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Characterization of Occupational Exposures to Respirable Silica and Dust in Demolition, Crushing, and Chipping Activities

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Abstract

Objectives: Exposures to respirable crystalline silica (RCS) and respirable dust (RD) were investigated during demolition, crushing, and chipping at several Massachusetts construction sites.

Methods: Personal breathing zone samples ($n = 51$) were collected on operating engineers working at demolition and crushing sites, laborers performing miscellaneous tasks at demolition sites, crushing machine tenders at crushing sites, and chipping workers at substructure bridge repair sites. Area samples ($n = 33$) were collected at the perimeter of demolition and crushing sites to assess potential bystanders' exposures. Exposures 'with' and 'without' the use of dust suppression methods were compared when possible. RD samples were analyzed for crystalline silica content with Fourier Transform Infrared Spectrophotometry (FT-IR) according to the National Institute for Occupational Safety and Health (NIOSH) Method 7602. Statistical analyses of the exposure data were performed in SAS version 9.4.

Results: Chipping workers had the highest exposure levels [the geometric mean (GM) time-weighted average (TWA) for RCS was 527 µg/m^3 and the GM for RD was 4750 µg/m^3]. The next highest exposures were among crushing machine tenders (RCS GM of 93.3 µg/m^3 and RD GM of 737.6 µg/m^3), while laborers and operating engineers had the lowest exposures (RCS GM of 17.0 and 6.2 µg/m^3, respectively). Personal 8-h TWA RCS exposures were higher than the new OSHA permissible exposure limit (PEL) of 50 µg/m^3 for 80% of samples collected on chipping workers ($n = 31$) and 50% of samples collected on crushing machine tenders ($n = 8$). Operating engineers ($n = 9$) and laborers ($n = 3$) had RCS exposures lower than OSHA PEL. The highest concentrations measured would have exceeded the PEL within 15 min chipping and within 2 h of crushing with no further exposure. Chipping workers' RCS exposures were higher than OSHA PEL even when they were adjusted to account for the assigned protection factor of the half-face N95 cartridge respirators used during chipping. Exposures of crushing tenders were reduced to levels under the OSHA PEL when a water spraying system in crushing machines was utilized, but not when a water cannon machine was used. Area samples at demolition and crushing sites indicate overall lower exposures than the PEL, however, bystander workers at crushing sites could be exposed to higher levels compared to demolition sites. Real-time dust monitoring during demolition indicate very high short-term peak exposures.

Conclusions: Controlling or reducing crystalline silica exposures to levels under the new OSHA PEL of 50 μg/m^3 remains challenging for chipping workers and crushing machine tenders. Even with the use of dust suppression controls, respiratory protection may be required for various tasks.

Keywords: chipping; construction; crushing; demolition; respirable crystalline silica; respirable dust

Introduction

In 2016, the Occupational Safety and Health Administration (OSHA) promulgated a new rule regulating occupational respirable crystalline silica (RCS) exposures by establishing a lower permissible exposure limit (PEL) and including a number of new provisions for exposure assessment, medical surveillance, dust control methods, respiratory protection, and recordkeeping for both general industry and construction workers (OSHA, 2016a). To ensure compliance with the new standard, construction contractors are required to assess 8-h time-weighted average (TWA) exposures through exposure monitoring or objective exposure data, or to use dust controls specified for 18 high silica exposure construction tasks listed in ‘Table 1’ of the OSHA standard. About 2.2 million construction workers are exposed to crystalline silica, which is known to be associated with development of silicosis, an incurable lung disease of scarring of lung tissue leading to inflammation, decreased lung function, and respiratory failure (OSHA, 2013). The International Agency for Research on Cancer (IARC, 1997) lists silica as a group I known carcinogen to humans and the National Toxicology Program (NTP, 2011) reports crystalline silica as ‘known human carcinogen’.

Overexposure to silica exposures in the construction industry has been documented by numerous studies (Rappaport *et al.*, 2003; Sauve *et al.*, 2013; OSHA, 2016c). Construction activities associated with high exposure levels include abrasive blasting, cutting and drilling, and road and bridge work (Rappaport *et al.*, 2003). Demolition, crushing, and chipping activities can potentially generate high silica exposures since they involve mechanical disruption of materials that contain crystalline silica. Demolition is a construction activity that aims at destroying building structures often using heavy equipment. Crushing is performed to reduce the size of demolition materials to produce a product useful for other construction jobs such as roadwork, asphalt work, etc. Concrete chipping in substructure bridge repair is done to remove old concrete using handheld pneumatic chipping guns. Even though demolition, crushing, and chipping are common in construction, little is known about silica and dust exposures and the effectiveness of dust suppression methods used during these activities. The goal of this study was to characterize occupational exposures to RCS and dust during demolition, crushing, and chipping activities and to evaluate the impact of currently used dust suppression methods on reducing workplace exposures. Task-based exposure data presented in this paper can help practitioners identify effective strategies to control silica exposures during these activities.

