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The Evaluation of Worker Exposure to Airborne Silica Dust During Five OSHA Table I Construction Tasks

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Abstract

Fifty-one (51) personal silica air samples were collected over 13 days on 19 construction employees while they performed five different construction tasks found in the Occupational Safety and Health Administration's (OSHA) respirable crystalline silica standard for construction, Table 1, which specifies engineering, work practice, and respiratory protection controls that employers can use in lieu of exposure monitoring to adhere to the standard. The average construction task time was 127 min (range: 18–240 min) with a mean respirable silica concentration of 85 μg m^{-3} (standard deviation [SD] = 176.2) for all 51 measured exposures. At least one OSHA-specified silica dust control measure was used during all 51 samples collected. The mean silica concentrations for the five tasks were: core drilling 11.2 μg m^{-3} (SD = 5.31 μg m^{-3}), cutting with a walk-behind saw 126 μg m^{-3} (SD = 115 μg m^{-3}), dowel drilling 99.9 μg m^{-3} (SD = 58.7 μg m^{-3}), grinding 172 μg m^{-3} (SD = 145 μg m^{-3}), and jackhammering 23.2 μg m^{-3} (SD = 5.19 μg m^{-3}). Twenty four of 51 (47.1%) workers were exposed above the OSHA Action Level (AL) of 25 μg m^{-3} and 15 of 51 (29.4%) were exposed above the OSHA Permissible Exposure Limit (PEL) of 50 μg m^{-3} when exposures were extrapolated to an 8-h shift. When silica exposures were extrapolated to 4 h, 15 of 51 (29.4%) of workers sampled were exposed over the OSHA AL and 8 of 51 (15.7%) were exposed over the OSHA PEL. A total of 15 area airborne respirable crystalline silica samples were collected on days where the personal task-based silica samples were taken, with an average sampling time of 187 min. Of the 15 area respirable crystalline silica samples, only four were greater than the laboratory reporting limit of 5 μg m^{-3}. The four area silica samples with reportable concentrations revealed background silica concentrations of 23 μg m^{-3}, 5 μg m^{-3}, 40 μg m^{-3}, and 100 μg m^{-3}. Odds ratios were used to analyze the apparent association between dichotomous background construction site exposures to respirable crystalline silica (detectable or not detectable), and personal exposure category (over or not over the OSHA AL and PEL) when exposure times were extrapolated to 8 h. The associations were strongly positive and significant between detectable background exposures and personal overexposures for workers conducting the five Table 1 tasks with engineering controls in place. The results of this study suggest that exposure to hazardous levels of respirable crystalline silica may be present even when OSHA-specified engineering controls are implemented. The current study findings also suggest that background construction site silica concentrations may potentially cause task-based overexposures, even when the OSHA Table 1 control methods have been put in place.

Keywords: construction; OSHA silica permissible exposure limit; OSHA Table I; silica controls; silica exposure

What's Important About This Paper?

This study demonstrates that silica exposures during construction tasks may exceed occupational exposure limits when the dust controls required by the United States Occupational Safety and Health Administration are used. Background silica concentrations at construction sites may contribute to overexposures. Though not required when the specified controls are in place, silica exposure monitoring and respiratory protection should be considered.

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Introduction

The Occupational Safety and Health Administration (OSHA) estimates that 2.3 million Americans are exposed to silica dust at work, including 2 million workers in the construction industry, exposed in more than 600 000 workplaces (OSHA, 2016; OSHA, n.d.). Chronic exposure to respirable crystalline silica (RCS) can have severe implications. Initial symptoms include respiratory irritation, coughing, shortness of breath, and other ailments. Ultimately, diseases associated with airborne silica exposure include silicosis, emphysema, chronic bronchitis, chronic obstructive pulmonary disease, silico-tuberculosis, and lung cancer (California Office of Environmental Health Hazard Assessment, 2005). The International Agency for Research on Cancer (IARC) declared crystalline silica a group 1A substance in 1996, meaning that there is sufficient evidence to support a causal relationship between exposure and the development of cancer (Borm *et al.*, 2011).

