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Pneumatic rock drill vs. electric rotary hammer drill: Productivity, vibration, dust, and noise when drilling into concrete

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ABSTRACT

Objectives: Both pneumatic rock drills and electric rotary hammer drills are used for drilling large holes (e.g., 10–20 mm diameter) into concrete for structural upgrades to buildings, highways, bridges, and airport tarmacs. However, little is known about the differences in productivity, and exposures to noise, handle vibration, and dust between the two types of drills. The aim of this study was to compare these outcomes with similar mass electric rotary and pneumatic rock drills drilling into concrete block on a test bench system.

Method: Three experiments were conducted on a test bench system to compare an electric (8.3 kg) and pneumatic drill (8.6 kg) on (1) noise and handle vibration, (2) respirable silica dust, and (3) drilling productivity. The test bench system repeatedly drilled 19 mm diameter x 100 mm depth holes into cured concrete block while the respective exposure levels were measured following ISO standards.

Results: Productivity levels were similar between the electric and the pneumatic drill (9.09 mm/s vs. 8.69 mm/s ROP; $p = 0.15$). However, peak noise (L_{Peak}: 117.7 vs. 139.4 dBC; $p = 0.001$), weighted total handle vibration (a_{hw}: 7.15 vs. 39.14 m/s^2; $p = 0.002$), and respirable silica dust levels (0.55 vs. 22.23 mg/m^3; $p = 0.003$) were significantly lower for the electric than the pneumatic drill.

Discussion: While there were no differences in drilling productivity between an electric and pneumatic drill of similar mass, there were substantial differences in exposure levels of noise, handle vibration, and respirable silica dust. Structural contractors should switch from pneumatic rock drills to electric rotary hammer drills for structural drilling into concrete in order to reduce worker exposures to the hazards of noise, hand vibration, and silica dust.

1. Introduction

Drilling large holes into concrete is performed in commercial construction for structural upgrades (e.g., dowel and rod) and for inserting anchor bolts. The work is physically demanding with high levels of exposure to hand vibration, noise and respirable silica dust. Therefore, such jobs may cause acute injuries, musculoskeletal disorders such as hand-arm-vibration syndrome, hearing loss, and silicosis or lung cancer (Atzeri et al., 1987; Flanagan et al., 2006; Forouharmajd and Nassiri, 2011).

These large holes, typically 1″ in diameter to a depth of 6–24”, are drilled with pneumatically powered rock drills, or, more recently, with electrically powered rotary hammer drills. The diameter and depth of the hole determines the size of the drill required. Typically, structural construction and mining operations used pneumatic drills while electrical and plumbing contractors used electric rotary drills. Reasons for selecting one drill over the other include tradition, power source, tool mass, bit designs, durability and cost. Recent advances in electric motor technology have led to the production of large electric rotary drills with mass and power that can compete with light and mid-weight pneumatic rock drills.

Pneumatic rock drills have historically been considered as the most robust and productive tool for cutting large holes by structural contractors, stone workers, and rock miners. However, pneumatic rock drills are the number one cause of acute injuries among minors due to their heavy weight and are associated with very high levels of noise and vibration levels (Marras et al., 1988). Electric rotary hammer drills are lighter and have been considered as less productive and less suitable for heavy use (Phillips et al., 2007; Camargo et al., 2010; Vergara et al., 2008; Zuchelli, 2011; Lopez-Alonso et al., 2013; Nataletti et al., 2014).

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However, the newer, heavier and more powerful electric rotary hammer drills may be competitive with pneumatic rock drills. To date, no studies have compared electric and pneumatic drills, of similar mass, on noise, vibration, dust and productivity under the same drilling conditions.

The purpose of this study was to use a new test bench system to measure productivity, respirable silica dust, noise, and handle vibration for a pneumatic rock drill and an electric rotary hammer drill, of similar mass, drilling into concrete block. The test bench system allows for the precise control of drilling force and depth.