Methods

Sampling sites

This study was conducted in partnership with several local contractors in Massachusetts specialized in demolition, crushing, and concrete chipping during substructure bridge repair. Exposure measurements were performed at two demolition sites, one crushing operation, and five bridge repair sites.

Demolition sites consisted of: (i) demolition of a multi-story building located in a commercial and residential area downtown Boston, MA (site A); and (ii) demolition of multiple three-story buildings located in a rural area outside of Boston, MA (site B). Sampling was performed for 4 days at site A and 5 days at site B (see Supplementary Table S1, available at *Annals of Work Exposures and Health* online). Different types of excavators were used at each site performing a variety of tasks including destruction of building walls, excavation, materials’ sorting, and debris’ removal. The types of heavy equipment machines utilized at both sites were very similar consisting of excavators, material handlers, loaders, trucks, etc. Demolition debris at site A was transported out of the site, while at site B debris was crushed onsite using a portable crushing machine.

Operation of the crushing machine at site B required a constant presence of a crushing machine tender, who stood at the top of the machine to remove unwanted materials. The job specifications at site A mandated to use of dust suppression methods to comply with city regulations for preventing community exposures to dust. Dust suppression methods consisted of a water spray system installed in a long reach excavator, water hoses held by laborers that were connected to nearby hydrants, and water tender trucks. The use of dust suppression methods at site B was not mandatory, since this site was further away from residential homes. As part of a demonstration project in collaboration with a supplier of dust suppression machines, demolition contractors used a water cannon machine for reducing dust exposures for 1 day at each demolition site. This machine, similar to those used on ski slopes to generate snow, connects via hoses to a water source and projects atomized water particles (50–100 microns) into the air through many spray nozzles and a high-powered fan. The water cannon machines used at both sites were very similar in design, but while one worked with electricity the other with a diesel generator. Trained workers were responsible for manually changing the direction of the water droplet stream towards the highest levels of visible dust.

Crushing was performed at a semi-mobile crushing site (site C) located outside of Boston. The raw material was brought to this crushing site from different local demolition sites. The crushing system here involved the use of three portable crushing machines, all set to crush the material to specific sizes. The entire operation involved the work of a heavy machine operator loading the material into the first crusher hopper, an operator overseeing the machines from inside of a control cabin, and two crusher tenders, who were working next to crushing machines' conveyor line to remove unwanted materials (wood, rebar, wire, etc.). Sampling was performed during three consecutive days. Every worker used N95 dust masks. Local regulations required application of wet dust suppression methods to reduce the levels of visible dust. A built-in water spraying system was present at each conveyor transfer point consisting of hoses with misting attachments to target the material. In addition, a water cannon misting machine, similar to the unit at site A, was used during 2 days of our sampling (see Supplementary Table S1, available at *Annals of Work Exposures and Health* online). The localized spraying system was shut off when the water cannon was used.

Concrete chipping was performed at five different substructure bridge repair sites. Workers performed chipping under bridges using handheld pneumatic chipping guns (35–40 lb) while standing in highly elevated scaffolds. There were three to five workers at each site and each of them wore a half-face N95 cartridge respirator with an assigned protection factor of 10 (APF 10). At the time of our sampling, the contractor was interested in evaluating the efficacy of an 'air curtain' device as a dust suppression method for reducing workers' exposures. The air curtain comprised a pneumatic style venturi air blower (Model ASI-1200) attached to a 10-foot long, 4" diameter aluminum duct with 3/4" holes spaced 6" from each other (Fig. 1). The air curtain was directed downward toward the chipping surface to blow dust away from workers' breathing zone. The air curtain was used at two sampling sites for 2–3 h each day. Personal breathing zone exposures 'with' and 'without' the use of the air curtain were compared.

Exposure measurements

Personal exposure monitoring

RCS and respirable dust (RD) exposures were measured in the breathing zone of operating engineers running different heavy equipment, laborers at demolition sites responsible for holding water hoses, crusher tenders at crushing site, and the handheld pneumatic chipping gun operators at substructure bridge repair sites. Every study participant signed a consent form approved by the UMass Lowell Institutional Compliance Office. Exposure monitoring was performed regardless of whether respirators were worn or not. RD samples were collected using 37 mm diameter polyvinyl chloride PVC filters, (Millipore, Billerica, MA) loaded into two-piece cassettes, housed in BGI 4 (Mesa Laboratories, Butler, NJ) respirable cyclones attached to GilAir 3 sampling pumps (Sensidyne, IH&S Instrumentation, Clearwater, FL). Filters were equilibrated before and after weighing in an environmental chamber at 25°C and 50% relative humidity. Sampling pumps were calibrated to