To prevent adverse health effects from exposure to RCS in the construction industry, OSHA announced the new permissible exposure limit (PEL) for construction in 2016 of 50 μg m^{-3} and an action limit (AL) of 25 μg m^{-3}, averaged over an eight-hour work shift (Occupational Safety and Health Administration, 2018). In an attempt to accommodate the construction industry, OSHA provided the Table 1: *Specified Exposure Control Methods When Working With Materials Containing Crystalline Silica*. The intended purpose of Table 1 is to offer companies a method for achieving OSHA compliance without having to monitor exposures. To accomplish this, Table 1 lists specific controls and work practices that should be implemented while performing specific construction tasks. The controls listed in Table 1 are based on OSHA's extensive review of published and unpublished silica exposure and control data sources in developing the technological feasibility analysis for the final silica rule. OSHA makes the assumption that these controls will reduce exposure below the PEL, protecting worker health and eliminating a necessity for exposure monitoring (Occupational Safety and Health Administration, 2016). The current study begins to evaluate those assumptions so that a determination can be made about the effectiveness of the OSHA Table 1 controls in protecting construction workers from hazardous RCS exposures.

Researchers have evaluated the general effectiveness of dust control methods for respirable dust and found that dust control methods were effective in reducing RCS exposure for concrete surface grinding (Akbar-Khanzadeh *et al.*, 2010), but not effective to reduce exposure below a concentration of 25 μg m^{-3} [the current American Conference of Governmental Industrial Hygienist's (ACGIH 2021) Threshold Limit Value (TLV) is 25 μg m^{-3}]. Echt *et al.* (2016) evaluated dust control systems on dowel drilling machinery under controlled conditions and reported a decrease in respirable dust concentrations up to 93%. Flanagan *et al.* (2003) assessed silica dust exposures for eight common construction activities and found that box fans reduced exposure by 57% for surface grinding and 50% for floor sanding; and a vacuum/shroud reduced exposures by 71% for surface grinding. However, the researchers found that dust controls for surface grinding would not reduce exposures below the ACGIH TLV (the 2003 ACGIH TLV for respirable dust = 3 mg m^{-3} and quartz = 0.05 mg m^{-3}).

Silica dust may also be generated on construction sites by haul trucks used for transporting materials and heavy equipment. The United States Environmental Protection Agency (US EPA) (1998) reported that haul trucks were responsible for 78–97% of total dust emissions on surface mining sites. Further, Reed and Organiscak (2006) wrote that haul trucks used in the construction industry were a concern for RCS exposure and that these trucks were often used in close proximity to other labourers and the general public.

To the researchers' knowledge, there are no published studies that have investigated the potential contribution of airborne, background construction site silica to the overall exposure profile on a construction site or the contribution of background silica to the personal exposures of those employees performing silica-generating tasks. However, researchers have reported the ambient silica levels in residential communities and near select job sites, but did not include the background silica concentrations on the actual job sites (EPA, 1996; Bhagia, 2012). Hence, construction workers may not only be exposed to silica generated from their work tasks, but may also be exposed to background construction site silica generated from other activities.

The current study was performed at a construction site for a large municipal utility. Prior to construction, the wastewater treatment facility existed as a lagoon treatment system with some improvements over time. The facility underwent construction to develop additional oxidation ditches, clarifiers, an expanded ultraviolet disinfection system, a new biosolids treatment system, and the build of Administration Building 1 (one level) and Administration Building 2 (three levels). While this construction project was underway, the current function of the wastewater treatment facility could not be hindered. The site was very active, as it consisted of wastewater treatment workers maintaining the functions of the facility, and hundreds of construction workers onsite every day. As construction workers performed their usual tasks, environmental data (e.g. wind

Table 1. Dust controls implemented by task.