2. Methods

The study involved 3 laboratory experiments, one measured handle vibration and noise, one measured respirable silica dust, and one measured productivity. These experiments could not be performed simultaneously because they had to be optimized for each outcome. The studies were conducted using a test bench system previously described and validated with some modifications to accommodate the high levels of vibration from the large drills tested (Rempel et al., 2017). The primary modification was the use of a mass and pulley system to advance the drill under constant load (88N force on bit - adjusted for system friction) rather than the computer controlled, closed-loop load cell and actuator system used in previous studies. This modification was made to prevent damage to the load cell. In addition, larger concrete block were used (610 mm length; 305 mm width; 610 mm high) compared to prior experiments.

The test bench system was programmed to drill a hole approximately every minute. After each hole was drilled the concrete block was automatically moved to a new location in preparation for the next hole. A "sampling" mannequin was fixed behind the drill in a location similar to where a worker would be in order to properly place noise and dust sampling equipment. Non-reinforced concrete blocks were prepared on site, as previously described, and cured for at least 28 days (Carty et al., 2017).

The electric rotary hammer drill used (Hilti TE-70 AVR; 8.3 kg; 46 Hz percussion frequency) is toward the high end of the weight range of electric drills. The pneumatic rock drill (American Pneumatic Tool, Model APT-115; 8.6 kg; 48 Hz percussion frequency) is toward the low end of the weight range of rock drills. For each study, the drills were fitted with new 19 mm diameter 2-carbide tipped bits of similar mass (Hilti TE-Y for the electric drill and Crowder WB77-750-14 for the pneumatic tool). The drills were held at the handle with a 4 fingered rubber lined mechanical gripper and supported at the chuck by a rubber lined Y fixture (Fig. 1).

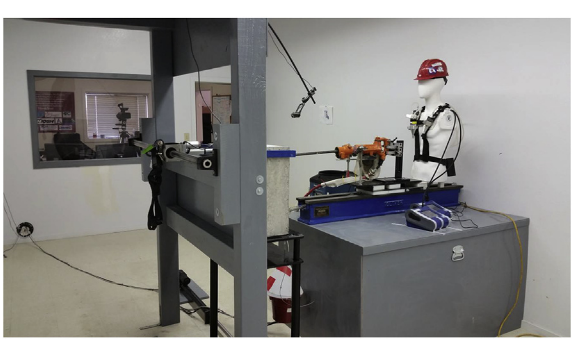

Fig. 1. The pneumatic drill mounted in the test bench system with rubber grips securing the handle and a Y mount supporting the drill near the bit. The drill mounting system slides on a lathe bed. After each hole is drilled actuators move the concrete block to a new location.

2.1. Vibration and noise experiment

Tool handle vibration acceleration magnitude was measured and interpreted following the ISO 28927-10 (2011) standard with some differences. ISO 28927-10 calls for downward drilling, but when drilling downward with an electric hammer drill, the bit may bind due to the lack of air flushing. Therefore, the test bench drilling was done horizontally. The ISO standard also calls for measuring handle vibration while the holes are drilled by test subjects. With the test bench, no humans handle the drill during testing, thereby increasing the precision of force and depth control.

Tool vibration was measured with a triaxial accelerometer (Svantek SV105AF; sensitivity of 0.6 mv/g) attached to the drill handle at the location of the hand grip using zip ties and oriented according to ISO 5349-1 and ISO 28927-10, i.e., the z-axis is aligned with the axis of the bit; the y-axis is vertical; and the x-axis is to the side. The accelerometer was connected to a 6-channel human vibration meter and analyzer (Svantek SV-106 A). All three axes were sampled simultaneously at 6000 Hz and analyzed (Svantec SVAN PC++) to generate the 1/3 octave spectra and the unweighted and weighted (a_{hw}) rms hand acceleration levels according to ISO 5349-1. The accelerometer was calibrated at the beginning and at the end of each test with a calibration shaker (PCB Piezotronics 394C06). Acceleration magnitudes (rms a) were interpreted according to ISO 28927-10.