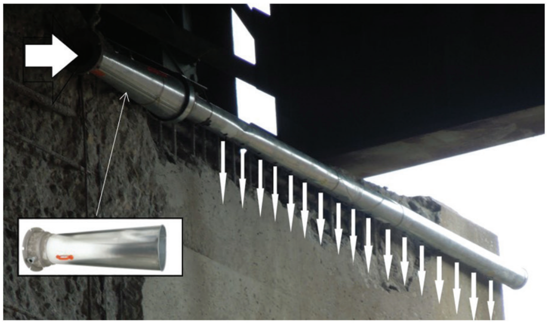

Figure 1. Venturi style (Model ASI-1200) air blower with attached air curtain used at two substructure bridge repair sampling sites.

a nominal flow rate of 2.2 l/min using a primary calibration standard DryCal DC-Lite (Bios International Corporation, Butler, NJ). Appropriate field blanks were collected for each site visit as part of the sampling protocol. Duration of sampling varied from site to site depending on the duration of tasks and workers' participation. In cases when exposures were deemed as very high (substantial visible dust were observed), sampling was restricted to shorter durations to avoid overloading of filters. The median sampling duration was 133 min at chipping sites, 295 min at demolition sites, and 193 min at the crushing site. Concentrations of RD were determined with gravimetric analysis according to the National Institute of Occupational Safety and Health (NIOSH) Analytical Method 0600 using an analytical microbalance (Mettler Toledo, XP26 model, Columbus OH) with a limit of detection (LOD) of 15 µg. Samples were analyzed for silica quartz content with Fourier Transform Infrared Spectrophotometry (FT-IR) according to NIOSH Analytical Method 7602, modified by Bello and Virji *et al.* (Bello *et al.*, 2002; Virji *et al.*, 2002). After weighing all filters were ashed and 5 mm KBr pellets were prepared to quantify quartz at its major peak at 978 cm^{-1}. The LOD of the analytical method for the 5 mm pellet is 1.3 µg quartz per sample.

Area exposure monitoring

Integrated area samples (n = 33) were collected at the perimeter of the work zone at demolition and crushing sites (see Supplementary Table S1, available at *Annals of Work Exposures and Health* online). Samples were stationed 10–15 m away from the center of work activities and 1.5 m above the ground. Sample location was determined by taking into account the physical barriers along each site and the layout of the buildings. At each site, three to four area samples were collected per day of sampling. Area samples at site B were collected only at the perimeter of the demolition zone and not at the area surrounding the crushing machine. Area samples were collected and analyzed following the methods described previously (see the section 'Personal exposure monitoring'). Duration of area samples ranged from 129 to 432 min with a median of 286 min. At site A, in addition to the integrated area samples, we performed real-time monitoring of RD using three direct reading aerosol monitors DataRAM pDR 1500 and pDR 1200 (Thermo Fisher Scientific, Franklin, MA) during three sampling days. All pDR instruments were calibrated prior to each sampling day and were set to record 1-min average RD concentrations. Real-time exposure data were downloaded using the equipment software. Concentrations of RD were corrected by applying correction factors, calculated as the ratio of daily average from direct reading instrument divided by the daily average of an integrated filter sample collected with the pDR.

Statistical analysis

Exposure data analyses were conducted with SAS version 9.4 (SAS Institute Inc., Cary, NC) software. Since the data were more lognormal than normal, all statistical testing were executed on exposure concentration logs resulting in geometric mean (GM) and geometric standard deviation (GSD) for RCS and RD. The univariate Proc GLM procedure and Proc mixed models were used to investigate association of RCS and RD exposures (depended variables) with task/job performed, exposure control, and site activity (independent variables). Personal exposures at demolition and crushing sites were compared by job/task performed (categories: operating engineers, laborers, and crushing tenders) using mixed models with site id as a random effect. The univariate Proc GLM procedure was used to assess the impact of exposure controls within each site categorized as: 'water cannon and hoses versus water hoses' for demolition site A, 'water cannon versus no dust suppression' for demolition site B, 'water cannon versus water spraying' for crushing site C, and 'with versus without air current' for chipping sites. Association of area exposures measured at sites A, B, and C with the activity performed (categories: demolition, crushing) was also investigated using mixed models with site id as a random effect. Since less than 8% of the personal samples had non-detectable RCS and GSD <3, they were substituted with the LOD/$\sqrt{2}$ for statistical analysis (Hornung and Reed, 1990; Croghan and Egeghy, 2003). LIFEREG procedure in SAS was used the calculate the GM for demolition area samples with > 15% non-detectable RCS levels (Jin *et al.*, 2011). Personal exposures were compared with the new OSHA PEL of 50 µg/m^3 by calculating the 8-h TWA (8 h-TWA) exposure assuming zero exposures for the unsampled time. Furthermore, real-time RD concentrations measured at demolition site A were analyzed with time series analyses in SAS to compare exposures for upwind and downwind samples. The Autoreg procedure in SAS was used to estimate the mean and standard error of the log concentration values after adjusting for an autocorrelation lag of two (Dahm *et al.*, 2013). Parameter estimates from the Autoreg procedure were then used to evaluate whether the difference in RD concentrations was statistically significant.