Task	Dust control methods observed	Dust control methods mandated by OSHA	Number of employees implementing the control
Core Drilling	Wet methods and HEPA filtration wet/dry vacuum in combination Integrated water system	Use tool equipped with integrated water delivery system that supplies water to cutting surface Operate and maintain tool in accordance with manufacturer's instructions to minimize dust emissions	10/11 1/11
Cutting with a Walk-Behind Saw	Integrated water system	Use machine equipped with integrated water delivery system that continuously feeds water to the cutting surface Operate and maintain tool in accordance with manufacturer's instructions to minimize dust emissions OR Use machine equipped with dust collection system recommended by the manufacture Operate and maintain tool in accordance with manufacturer's instructions to minimize dust emissions Dust collector must provide the air flow recommended by the manufacturer, or greater, and have a filter with 99% or greater efficiency and a filter-cleaning mechanism When used indoors or in an enclosed area, use a HEPA-filtered vacuum to remove loose dust in between passes	10/10
Dowel Drilling	Shroud and HEPA filtration vacuum dust collection system	For tasks performed outdoors only: Use shroud around drill bit with a dust collection system. Dust collector must have a filter with 99% or greater efficiency and a filter-cleaning mechanism	10/10
Grinding	Wet methods and HEPA filtration wet/dry vacuum in combination Shroud and HEPA filtration vacuum dust collection system	Use grinder equipped with commercially available shroud and dust collection system Operate and maintain tool in accordance with manufacturer's instructions to minimize dust emissions Dust collector must provide 25 cubic feet per minute (cfm) or greater of airflow per inch of wheel diameter and have a filter with 99% or greater efficiency and a cyclonic pre-separator or filter-cleaning mechanism	6/10 4/10
Jackhammering	Integrated water system	Use tool with water delivery system that supplies a continuous stream or spray of water at the point of impact: -When used outdoors -When used indoors or in an enclosed area OR Use tool equipped with commercially available shroud and dust collection system Operate and maintain tool in accordance with manufacturer's instructions to minimize dust emissions Dust collector must provide the air flow recommended by the tool manufacturer, or greater, and have a filter with 99% or greater efficiency and a filter-cleaning mechanism: -When used outdoors -When used indoors or in an enclosed area	10/10

speed, humidity, temperature) were collected as well as personal and area air monitoring for airborne silica dust. The aims of this study were to (i) characterize personal exposures to RCS of construction workers performing five OSHA Table 1 tasks, (ii) determine the effectiveness of OSHA-mandated dust controls, and (iii) assess the contribution of background airborne RCS to worker exposures.

Methods

The study was performed in the summer and fall of 2020 at a northern Colorado construction site. Participants in this study included 19 construction workers who were male and 18 years of age or older. Fifty-one (51) personal samples were collected on 13 sampling days, including eight employees that were sampled one time, five employees sampled two times, three employees sampled three times, two employees sampled four times, two employees sampled five times, and one employee sampled six times. In addition, 15 area background silica samples were collected with at least one sample collected per day. Dust controls such as wet methods, shrouds, and HEPA filtration vacuums were implemented throughout the duration of every task monitored. The models and manufacturers of construction equipment and dust controls could not be inspected by the researchers due to COVID-19 distancing and safe work protocols and were not able to verify the specified flow-rates of the dust collection systems. The study was performed in compliance with a human subjects study protocol approved by Colorado State University's Institutional Review Board.

Personal air monitoring

A total of 51 RCS personal breathing zone air samples were collected during five OSHA Table 1 tasks that involved work on dried concrete/mortar and included: grinding, dowel drilling, core drilling, jackhammering, and cutting with a walk-behind saw. A total of ten personal air samples were collected for each of the construction tasks, except for core drilling where eleven samples were collected. While the initial goal was to collect four-hour samples in line with the OSHA Table 1 categorization of task duration as less than or greater than four hours, this was not always possible to achieve due to task length. The sampling periods ranged from 18 minutes to 240 min, with the average sample time of 127 min.

The SKC (Eighty Four, PA) disposable (pre-weighed) respirable parallel particle impactor (PPI) was used to collect all silica samples connected to a Zefon (Ocala, FL) Escort ELF personal sampling pump operated at a flow rate of 2.0 L min^{-1} to conform to the International Organization for Standardization's (ISO) standard 7708 (1995) particle collection efficiency curve with a cut point of 4 µm. The pumps were attached to the workers' waists and the PPI's were secured to the workers' collars within their breathing zones. One field blank was handled per sampling day for quality control. Pre and post-calibration of the sampling pumps were performed immediately before and after each sampling day with a Mesa Labs (Lakewood, CO) DryCal Defender Series primary gas flow calibrator and an SKC (Eighty Four, PA) calibration adapter.

