test to adjust for multiple comparisons (Mathematica 10.4.1.0, Wolfram Research Inc.).

Results

Tables 1 and 2 summarize the outcome measures for the three test conditions: sharp, medium, and dull bit.

Productivity

The ROP was highest with the sharp bit and decreased with increasing bit wear. Differences in productivity

Table 1. Mean (SD) dust, noise, and productivity values by bit wear condition

	Wear state of drill bit[a]			*P* value
	Sharp	Medium	Dull	
Respirable dust 1 (mg m^{-3})	1.89^{AB} (0.03)	3.01^{A} (0.43)	3.47^{B} (0.64)	0.012
Respirable dust 2 (mg m^{-3})	1.90^{A} (0.04)	3.35 (0.85)	4.19^{A} (0.94)	0.024
Inhalable dust (mg m^{-3})	9.04^{A} (0.23)	17.60 (4.60)	21.69^{A} (5.51)	0.025
L_{AE} (dBA)	112.8^{A} (1.45)	113.1^{B} (1.38)	114.4^{AB} (1.61)	<0.00001
Productivity (mm s^{-1})	10.16^{AB} (0.57)	8.51^{AC} (0.60)	7.76^{BC} (0.53)	<0.00001

[ABC]Same superscript letters in a row identify statistically significant pairs by the Tukey test.
[a]Sample sizes for each mean value: dust *N* = 3; sound *N* = 103; and productivity *N* = 120.

Table 2. Estimated respirable silica dust concentration and hazard ratio associated with each bit wear condition

Bit wear	Respirable sampler 1		Respirable sampler 2	
	Mean mg m^{-3} (range)	Hazard ratio[a]	Mean mg m^{-3} (range)	Hazard ratio[a]
Sharp	0.41 (0.40–0.42)	8.2	0.41 (0.41–0.42)	8.3
Medium	0.67 (0.58–0.77)	13	0.75 (0.59–0.96)	15
Dull	0.74 (0.59–0.85)	15	0.89 (0.73–1.11)	18

[a]Silica hazard ratio equals mean exposure divided by 0.05 mg m^{-3}, the NIOSH REL.

between each test condition were significant based on the Tukey test. Productivity for the medium bit was 16% less than the sharp bit and productivity for the dull bit was 24% less than the sharp bit.

Dust levels

Respirable and inhalable dust levels were significantly different among test conditions with the highest levels occurring with the dull bit. Follow-up analysis with the Tukey test identified significant differences for respirable dust sampler 1 between the sharp and medium bits and between the sharp and dull bits. Follow-up analysis with the Tukey test identified significant differences for respirable dust sampler 2 and inhalable dust levels only between the sharp and the dull bits.

The single sample quartz analyses were 21.8%, 22.3%, and 21.2%, by weight for sharp, medium, and dull test conditions, respectively. Analytical results for both cristobalite and tridymite were less than the limit of detection (1.3%, 0.8%, and 0.7% for sharp, medium, and dull test conditions, respectively). The quartz concentrations were used to estimate silica concentration in the dust samples (Table 2). For the sharp bit, the mean estimated respirable silica dust levels were 0.41 mg m^{-3} (respirable samplers 1 and 2). For the medium bit, the mean respirable dust levels were 0.67 mg m^{-3} (sampler 1) and 0.75 mg m^{-3} (sampler 2). For the dull bit, the mean respirable silica dust levels were 0.74 mg m^{-3} (sampler 1) and 0.89 mg m^{-3} (sampler 2).

Noise exposure

Sound exposure levels are summarized for the three bit wear conditions in Tables 1 and 3. Overall, there were significant differences in L_{AE} between bits of different wear, and, based on the Tukey follow-up test, the L_{AE} for the dull bit was significantly higher than for either the sharp or medium bit. In addition, the exposure duration for the dull bit was longer than the sharp or medium bit due to the reduced ROP.

A summary of L_{AE} associated with drilling 48 holes for the three bit wear levels appears in Table 4. L_{AE} values for a single sample (i.e., the total noise energy measured while drilling a single hole, normalized to 1 s) were converted to measures representative of the total noise exposure expected to result from drilling 48 holes over the course of a work shift (e.g., 1 hole every 10 min over a 480-min workday). These measures were computed using equation (5).

$$L_{AE,48} = L_{A_{eq},48T} + 10\log\left(\frac{48T}{T_o}\right) \quad (5)$$

The $L_{AE,48}$ values were then compared to the allowable $L_{AE,NIOSH}$ from NIOSH and ACGIH (i.e., a 1-s 129.6 dBA exposure, equivalent in energy to 8 hours at 85 dBA) in the form of a hazard ratio (HR) using equation (6).

$$HR = \frac{10^{(L_{AE,48},/10)}}{10^{(L_{AE,NIOSH}/10)}} \quad (6)$$

Drilling 48 holes into concrete using a sharp bit would lead to an average exposure that is slightly below the NIOSH L_{AE} REL, while drilling 48 holes with a medium-dull or dull bit is associated with levels above the NIOSH REL with HRs of 1.05 and 1.40 over the REL (Table 4), equivalent to $L_{Aeq,8hr}$ values of 85.2 and 86.5 dBA, respectively.