Results

Personal silica and dust exposures

Personal exposures during chipping in substructure bridge repairs

The crystalline silica content in personal samples collected during chipping at substructure bridge repair sites (n = 31) had a median value of 13.4%. All samples collected in the breathing zone of chipping workers had detectable RCS levels with air concentrations that ranged from 101 to 1554 µg/m^3 (Table 1). The new OSHA PEL would have been exceeded within 0.3–4 h of chipping with no further exposure. Overall, the calculated 8 h-TWA exposure, assuming zero exposures for the unsampled time, was higher than PEL for 80% of personal samples. Exposures to RCS were reduced by 25% when the air curtain was used (n = 12) compared to when chipping was done without the air curtain (n = 19), however this reduction was not statistically significant (P = 0.27). On the contrary, the use of the air curtain achieved a 95% reduction (P = 0.02) of the RD levels (Table 2). RD exposures were on average nine times higher and predicted significantly RCS exposures (R^2 = 86%).

Personal exposures during demolition and crushing activities

Crystalline silica quartz was detected on 80% of personal samples collected at demolition and crushing sites (n = 20) with a median value of 11.5%. The highest personal RCS exposures were measured on crushing machine tenders (GM 93.3 µg/m^3) followed by laborers and operating engineers (GM 17 and 6.2 µg/m^3, respectively) (Table 1). Personal RD exposures were highly variable across all samples collected at demolition and crushing sites ranging from 3 to 1423 µg/m^3.

Exposures of crushing machine tenders were significantly higher compared to operating engineers (P-values for RCS and RD < 0.001). Moreover, the calculated 8 h-TWA exposures (assuming zero exposure for unsampled time) of crushing machine tenders (n = 8) were higher than PEL for 50% of samples. The highest RCS concentration was measured on a crushing machine tender at site C. Crushing tenders' exposures at site C were higher when the dust cannon was used (GM = 151.7 µg/m^3) compared to when the water spraying system was applied (GM = 65.2 µg/m^3) (P = 0.14). In addition, RCS exposure of the crushing machine tender at site B was lower when crushing was performed a day after raining (21 µg/m^3) compared to when the material was dry (121 µg/m^3).

Operating engineers (n = 9) and laborers (n = 3) had the lowest RCS personal exposures measured, with levels lower than the OSHA PEL (Table 1). The highest exposure of 0.51 µg/m^3 was measured on the breathing zone of a ground labor worker responsible for holding water hoses at demolition site A. Higher exposures for this worker could be related to his proximity with the truck loading activity that generated a visible amount of dust.

Silica and dust levels at the perimeter of demolition and crushing sites

Perimeter area samples indicate lower daily average exposures compared to the personal samples. Among all

Table 1. Concentrations of RCS and RD in personal samples.

Job/task	Sampling duration	n[a]	TWA Respirable silica conc.[b] (µg/m^3)		TWA Respirable dust conc. (µg/m^3)		Time (hours) needed to exceed the new PEL of 50 µg/m^3	Percent of samples with 8-h. TWA RCS^2 conc .>PEL
			GM (GSD)	Range	GM (GSD)	Range		
Chipping workers	54–318	31	527 (2.1)	101–1554	4,750 (2.1)	471–19,525	0.25–3.93	80%
Crushing machine tenders[c]	120–378	8	93.3 (2.2)	21–220	737.6 (2.3)	138–1423	1.82–19.05	50%
Laborers in demolition	222–295	3	17.0 (2.6)	8–51	231.0 (1.6)	138–356	7.8–50	0%
Operating engineers[d]	267–380	9	6.2 (2.4)	Nd[e]–29	68.4 (4.1)	3–311	Nd–64.5	0%

[a] n = Number of samples collected.

[b] TWA concentrations for the duration of sampling.

[c] Includes the crushing tender at site B.

[d] Operating engineers in both demolition and crushing sites.

[e] Nd = Non-detectable levels (n = 4, 44% of operating engineers' samples).

Table 2. Concentration of RCS and RD during chipping tasks 'with' and 'without' the air curtain.

Task/control used	*n*[a]	Sampling duration (hours)	Respirable silica conc. (μg/m³)		Respirable dust conc. (μg/m³)		% of samples with RCS conc. > OSHA PEL of 50 μg/m³
			GM (GSD)	Range	GM (GSD)	Range	
Chipping/without air curtain	19	72–318	590 (2.02)	152–1553	5980 (1.55)	240–17,511	100%
Chipping/with air curtain	12	54–168	440 (1.55)	101–1343	330 (2.54)	470–19,525	100%

[a] *n* = Number of samples collected.

Table 3. Concentration of RCS and RD measured from stationary area samples at the perimeter of demolition and crushing sites.