Tool noise was measured for the entire duration of each hole drilled according to the ISO 9612:2009. The microphone was positioned within 0.1 m of the mannequin ear. Noise samples were collected using a Type 2 personal noise dosimeter (Model 706RC; Larson Davis, Depew, NY) configured to measure noise according to the Threshold Limit Value (TLV) of the American Conference of Governmental Industrial Hygienists (ACGIH, 2018) and analyzed using Blaze software (Larson Davis v 6.0.1). Data were collected in terms of L_{eq} in A-weighted decibels (dBA) and L_{Peak} in C-weighted decibels (dBC) for each hole drilled. Noise measurements made inside the test room required the microphone to be located approximately 1 m from the room walls, consistent with real-world use of the tool in rooms and other enclosed environments (e.g., tunnels, vaults, etc). The compressor power source for the pneumatic drill was outside the test room and did not contribute to the measured noise level. The dosimeter was calibrated at sound pressure levels of 94 dB and 114 dB before and after each sampling session (Model CAL150; Larson Davis).

Three test holes were drilled for each drill to a depth of 100 mm. Differences in acceleration, noise and productivity were evaluated statistically using two sample *t*-test.

2.2. Respirable silica dust experiment

The study consisted of two trials for each drill. For each trial, the test bench drilled 60 holes over approximately 70 min. Each hole was drilled to a depth of 100 mm. 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.

During each trial, three respirable dust samples (4 μm median cut point) were simultaneously collected in the mannequin's breathing zone, e.g., within 30 cm of the nose or mouth. Two of the respirable samplers followed the German methods and were FSP-10 cyclones with 37 mm filters (previously described in Carty et al., 2017); one positioned on the left shoulder and one on the right (Fig. 2). The third respirable sampler followed the US/NIOSH method and was a GK 4.162 cyclone (BGI by Mesa Labs, Inc., Butler, NJ) holding a pre-weighed 47 mm polyvinyl chloride (PVC) filter positioned on the right shoulder. The purpose for using 3 cyclones was to compare, side-by-side the German to the US method with the apriori decision to primarily rely on the US method. In addition, two direct-reading aerosol monitors (DustTrak II and DustTrak DRX, TSI Inc., Shoreview, MN) were located

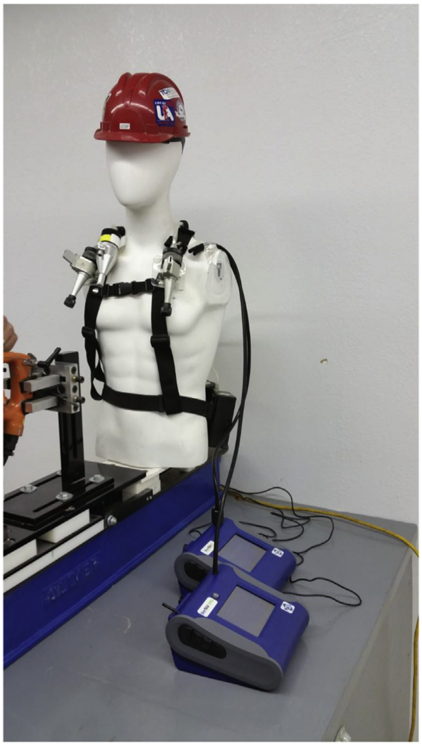

Fig. 2. The mannequin with location of 3 cyclones for respirable air sampling plus location of tubing for continuous air monitoring.

in the room with intake ports in the mannequin's breathing zone.

Portable battery-powered pumps were used to draw air through the samplers (previously described in Carty et al., 2017). The pumps used with the FSP-10 cyclones were calibrated to provide a flow rate of $10\,dm^3\,min^{-1}$ and the pump used with the GK 4.162 cyclone was calibrated to $9\,dm^3\,min^{-1}$. All pumps were calibrated before each session and verified after each sampling session with a digital volumetric flow meter (model 4146 primary calibrator; TSI Inc., Shoreview, MN).