Discussion

This study found that when drilling into concrete bit wear had a significant effect on productivity, noise level, and respirable and inhalable dust concentrations. Drilling with a medium bit increased respirable dust concentrations by 59 to 76% compared to drilling with a sharp bit, while drilling with a dull bit increased respirable dust concentrations by 84 to 120% compared to a sharp bit. The estimated respirable silica dust levels for the medium bit were 63 to 80% higher than for the sharp bit and for the dull bit were 80 to 114% higher than for the sharp bit. Silica concentrations in the respirable size fraction were 8 times higher than the NIOSH REL for a sharp bit, 13 to 15 times the REL for a medium bit, and 15 to 18 times the REL for a dull bit. These findings

Table 3. Average ($L_{Aeq,T}$) noise levels and drilling time per hole (SD) using bits in 3 different wear states

Bit wear	Number of holes	Mean drill time per hole (s)	Mean (range) $L_{Aeq,T}$ (dBA)	Mean allowable duration of exposure (min)
Sharp	104	10 (0.63)	102.7 (99.6–106.0)	8.5 (2.6)
Medium	103	12 (0.91)	102.2 (100.2–106.5)	9.3 (2.7)
Dull	101	13 (0.94)	103.1 (100.5–107.2)	7.7 (2.6)

Table 4. Mean L_{AE} levels and hazard ratios associated with drilling 48 holes with bits of different wear states

Bit wear	Personal noise dosimeter			
	Mean drilling time per hole (s)	Mean $L_{AE,48}$ values (range) (dBA)	Hazard ratio[a]	Equivalent $L_{Aeq,8hr}$ (dBA)
Sharp	10	129.6 (126.4–132.8)	1.00	85
Medium	12	129.9 (127.4–134.1)	1.05	85.2
Dull	13	131.2 (128.1–135.2)	1.40	86.5

[a]Noise hazard ratio computed from equation (6); represents the energy ratio of the noise from 48 holes drilled in a single shift over the NIOSH and ACGIH-allowable 8-hour noise exposure.

indicate that using a duller bit increases respirable silica exposure compared to a sharper bit.

No other studies were identified that evaluated the effects of concrete bit sharpness on respirable silica dust. Prior laboratory and field studies have measured respirable silica dust when drilling into concrete with sharp bits and the reported exposure levels are similar to our levels for sharp bits. For example, Lofgren (1993) reported that construction workers who used pneumatic and electric drills with 1.9-cm bits to drill holes into a concrete parking structure, without dust control, had a mean silica exposure of 0.22 mg m^{-3}. This was approximately half the concentration measured in our study with the sharp bit, which may be due to sampling in a workspace with airflow and longer periods of lower or no exposure. A laboratory study, without dust control, evaluated drilling with 0.6-cm and 1-cm diameter bits to depths of 5 cm and 8 cm, respectively (Hallin, 1983). The mean respirable silica concentration was greater than 0.24 mg m^{-3} with the 0.6-cm bit and 0.3 mg m^{-3} with the 1-cm bit, both levels lower than what was measured in our study with a sharp bit. A more recent study used 0.8-cm diameter bits to drill repeatedly to a depth of 7.6 cm into concrete without local exhaust ventilation (Shepherd *et al.*, 2009). The mean respirable silica concentration was 0.31 mg m^{-3}. Finally, a study on a large highway construction project measured exposures of laborers drilling vertically, overhead into concrete (Blute *et al.*, 1999). Pneumatically powered drills were used to drill 26 000 holes measuring 1.9 cm in diameter and 12.7 cm in deep. The mean respirable silica exposure was 0.43 mg m^{-3} (mean % silica 12.0), similar to what was measured in our study for sharp bits.

The analytical results from personal sampling during 41-hole drilling sessions showed that silica exposure levels would exceed the NIOSH REL of 0.05 mg m^{-3} in all drilling conditions, assuming that the tasks sampled were performed continuously over a 10-hour work shift. Based on these mean respirable silica concentrations, the allowable exposure time per day, to remain under the NIOSH REL, is 72 to 73 min for a sharp bit, 40 to 45 min for a medium-dull bit, and 34 to 40 min for a dull bit. These allowable durations assume no silica exposure for the remainder of the workday. These differences and the impact on worker productivity may provide contractors with a financial incentive for adopting a bit replacement program. However, return-on-investment calculations are complex and will depend on bit and labor cost, drilling frequency, bit diameter, drilling depth, and other factors.