Site ID	Activity	Number of samples	Average sampling duration (min)	Respirable silica conc. (μg/m³)			Respirable dust conc. (μg/m³)	
				% non-detect.	GM (GSD)	Range	GM (GSD)	Range
A	Demolition	12	339	25%	3.2 (3.0)	Nd[a]–12.0	53.6 (3.1)	12.0–745.8
B	Demolition	15	259	100%	Nd	Nd	20.1 (3.6)	2.8–395.8
C	Crushing	6	244	0%	33.3 (2.8)	13.0–239.6	218.2 (1.9)	83.9–613.0

[a] Nd = Non-detectable levels.

area samples (*n* = 33) collected at crushing and demolition sites (area samples were not collected at chipping sites), 45% had detectable RCS levels with an average silica content of 12.8%. Concentrations of RCS at the perimeter of the crushing site (*n* = 6) ranged from 13.0 to 239.6 μg/m³ with 100% detects, while at the perimeter of demolition sites (*n* = 27), RCS concentrations ranged from Nd (non-detectable levels) to 12 μg/m³ (67% non-detects). The highest RCS concentration (239 μg/m³) was measured at site C downwind of a crushing machine, when the water cannon was used (Table 3).

RD concentrations in all area samples had an overall GM of 44.6 μg/m³ (GSD = 4.1). The average daily RD concentrations among all sites ranged from 2.8 to 745.8 μg/m³ with the highest levels measured at site A during the first day of demolition (Table 3). Concentrations of RD at the perimeter of the sites were significantly higher during crushing compared to demolition activities ($P = 0.02$) (Fig. 2).

Samples collected at site A indicate significantly higher RD exposure ($P = 0.03$) when the water cannon was used in combination with water hoses compared with when only water hoses were used (Fig. 3). It should be noted that data at site A were obtained only 'with' dust controls in place, since a continuous use of dust controls here was required by the city ordinances. At site B, area samples collected 'with' and 'without' controls indicate lower RD concentrations when the water cannon was used compared to when dust suppression methods were not used. However, this difference was not statistically significant ($P = 0.73$), most likely due to the small number of samples collected (see Supplementary Figure S1, available at *Annals of Work Exposures and Health* online). Similarly, at the crushing site C, area RD exposures were lower when the localized misting system was used compared to when the water cannon was used ($P = 0.14$) (see Supplementary Figure S2, available at *Annals of Work Exposures and Health* online).

Direct reading measurements for RD performed at the perimeter of site A (*n* = 9) indicate temporal and spatial exposure variations. Real-time exposure profiles indicate very high peak exposures during specific times of the workday as showed in the example presented in Fig. 4. The highest peak observed from the real time RD concentration profile (1983 μg/m³) was recorded in the morning of the first day of demolition when large pieces building walls levels fell on the ground generating clouds of dust. Trucks driving in and out of the site were another source of dust re-suspension. The highest RD concentrations were measured from a real-time sampler located between the building that was being demolished and an adjacent multi-story building (GM = 52.9 μg/m³;

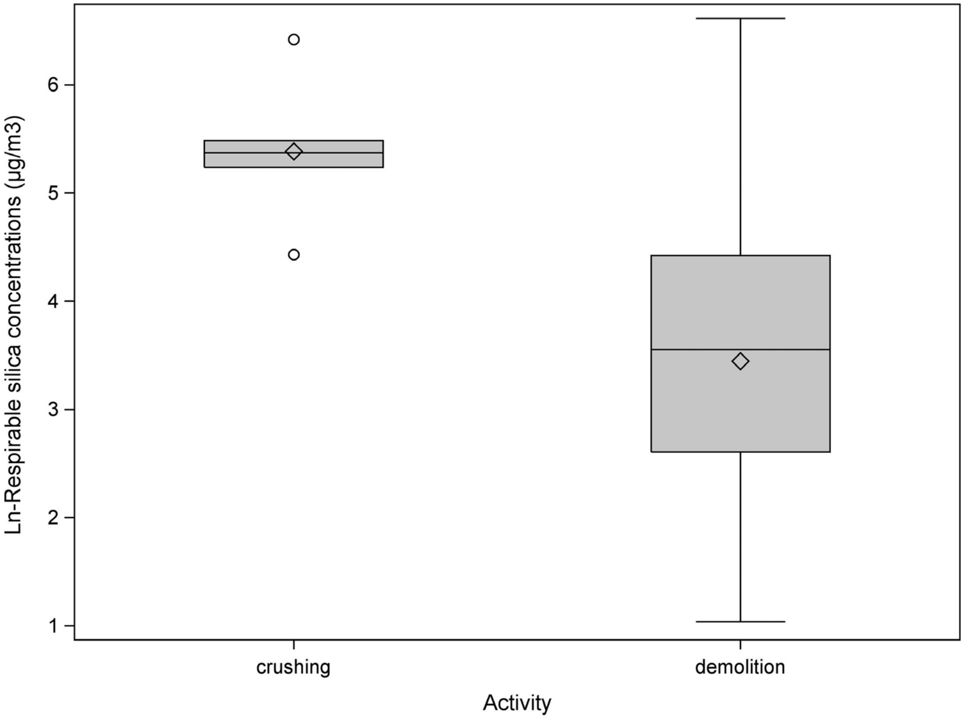

Figure 2. Distribution of ln-RD concentrations (µg/m^3) in area samples collected at the perimeter of demolition and crushing sites (*P* = 0.02).