Area air monitoring

A minimum of one area silica sample was collected per sampling day during the same time that the personal silica samples were collected, resulting in a total of 15 area samples. Area samples were positioned in a stationary location away from silica-generating tasks to estimate the silica dust concentration present in the background air. Area sampling and calibration were performed using the same equipment as reported in the personal air monitoring section of this paper. Sampling times ranged from 57 to 240 min, with an average sample time of 187 min.

Sample analysis

All sample analyses were performed by the Wisconsin Occupational Health Laboratory (WOHL), following the National Institute for Occupational Safety and Health (NIOSH) Method 7500 for ECS (all forms), and NIOSH Method 0600 for respirable dust (NIOSH, 1994).

Environmental monitoring

Environmental data were collected every 30 min throughout the sampling period on each sampling day so that exposures could be evaluated against wind speed, relative humidity and temperature. A wind speed of greater than or less than 1 m s^{-1} was selected as an evaluation criterion to compare results to Akbar-Khanzadeh *et al.* (2002). A TSI VelociCheck air velocity meter, Model 8330 (Shoreview, MN), was used to detect windspeed, along with a Fluke, Model 971 (Everett, WA), temperature and humidity meter.

Statistical analysis

Of the 51 personal breathing zone silica samples collected, eight of 51 (15.7%) were below the laboratory's reporting limit of 5 µg. These eight left-censored results were replaced by simple substitution (reporting limit divided by the square root of 2) when computing descriptive statistics and comparing personal task-based exposures to occupational exposure limits. In contrast, 11 of 15 (73.3%) area samples were below the laboratory's reporting limit for RCS. Because of the severe left-censoring in the area samples, no attempt was made to describe typical statistical measures of central tendency and variability of those exposures. Instead, area exposures were dichotomized into either detectable background RCS or non-detectable, and odds ratios were computed to describe the association between background construction site exposure category and personal/task exposure status (either projected to be over or not over the OSHA PEL and AL for RCS over an 8-h shift). The significance of the odds ratios was determined using a χ^2 test of association.

The differences in personal RCS exposures due to environmental variables of wind speed and open-air or semi enclosed location on personal task-based exposures was also evaluated. A two-sample t-test was performed comparing the mean personal RCS concentrations measured in low (≤ 1 m s^{-1}) and high (> 1 m s^{-1}) wind speed, and open (not enclosed) versus partially enclosed work locations. The log-base-10 of each RCS concentration was found prior to the analysis, to normalize the distribution and improve homogeneity of variance. All statistical analyses were performed in SAS JMP Pro 15 and Microsoft Excel (2013).

Results

Personal air monitoring

To compare the work shift silica exposures to the OSHA Table 1 categories of less than or equal to (≤) a 4-h work shift or greater than (>) a 4-h work shift, two estimated time-weighted averages (TWA) were calculated for the silica exposures. For the > 4-h shift exposures, the calculated silica concentration TWAs for the work shifts were assumed to occur at the same concentrations over an 8-h shift. For the ≤ 4-h shift comparison, the work shift TWAs were assumed to occur over a 4-h period and a negligible exposure (i.e. zero) for the remainder of the shift, resulting in an estimated 8-h TWA with four hours of exposure and 4 h of no exposure. Assuming 8-h exposures at the task TWAs resulted in 24 of 51 (47.1%) employee exposures that had the potential to be at or above the OSHA AL of 25 μg m^{-3}, and 15 of 51 (29.4%) employee exposures that had the potential to be at or above the OSHA PEL of 50 μg m^{-3}. Assuming 4-h shift exposures (and negligible exposure for the remaining 4 h) resulted in 15 of 51 (29.4%) exposures at or above the AL, and 8 of 51 (15.7%) exposures at or above the PEL. The dust control methods that were observed for each task are presented in Table 1.