The samples collected with the BGI cyclone and direct-reading aerosol monitors 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. The samples collected with the FSP-10 cyclones were weighed before and after each trail to determine change in mass (method previously described in Carty et al. (2017)).

T-test statistics are used to compare findings, but they should be interpreted with caution since just 2 sampling trials were conducted per drill.

2.3. Drilling productivity experiment

For this study, 3 holes were drilled to a depth of 200 mm with each drill. New drill bits were marked with tape and a ruler with 13 mm increments marked was placed parallel and close to the bit. A video camera was set to view the bit from the side, approximately 1 m from the bit, to record bit location relative to the ruler during drilling. The video was analyzed on a frame-by-frame basis to record the time for the tape on the bit to reach each 13 mm increment. A straight line was fit to the drilling depth by time data for each hole drilled (R^2 range: 0.9985 to 0.9998) and the slope was used to estimate the rate of penetration (mm/s). Each hole took approximately 23 s to be drilled.

Table 1
Mean (S.D.) levels of handle vibration and noise.

	Electric Rotary Drill	Pneumatic Rock Drill	p-value
Force on bit (N)	88	88	
Number of holes drilled	3	3	
Vibration			
Unweighted total (m/s^2)	78.76 (4.0)	346.94 (14.82)	0.001
Weighted total a_{hw} (m/s^2)	7.15 (0.11)	39.14 (2.53)	0.002
Noise			
Leq (dBA)	102.0 (0.1)	116.2 (0.4)	0.0001
L_{Peak} (dBC)	117.7 (1.0)	130.4 (0.6)	0.0001

3. Results

3.1. Vibration and noise

Mean ISO weighted handle vibration was more than 5 times greater for the pneumatic rock drill than the electric rotary drill (p = 0.002) (Table 1). A similar difference was observed for the unweighted handle vibration (p = 0.002). For the electric drill, the mean weighted vibration level (rms a) across the 3 trials was highest along the x-axis ($4.92\,m/s^2$) while for the pneumatic drill it was along the z-axis ($35.88\,m/s^2$). The mean unweighted vibration level across the trials was highest along the y-axis ($56.84\,m/s^2$) for the electric drill and was highest along the along the x-axis ($240.84\,m/s^2$) for the pneumatic drill. Across the frequency spectra, the highest unweighted acceleration levels for the electric drill were in the 100–800 Hz frequency range while for the pneumatic drill they were in the 800 and 1600 Hz range (Fig. 3). A peak near 50 Hz, associated with the percussion frequency, was observed for both drills. However, the peak was approximately 10 times greater for the pneumatic than the electric drill.

Both the mean L_{Peak} sound levels (dbC) and the mean sound L_{eq} levels (dbA) were higher for the pneumatic drill than the electric drill (p = 0.0001).

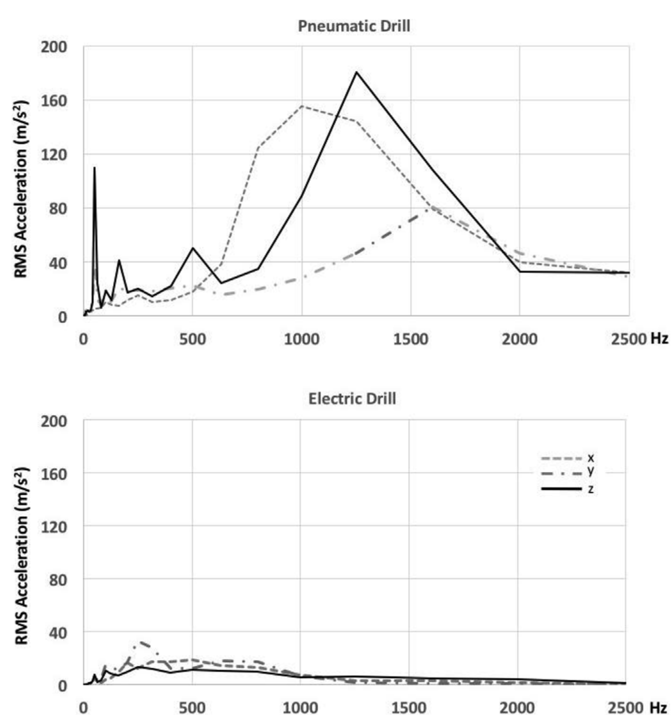

Fig. 3. One-third octave band frequency spectra for unweighted vibration for each axis during the first drilling trial for each drill.