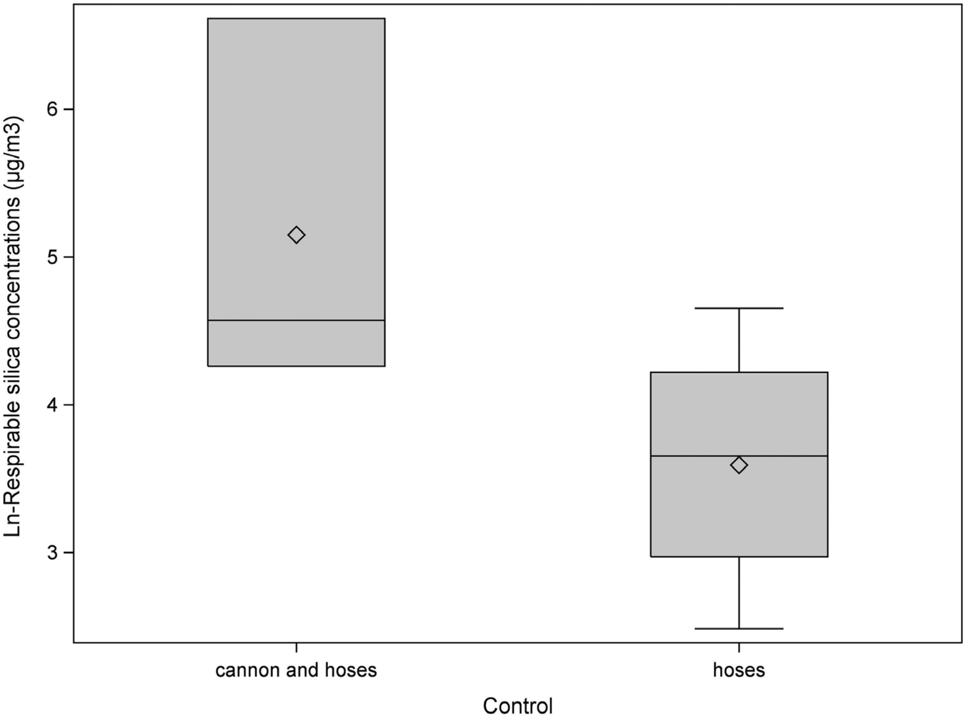

Figure 3. Comparison of area RD concentrations (µg/m^3) at demolition site A with combination of water cannon and water hoses versus water hoses (*P* = 0.03).

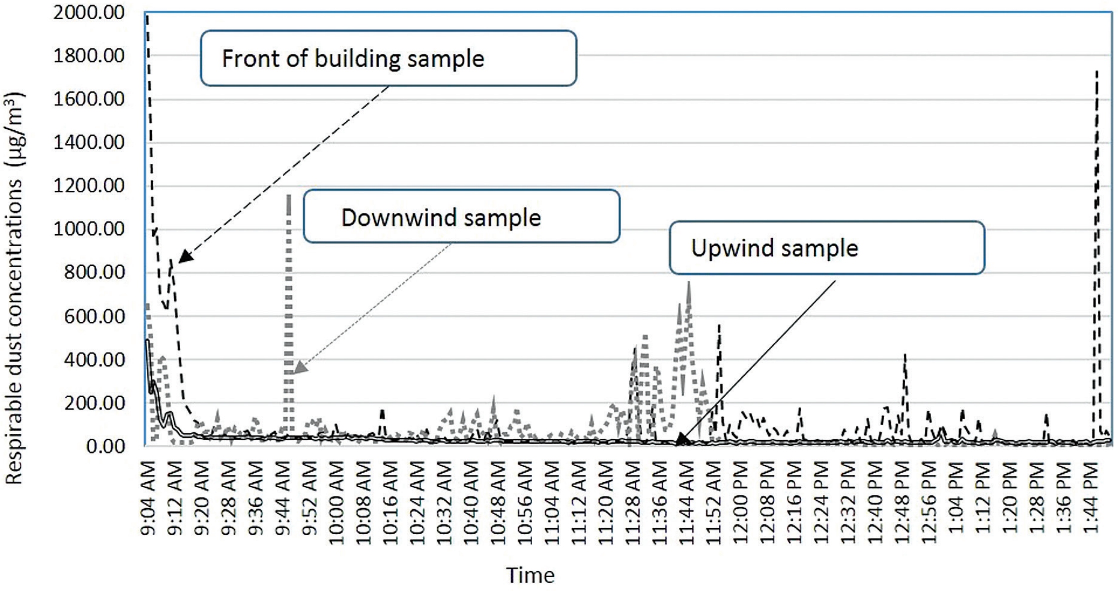

Figure 4. Real-time RD concentrations (µg/m³) during the demolition of a multi-story building at site A. RD time-exposure profiles (1-min averages) during demolition of a multi-story building in downtown Boston. Three pDR units were positioned in three different locations at the perimeter of the site, at 10–15 m from the building.