The OSHA Table 1 uses two categories for work: less than 4 h and greater than 4 h. The 8-h and 4-h "extrapolated" silica exposures are presented in Table 2. Based on the descriptive statistics for the 8-h estimated silica exposures, the mean RCS concentrations ranged from 11.2 μg m^{-3} for core drilling to 172 μg m^{-3} for grinding. The percent of samples that were above the AL ranged from 9.1% for core drilling to 90% for grinding, and the percent of samples above the PEL ranged from 0% for core drilling and jackhammering to 80% for grinding.

Based on the descriptive statistics for each of the five tasks for the 4-h estimated silica exposures, the mean RCS concentrations ranged from 5.73 μg m^{-3} for core drilling to 86 μg m^{-3} for grinding. The percent of samples that were above the AL ranged from 0% for core drilling and jackhammering to 70% for grinding, and the percent of samples above the PEL ranged from 0% for core drilling and jackhammering to 40% for dowel drilling.

Environmental data

The mean wind velocity ranged from 0.52 m s^{-1} for core drilling to 1.45 m s^{-1} for jackhammering, and the mean relative humidity ranged from 23.52% for grinding to 35.50% for jackhammering. Further, the mean temperature ranged from 14.7°C for dowel drilling to 22.7°C for grinding (Table 3).

Wind velocity was categorized into two groups: wind speeds less than or equal to 1 m s^{-1} (74.5%), and wind speeds greater than 1 m s^{-1} (25.5%). A two-sample *t*-test was performed on the log-transformed silica concentrations to assess whether the means of silica concentrations among the two wind velocity categories were significantly different. The test was statistically significant ($P < 0.01$) and showed that the mean silica dust concentration (mean [SD] 1.54 μg m^{-3} [0.67]) at wind speeds less than or equal to 1 m s^{-1} was greater than the mean silica dust concentration (mean [SD] 1.01 μg m^{-3} [0.41]) at wind speeds greater than 1 m s^{-1} (Table 5). The researchers observed that the four area silica air samples that were above the laboratory reporting limit all occurred at wind speeds less than or equal to 1 m s^{-1}. Observationally, this suggests a similar outcome where the personal silica sample concentrations were greater at wind speeds less than or equal to 1 m s^{-1}. In addition, a two-sample *t*-test was performed on log-transformed silica concentrations to determine if the means were significantly different between two sampling locations (i.e. outside, and partially enclosed). The test revealed a significant difference ($P < 0.01$) between the log-mean of silica concentrations (mean [SD] 1.10 μg m^{-3} [0.44]) outside and the log-mean of silica concentrations (1.62 μg m^{-3} [0.70]) in partially enclosed environments. Outside locations had lower silica concentrations than those in areas that were partially enclosed from open-air (Table 4).

Area air monitoring

Odds ratios using the dichotomous categorization of background construction site RCS exposure and personal exposure status is provided in Table 5 and are illustrated in Fig. 1. The associations between background RCS detection and overexposure were strong and significant ($P < 0.001$) whether comparing extrapolated 8-h personal exposures to the OSHA AL or the OSHA PEL.

Table 2. Descriptive statistics of silica concentrations by task, extrapolated to a full 8-h shift and a 4-h shift.