Table 2
Mean levels (S.D.) of respirable dust and respirable silica dust.

	Electric Rotary Drill	Pneumatic Rock Drill	p-values
Force on bit (N)	88	88	
Number of trials	2	2	
Number of holes per trial	60	60	
A. Respirable dust (mg/m^3)	3.79 (0.83)	98.89 (27.80)	0.040
C. Respirable dust (mg/m^3)	3.91 (0.67)	92.52 (28.24)	0.047
B. Respirable dust (mg/m^3)	3.32 (0.65)	85.15 (15.28)	0.017
Respirable quartz by weight (%)	16.8 (1.9)	26.4 (2.6)	0.052
A. Respirable silica dust (mg/m^3)	0.63 (0.07)	26.42 (9.91)	0.067
C. Respirable silica dust (mg/m^3)	0.65 (0.04)	24.75 (9.86)	0.074
B. Respirable silica dust (mg/m^3)	0.55 (0.05)	22.23 (1.79)	0.003
A. Hazard Ratio	12.5	528.4	
C. Hazard Ratio	12.9	495.0	
B. Hazard Ratio	11.0	444.6	

A = German FSP Respirable Cyclone Pump A.
B = US BGI Respirable Cyclone Pump B.
C = German FSP Respirable Cyclone Pump C.
Hazard Ratio is based on Silica PEL of 0.05 mg/m^3 (OSHA, 2016).

3.2. Respirable silica dust

Mean respirable dust levels as collected by the 3 different cyclones were approximately 25 times higher for the pneumatic drill than the electric drill (Table 2). Mean quartz levels in samples by weight were 16.8% for the electric drill and 26.3% for the pneumatic drill. Therefore, mean respirable silica dust levels were approximately 40 times higher for the pneumatic drill than the electric drill. When compared to the silica PEL of 0.05 mg/m3, the silica dust levels for the electric drill were approximately 12 times the PEL while the levels for the pneumatic drill were approximately 500 times the PEL. Sampling duration was approximately 70 min for each trial.

3.3. Productivity - rate of penetration (ROP)

Mean ROP was slightly greater for the electric drill (9.09 mm/s (SD = 0.09)) than the pneumatic drill (8.69 mm/s (SD = 0.37)) but the difference was not significant (p = 0.15).

4. Discussion

This study compared an electric rotary hammer drill to a pneumatic rock drill of similar mass with similar bits and concrete drilling conditions on productivity and the hazards of handle vibration, noise and respirable silica dust. Surprisingly, there was little difference in productivity (e.g., rate of penetration) between the drills. However, the differences in measured noise, vibration and dust were very large. Mean L_{eq} and L_{Peak} noise levels were 13–14 dB higher, handle vibration was more than 5 times higher, and respirable silica dust levels were 40 times higher with the pneumatic drill than the electric drill.

Productivity levels were essentially the same with the electric and pneumatic drills. The productivity for the electric drill was similar to a prior study conducted with the same test bench, drill, and bit but a force on bit of 150 N; the mean ROP was 9.7 mm/s (Botti et al., 2017). The feed force differences (88 vs 150 N) had little effect on ROP. A South African study compared various drills during mine drilling and reported penetration rates of 5.8 mm/s for a pneumatic drill and 2.2 mm/s for an electric drill (Phillips et al., 2007). However, the study did not report the drill manufacturers or drill masses.