GSD = 2.2) at site A. Time series analysis indicate that downwind samples had significantly higher ($P < 0.001$) RD concentrations [GM = 43.8 µg/m³; confidence interval (CI): 40.0–48.0] compared to the upwind samples (GM = 20.9 µg/m³; CI: 19.4–22.5).

Discussion

This study demonstrates overexposures to RCS during concrete chipping in substructure bridge repairs and crushing activities. The 8-h TWA personal exposure data indicate that 80% of chipping workers were exposed at levels higher than OSHA PEL. These results underestimate the true daily exposures, given that the 8-h TWA calculations are based on short sampling durations (54–318 min) and assumption of no exposure for the unsampled time. Since these workers typically chip for 6–8 h per day, their daily TWA exposures approximate the task level exposures, which were higher than OSHA PEL for 100% of samples (range 101–1554 µg/m³). High exposures of chipping workers we report here are consistent with exposure profile data presented in the OSHA technological feasibility report (Table IV.5.5-B) indicating that 8-h TWA exposures of workers using handheld power chipping tools were higher than PEL for 72% of samples (n = 66) (OSHA, 2016b). Even when the protection from the half-face cartridge respirators with an APF of 10 was factored in, 58% of chipping workers still had higher exposures than the PEL. These results suggest that when chipping without any exposure controls workers would need a respirator with APF > 25 (e.g. full-face air purifying respirator) to reduce RCS exposures under 50 µg/m³.

Although the use of the air curtain during chipping tasks reduced RD exposures, it did not result in significant reduction of RCS exposures. More importantly, the air curtain dust control is not a preferable engineering control since it distributes the dust from workers breathing zone to other areas in the environment. Several studies have demonstrated the effectiveness of other engineering controls such as local exhaust ventilation (LEV) and wet techniques in reducing exposures from handheld powered chipping tools. Shepherd *et al.* found an average of 94% reduction in silica exposures when using hammer drills with LEV (Shepherd *et al.*, 2009) and Etch *et al.* report a 70–90% reduction on dust exposures when applying water spraying during concrete breaking with jackhammers (Echt *et al.*, 2003). Currently, chipping tools equipped with dust controls are commercially available and have been successfully used in the industry (OSHA, 2016a). The new OSHA 'Table 1' requires that workers operating handheld powered tools should use tools with water delivery systems that supply water from portable water tanks, as well as wear respirators with APF 10 if they perform the work for more than 4 h/shift. Alternatively, workers could use tools with shroud and dust control systems that provide a sufficient air flow and filter with 99% collection efficiency, in addition to wearing respirators with APF 10 when working more than 4 h/shift (OSHA, 2016b).

Crushing tenders had the highest personal exposures measured among all workers in demolition and crushing sites. About 50% of the personal samples on crushing tenders had RCS concentrations higher than the new OSHA PEL. The highest RCS exposures measured would have exceeded the PEL within 2 h of the crushing tenders job. Crushing tenders generally work at this task over 8 h per day, so their task exposures are expected to be similar to their daily TWA exposures. The use of an N95 dust mask with APF 10 ensures compliance with the OSHA PEL of 50 µg/m^3 for these jobs. All crushing tenders at site C wore N95 respirators, while the crushing tender at site B did not wear any respirator. The effectiveness of material wetting on exposure reduction was shown at site B, where significantly lower exposures were found from a sample collected when the material was wet a day after raining (21 µg/m^3) compared to a sample collected in a dry day (121 µg/m^3). Data from site C show that exposures of crushing tenders were reduced to under the 50 µg/m^3 when the water spraying system was applied, but not when the water cannon machine was used. The water spraying system is potentially more effective for reducing dust levels during crushing activities since it targets the material at the source while the water cannon targets the dust after its suspension in the air. In addition, the effectiveness of the water cannon is determined by the size of water droplets that collide with dust particles present in the air. Smaller size droplets (10–50 µm) have shown to be more effective on reducing dust levels in the air (Colinet *et al.*, 2010) compared to larger droplets (100 µm) generated by the water cannon used as part of this study. Redesigned wet dust suppression systems that generate smaller water droplets could potentially be more effective in reducing exposures to RD particles. Furthermore, detailed particle size distribution measurements during these activities could inform designing more effective control measures.