	Core drilling	Cutting	Dowel drilling	Grinding	Jackhammering
Number of samples (*n*)	11	10	10	10	10
Range (µg m^{-3}) (8 h)	3–37	3.54–70	3.54–380	5–950	11–48
(4 h)	2–19	2–335	2–190	2–475	6–24
Mean (µg m^{-3}) (8 h)	11.2	126	99.9	172	23.2
(4 h)	5.73	63	50	86	11.6
Confidence interval for the mean (µg m^{-3}) (8 h)	(4.16–18.27)	(0–290.60)	(15.89–183.96)	(0–379.20)	(15.51–30.75)
(4 h)	(2.08–9.13)	(0–145.30)	(7.94–91.98)	(0–189.60)	(7.75–15.38)
Median (µg m^{-3}) (8 hr)	7	7	42.5	70	20.5
(4 hr)	4	3	21.5	35	10.5
Standard Deviation (µg m^{-3}) (8 h)	10.6	230	118	290	10.6
(4 h)	5.31	115	58.7	145	5.19
Geometric mean (µg m^{-3}) (8 h)	8.04	20.1	48.2	70.6	21.4
(4 h)	4.24	10.2	24.4	34.7	10.8
Geometric standard deviation (µg m^{-3}) (8 h)	2.31	8.02	4.09	4.01	1.51
(4 h)	2.17	7.82	4.01	4.20	1.48
Percent above AL (25 µg m^{-3}) (8 h)	9.1%	40.0%	70.0%	90.0%	30.0%
(4 h)	0.0%	40.0%	40.0%	70.0%	0.0%
Percent above PEL (50 µg m^{-3}) (8 h)	0.0%	40.0%	40.0%	80.0%	0.0%
(4 h)	0.0%	20.0%	40.0%	20.0%	0.0%

*The analytical laboratory was able to provide concentration values below the NIOSH estimated limit of detection/laboratory reporting limit of 5 µg for 19 of 51 total samples.

Table 3. Mean wind velocity, relative humidity, and temperature collected during construction tasks.

	Core drilling	Cutting	Dowel drilling	Grinding	Jackhammering
Mean wind velocity (m s^{-1})	0.52 m s^{-1}	1.07 m s^{-1}	0.59 m s^{-1}	0.54 m s^{-1}	1.45 m s^{-1}
Mean relative humidity (%)	34.20%	33.30%	31.35%	23.52%	35.50%
Mean temperature (°C)	20.7°C	17.7°C	14.7°C	22.7°C	15.6°C

Figure 2 demonstrates log-transformed RCS exposures for all tasks sampled when compared to log-transformed background silica concentrations, illustrating elevated RCS concentrations above the PEL occurring on days where background silica dust was detected. All left-censored data were adjusted by substituting a value of '1' for the non-detect sample value prior to converting them into the log scale. This substitution was performed only for the purposes of Fig. 2 so that the left-censored background silica concentrations could be viewed as 'zeros' when log-transformed.

Table 4. Log-transformed respirable crystalline silica personal exposures by wind velocity category and location.

	Wind speed		Location	
	Log10 silica concentration (wind speed ≤ 1 m s^{-1})	Log10 silica concentration (wind speed > 1 m s^{-1})	Log10 silica concentration (outside)	Log10 silica concentration (partially enclosed)
n	38	13	21	30
Mean ± SD	1.54 ± 0.67	1.01 ± 0.41	1.10 ± 0.44	1.62 ± 0.70
Range	0.54–2.98	0.55–1.68	0.55–1.89	0.54–2.83
Median	1.56	0.99	1.19	1.60
GM ± GSD*	34.67 ± 4.68	10.23 ± 2.57	12.59 ± 2.75	41.69 ± 5.01

*Inverse log transformation was computed to obtain the GM and GSD (e.g. $10^{1.54}$ = 34.67), and the resulting units are in μg m^{-3}.

Table 5. 2 × 2 Frequency tables for the dichotomous categorization of background construction site RCS concentrations and extrapolated worker RCS exposure status under OSHA construction industry regulations.

Background RCS concentration	Task over AL	Task not over AL	Odds ratio (95% CI)	χ^2	*P*-value
Frequency table for background and personal exposure categories using the OSHA AL					
Detectable	18	4	17.25 (4.22, 70.48)	18.76	<0.001
Non-detectable	6	23			
Background RCS concentration	Task over PEL	Task not over PEL	Odds ratio (95% CI)	χ^2	*P*-value
Frequency table for background and personal exposure categories using the OSHA PEL					
Detectable	14	8	49.00 (5.56, 431.58)	21.83	<0.001
Non-detectable	1	28			