A worker exposed to these levels of silica dust for longer durations will require exposure controls. Because crystalline silica is classified as a carcinogen it is important to minimize exposure (IARC, 1997). Engineering controls, such as local exhaust ventilation or wet dust suppression, should be used first. There is good evidence that local exhaust ventilation will reduce exposure well below the NIOSH REL (Cooper *et al.*, 2012). If, with engineering controls, exposures are still above the NIOSH REL, then administrative controls, such as reducing the exposure duration should be considered. The third option is to use a respirator with an appropriate assigned protection factor. Other factors, such as work practices, environmental conditions, and materials cut (concrete materials can vary widely in silica content from a few percent to over 50%) can influence exposures, and these factors should be considered when planning for the protection of workers (Greenberg, 2002).

Few studies have evaluated noise exposures associated with concrete drilling and none evaluated the effect of bit wear on noise. In a study of carpenters by Kerr *et al*. (2002), mean integrated sound levels were ~96 dBA drilling holes into concrete using a hammer drill with a 0.6-cm bit. While above the ACGIH TLV of 85 dBA, this exposure is less than levels measured in our study. The Kerr study involved a smaller hammer drill, a smaller diameter bit, and outdoor sampling.

Under all three test conditions, L_{AE} in the hearing zone of the mannequin associated with drilling a hole in concrete were below the daily allowed L_{AE} of 129.6 dBA, representing the maximum daily accumulation of noise energy stipulated by the NIOSH REL of 85 dBA TWA for an 8-hour work period. While it is below the L_{AE} equivalent to the NIOSH REL, NIOSH recommends hearing protection for any noise over 85 dBA regardless of duration to prevent hearing loss (NIOSH, 2002). L_{EQ} levels from drilling a hole were lowest when a sharp bit was used, slightly higher—although not statistically significantly so—when a medium-dull bit was used, and highest when a dull drill bit was used. However, assuming that drilling one hole produces the average sound exposure observed, workers without hearing protection would be overexposed to noise after drilling 49 holes with a sharp bit or 45 holes with a medium-dull bit, or 34 holes if a dull drill bit. The average $L_{Aeq,T}$ levels measured while drilling with sharp, medium, and dull bits were 102.7, 102.2, and 103.1 dBA, respectively. These levels are higher than the manufacturer's published typical sound pressure level of 94 dBA (Hilti, 2017).

All noise levels measured in our study exceeded a TWA of 85 dBA; therefore, enrollment in a HCP would be recommended assuming drilling tasks are performed for 8 or more hours per day (ANSI/ASSE, 2007; ACGIH, 2017). Such a program would include noise monitoring to design engineering noise controls and providing HPDs, such as earplugs, canal caps, and/or ear muffs. Use of engineering controls such as enclosures, barriers, or distance should be considered first for noise reduction because HPDs may not always be effective, and the effective protection they provide is strongly influenced by wear time among construction workers (Neitzel and Seixas, 2005). However, if controls are infeasible and a worker continuously performs the drilling tasks sampled over a work shift, a HPD with a noise reduction rating (NRR) of at least 25 dB is required if a factory-sharp bit or medium-dull bit is used, while a HPD with a NRR of at least 26 dB would be required with a dull bit based on the A weighting-scale adjustment to the NRR.

A few limitations should be considered when interpreting the data from this pilot study. For dust sampling, the number of trials per condition was small ($N = 3$) and the findings should be repeated with a larger sample size. The FSP-10 cyclone used to sample respirable dust has been reported to oversample when operated at the manufacturer-recommended flow rate (Lee *et al*., 2010). The size distribution of the dust and silica generated during drilling is unknown and may result in underestimation or overestimation of respirable dust and silica. Although the drill bit-block interface was located near the center of the test room during drilling, both noise and particulate measurements may have been affected by the structure of the enclosed space. For example, sound may have reflected off the hard surfaces of the walls and test bench system and thus drilling may have been louder than would be the case if done in an open space. With regards to measuring noise from drilling, there were in actuality two sources of noise measured in this study: the drill and the contact of the drill bit and concrete. We measured these sources in aggregate. Differences in noise with bit wear were unlikely due to changes in the drill because the feed force and rotational speed were constant between test conditions. Finally, standardized tool noise emission measurements are typically made in an anechoic chamber, rather than the laboratory setting as was done here. However, while the acoustical environment in which the measurements were made was not anechoic, it did not change over the course of our experiments, so our results should have excellent internal validity, although the reverberant conditions under which measurements were made represent a worst-case exposure condition.

Conclusions and Recommendations

This study of drilling into concrete demonstrates that respirable silica dust and noise increase with increasing bit wear. In order to reduce exposures, contractors should replace bits that are worn based on usage history or bit tip wear pattern. In addition, as is well known, the time to drill a hole increases with increasing wear. Together, these findings should provide a financial and health incentive for contractors to adopt a bit replacement program.

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Disclosures

The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the NIOSH or CPWR. Mention of product names does not imply endorsement. The authors identify no conflicts of interest in the conduct of this study.

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