Our findings support the OSHA 'Table 1' specification that use of crushing equipment with water spraying systems at transfer points does not require additional respiratory protection. In their technical feasibility report, OSHA specifies that the spray nozzles should be located upstream of dust generation points to ensure that the material is sufficiently wetted (OSHA, 2016b). However, high exposures among crushing tenders we report here support the need for implementation of dust controls and suggest that respiratory protection may also be needed when water suppression is inadequate. Other controls listed in OSHA's 'Table 1' include remote control stations and ventilated, climate-controlled control booths. In addition, local exhaust ventilation systems (LEV) can be used to reduce exposures to very fine particles that can't be captured by wet suppression methods (Colinet *et al.*, 2010). The number of workers at risk for this occupation is ~30,000 and the highest employment rates are in large states such as California and Texas (Bureau of Labor Statistics, 2016). The demand for crushing-related jobs will likely increase as the need to reduce recycling cost and to obtain LEED certification for reuse on site increases.

Occupational exposures of heavy machine operators in both demolition and crushing sites were the lowest we measured, much lower than PEL of 50 µg/m^3. Heavy machine operators typically work in enclosed cabins, presenting a physical barrier to airborne particles. Exposures of laborers at the demolition site A, where dust suppression methods were used continuously, were lower than the OSHA PEL. These results are comparable with the data presented in Table IV.5.3-B of the OSHA new standard technological feasibility chapter (OSHA, 2016b). It should be noted that none of the operating engineers and laborers in this study used respirators. Rappaport *et al.* reported that the use of ventilated cabs reduced exposures by ~6-fold for operating engineers and that the use of wet dust suppression reduced significantly RCS exposures by 3-fold for laborers (Rappaport *et al.*, 2003). Our findings support 'Table 1' of the OSHA standard, where respiratory protection is not required when heavy equipment operators working in demolition activities operate the equipment in enclosed cabs or when workers are outside the cab during demolition if dust suppression methods or water are used to reduce exposures.

Concentrations of RCS and RD in area samples at demolition and crushing sites were much lower compared to the personal samples. Area exposures varied widely by site due to the variety of site activities and their duration per day, sample location, and dust controls used. Results show significantly higher RCS and RD levels at the perimeter of the crushing site (10–15 m from the center of activity) compared to the perimeter of the demolition sites. This results could be related to a number of factors: (i) higher silica content in the material being crushed at site C (17.8% compared to 10.2% quartz in the demolished material); (ii) greater physical barriers surrounding site C: about two-third of the perimeter of the crushing site was surrounded by large piles of demolition materials and other small buildings that potentially prevented dust movement in the open environment; and (iii) water cannon at the crushing site covered only a portion of the site and was unable to cover all three crushing machines. The difference on area exposures at two demolition sites could be related to the duration of activities within a day and between different days. For example, demolition the multi-story building at site A lasted during the entire shift while demolition of the two-story buildings at site B was completed within 2–3 h and the rest of daily activities involved material sorting. Area sampling results at demolition sites are comparable with the results of a recent study by Stacey *et al*. (Stacey *et al*., 2018). This study reported upwind and downwind levels of RCS at three demolition sites in UK (n = 22) that ranged from LOD-11.5 µg/m^3 compared to the range of LOD-12 µg/m^3 we report here (Table 3). Overall, our results provide evidence of low RCS exposures within the perimeter of demolition sites, suggesting that bystanders may not need respirators when performing different tasks within the grounds of demolition sites.

Due to the modest sample size, we had limited statistical power to detect statistically significant differences in exposures and our results cannot provide any conclusive evidence on the efficacy of water cannons for reducing RD exposures. Data from demolition site B indicate that dust exposures ‘with’ water cannon were lower compared to exposures measured ‘without’ any controls, however, these results were not statistically significant. On the contrary, dust exposures at site A were significantly higher when the water cannon was used. This conflicting evidence could be related to high exposures on the first day of demolition when the water cannon was used compared to other sampling days at site A. Our work observations show that at the beginning of demolition jobs exposures are elevated since the work involves mostly wall destruction, then most of the work involves material sorting which results in less visible dust. Furthermore, data from the crushing site did not provide any supporting evidence on the efficacy of water cannon for reducing dust concentrations. The variability of activities performed from one day to another, from one site to another can negatively impact the analysis of the efficacy of controls in field investigations. The use of dust suppression methods in sites A and C was driven mostly by local environmental regulations/guidelines to prevent exposures of surrounding communities. Future field investigations are needed to evaluate the efficacy of water cannons for reducing workers’ exposure at demolition and crushing sites.

Conclusions

Controlling or reducing crystalline silica exposures to levels under the OSHA PEL of 50 µg/m^3 remains challenging. Even with the use of water suppression, respiratory protection may be required for chipping at substructure bridge repairs and some crushing tasks. Application of effective engineering controls is essential for reducing exposures among chipping workers. The use of dust suppression methods at demolition sites can be effective in reducing TWA daily exposures, nevertheless workers and bystanders are exposed to high short-term peak exposures for which occupational standards do not exist.

Supplementary Data

Supplementary data are available at *Annals of Work Exposures and Health* online.

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