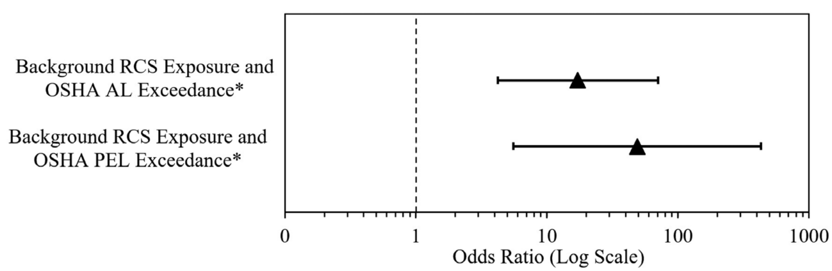

Figure 1. Odds ratios and 95% confidence intervals of the background construction site RCS concentration (detectable or not detectable) for the day and whether or not measured worker exposure while performing OSHA Table 1 tasks would meet or exceed the OSHA action level of 25 μg m^{-3} or the OSHA PEL of 50 μg m^{-3} when extrapolated to an eight-hour exposure time (*n* = 51 measured tasks). The reference line indicates no association with an odds ratio of 1. *The association was significant at the alpha = 0.05 level.

Discussion

Personal air monitoring

As presented in Table 2, the worst-case scenario (i.e. 8-h extrapolated exposure) is important to highlight because construction tasks may take 8 h to complete during a build or project. For example, the employees in the current study expressed that there are projects where concrete smoothing requires workers to use grinders for full 8-h shifts for weeks to months at a time whereas the grinding tasks observed in the current study averaged 217 min. For the 8-h extrapolated data (Table 2), 15 of 51 (29.4%) of the silica samples exceeded the OSHA PEL of 50 μg m^{-3}. Further, the results suggest that dust controls were inadequate for cutting with a walk-behind saw (126 μg m^{-3}), dowel drilling