The mean peak noise level for the pneumatic drill, 130.4 dBC, was significantly greater than for the electric drill (117.7 dBC). Note that neither of these levels exceeded the 140 dBC peak limit specified by ACGIH (2018). The noise levels for both drills would require hearing protection but the levels for the pneumatic drill would require double protection (e.g., a combination of earplugs and earmuffs) (Luo et al., 2014). Most noise studies for pneumatic rock drills have been conducted during mining or rock drilling. The Phillips study (2007) reported L_{eq} levels of 107.9 dBA for a pneumatic rock drill and 94.7 for an electric rock drill. A study comparing a pneumatic and electric jack leg drill for hardrock mining reported sound power levels, adjusted for penetration rate, of 115.3 dBA for the electric drill and 123.4 dB for the rock drill (Camargo et al., 2010). A field study of pneumatic rock drills (mass and bit diameter not listed) used in road construction reported mean levels near the operator's ears of 107.4 dBA. The corresponding level normalized to 8 h (i.e., the $L_{eq(8h)}$) was 104.8 dBA (Tah-Chew and Keung, 1991).

There are databases of published and manufacturer reported noise and vibration levels (HAVTEC-OPERC, 2018; Umea University, 2018). Extracting just data on drilling holes with drills of similar mass (5–10 kg) and of similar bit diameters drilling into concrete, L_{eq} noise levels for electric hammer drills appear to be less than 100 dBA, while for pneumatic rock drills levels are greater than 100 dBA. Note that the differences observed between the pneumatic and electric drills are much greater than those associated with an electric hammer drill using a dull vs. a sharp drill bit (Carty et al., 2017), as well as for the reductions in noise associated with noise controls tested in mining environments (Michael et al., 2011).

For the pneumatic drill, the extremely high vibration energy around 50 Hz (Fig. 3) corresponds to the percussion frequency and also contributes to peaks at higher harmonic frequencies. According to the ISO weighting factors, the high level of acceleration at this frequency presents a serious health risk. Based on ISO weighting the health risk is much higher for frequencies in the 4–50 Hz range than in the 63–1250 Hz range. In comparison, the much lower vibration levels generated by the electric drill show that the design reduced vibration across a wide range of frequencies.

Handle vibration levels were much higher for the pneumatic than the electric drill. According to the allowable upper limit of daily vibration exposure A (8) (ISO 5349-1, 2004), a worker would be allowed to operate the electric drill for up to 3 h 55 min per day while the pneumatic drill could be operated for only 8 min per day. Drill handle vibration levels for the electric drill are similar to levels reported in other bench studies. In a prior study, drilling with a 19 mm diameter bit and a feed force of 150 N was associated with a weighted handle vibration level of 7.8 m/s^2 and an unweighted level of 92.1 m/s^2 (Antonucci et al., 2017). The higher values reported in the Antonucci paper may be due to the higher feed force used in that study. Most field vibration studies of pneumatic rock drills are recorded during the work of stoneworkers or miners. The Phillips study (2007) of miners reported total weighted handle vibration levels (a_{hv}) of 21.9 m/s^2 for the pneumatic rock drill and 9.2 for the electric drill (mass of drills not reported). A study of stoneworkers using pneumatic rock drills reported a mean weighted handle vibration of 30.7 m/s^2, but, again, the mass of drill and bit size were not reported (Bovenzi et al., 1994). A field study of construction workers using electric rotary drills reported a mean frequency weighted handle vibration level of 5.1 (SD = 3.7) m/s^2 - again size of the drills and bit were not reported (Vergara et al., 2008). A review of manufacturers' data on handle vibration reported higher levels for pneumatic hammer drills than electric hammer drills but did not evaluate effects of tool weight or bit diameter (Lopez-Alonso et al., 2013). A study of handle vibration on 19 different electric rotary hammer drills, following ISO 5349-1 (2001) protocol, found that vibration level increased with increasing bit diameter. For 19 mm bits, handle vibration levels ranged from 8 to 17 m/s^2 across the drills tested (Mansfield, 2006).

Respiratory silica dust levels were an astonishing 40 times higher with the pneumatic drill than with the electric drill. The large difference was due to a combination of higher respirable dust levels generated by the pneumatic drill, approximately 25 times higher than the electric drill, and the finding that the percent of quartz from the respirable dust of the pneumatic drill was 57% higher than the dust from the electric drill. The higher dust levels are due to the clearing mechanism of the pneumatic rock drill; high-pressure air is forced down the center of the rock drill bit and rapidly ejects the dust from the hole into the worker's breathing zone. The electric rotary drill generates much less visible dust; most of the dust and debris is pulled out of the hole by the spiral thread on the bit. It is not known why the pneumatic rock drill generates higher levels of quartz per dust weight than the electric rotary drill. It may be that the mechanism of bit impact with the concrete with the pneumatic drill releases more respirable particles with silica than the impact mechanism with the electric drill. Both bits were new so that would not account for the difference. It could also be that the high airflow flushing dust from a hole with the pneumatic drill differential distributes silica particles compared to the dust emerging from a hole drilled by an electric drill because small particles with quartz may move differently with high air flow than particles without quartz.

The levels of respirable silica dust generated by both drills were well above the PEL (0.05 mg/m^3; OSHA, 2016) and would require a respirator; the type depending on length of exposure. However, the much higher dust levels from the pneumatic drill may require an air-supplied regulator with frequent filter change to avoid filter saturation. Generalizing the findings to construction sites should be done with caution. With this test bench system, a hole was drilled every minute and dust gradually accumulated in the closed room. Most drilling at construction sites is less frequent and conducted in larger spaces with air movement. Previously, we measured respirable silica dust outdoors while a worker drilled 22 mm diameter holes into concrete with a pneumatic drill at a rate of 0.6 holes/min for 25 min (Cooper et al., 2012). Respirable silica dust levels across the 4 trials ranged from 0.42 to 0.84 mg/m^3; the mean hazard ratio was 14. Dust levels during drilling in an outdoor setting are likely to be much lower than in a closed space and will be strongly influenced by the air exchange rate or wind. Indeed, Blute et al. (1999) found that workers drilling thousands of 19 mm diameter, 127 mm deep holes overhead into concrete, using pneumatic drills, had widely varying respirable silica dust levels in their breathing zone, ranging from 0.05 to 1.49 mg/m^3. In a prior laboratory study with workers drilling into concrete, just a single air exchange per hour (70 m^3/h) can reduce the respirable quartz level by a factor of 10–20 (Hallin, 1983). The strong effect of wind and air exchange makes it very difficult to conduct controlled dust experiments in outdoor settings.

A limitation of this test bench study was that the vibration measurements were not conducted completely according to ISO guidelines (5349-1). The ISO guidelines call for having workers do drilling rather than using an automated test bench system. The advantage of having workers do drilling is that they can apply varied grip and push forces according to their familiarity with the tool, thereby producing a wide range of handle vibration levels similar to those that workers might be exposed to in the real world. However, the variability is also a disadvantage and may introduce worker bias, e.g., workers may apply different push forces for a pneumatic drill than an electric rotary drill. With a test bench, the applied force magnitude and direction are the same for both drills tested and for all holes drilled. Although the vibration levels obtained in the standardized condition of the test bench may not be fully representative of real exposures, it is widely accepted that the lower the vibration of the tool in a test bench study the lower the exposure will be in real operations. Another limitation for the noise sampling is the collection inside a test room with the microphone about 1 m from a wall. However, this condition is not that dissimilar to drilling inside buildings or tunnels.

5. Conclusions and recommendations

The electric hammer drill was competitive with the pneumatic rock drill in terms of productivity but generated substantially less vibration, noise, and respirable silica dust exposure. Contractors who do structural upgrades to of bridges, roads, airport runways and buildings tend to use pneumatic rock drills for dowel and rod work. However, electric rotary drills with torque and mass similar to rock drills are now available. Given the findings that drilling productivity is similar between a pneumatic rock drill and an electric rotary drill of a similar mass and that the health hazards of the electric rotary drill are much less than the pneumatic drill, structural contractors should be advised to switch to electric rotary drills for dowel and rod and other similar concrete drilling work.

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