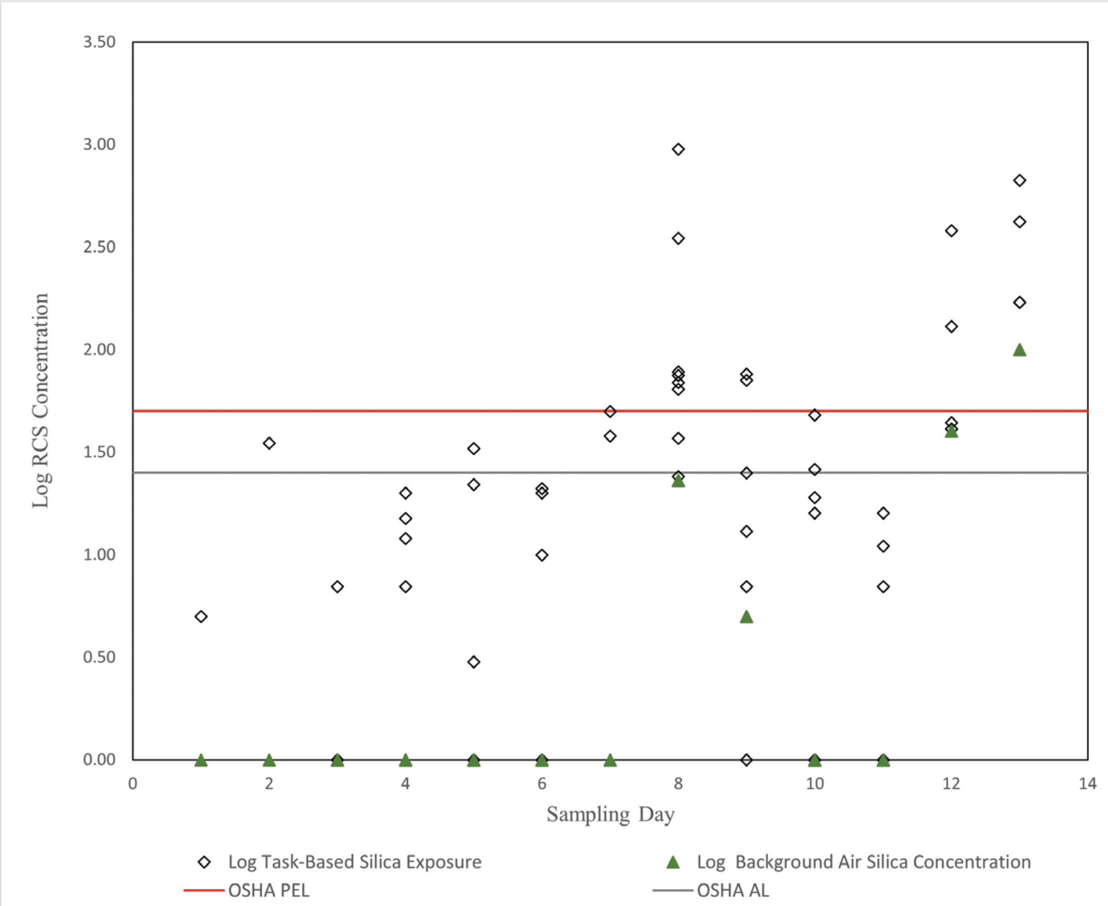

Figure 2. Log background air silica concentrations compared to log task-based silica concentrations.

(99.9 µg m^{-3}), and grinding (172 µg m^{-3}) when compared to the OSHA PEL of 50 µg m^{-3}. Core drilling (11.2 µg m^{-3}) and jackhammering (23.3 µg m^{-3}) were below the OSHA AL of 25 µg m^{-3}, which suggests that dust control measures were effective for these tasks.

When considering the extrapolated 4-h silica exposures as presented in Table 2 (assuming an additional 4 h of zero silica exposure), 8 of 51 (15.7%) construction workers were predicted to be overexposed to the OSHA PEL while conducting OSHA Table 1 tasks and using dust control methods. The results from Table 2 suggest that dust controls were inadequate for cutting with a walk-behind saw (63 µg m^{-3}), dowel drilling (50 µg m^{-3}), and grinding (86 µg m^{-3}) when compared to the OSHA PEL of 50 µg m^{-3}. Core drilling (5.73 µg m^{-3}) and jackhammering (11.6 µg m^{-3}) were below the OSHA AL of 25 µg m^{-3}, which suggests that dust control measures were effective for these tasks.

During sample collection for walk-behind saws, all of the work was performed outside while using dust control methods. Based on the OSHA Table 1 criteria, walk-behind saw cutting with the prescribed controls in place do not require any respiratory protection even when conducted for a full shift. However, 40% of the samples from the cutting tasks performed with a walk-behind saw were above the PEL when extrapolated to an 8-h shift. For core drilling, the OSHA Table 1 requires no respiratory protection as long as wet methods are used, including eight-hour shifts. Alternatively, the data for core drilling silica samples from the current study revealed no worker silica exposures above the PEL, therefore, it was assumed that the dust control methods worked appropriately for this task without the need for respiratory protection. The OSHA Table 1 guidelines for dowel drilling specify that the task is to be performed outdoors only and in accordance with a dust collection system. This task still requires respiratory protection, such as a filtering facepiece (APF 10) (OSHA, 2018), even if dust control methods are used. This requirement seems appropriate since 40% of the workers sampled for this task had the potential to be exposed above the PEL for tasks conducted over an 8-h shift. All grinding activities that were sampled in the current study were performed outside and dust control methods were used. The OSHA Table 1 requires no respiratory protection for concrete grinding when these two conditions are met (i.e. performed outdoors with dust control methods). Of the five tasks sampled, grinding is perhaps the greatest concern with the OSHA Table 1 controls based on the results of this study. Eight of 10 (80%) employees sampled had the potential to be exposed above the PEL for grinding performed for an 8-h shift. In reference to jackhammering, the OSHA Table 1 specifies that respiratory protection, such as a filtering facepiece with an assigned protection factor (APF) of 10 must be used when jackhammering outside if the task exceeds 4 h, even while using wet methods (OSHA, 2018). Since zero of 10 (0.0%) employees monitored had the potential to be overexposed while jackhammering for a full 8-h shift, it appears that the dust control methods for jackhammering in OSHA Table 1 were effective at protecting workers.

In regard to concrete grinding, Akbar-Khanzadeh *et al.* (2010) concluded that, 'No combination of control methods reduced an 8-h exposure level to below the recommended criterion of 0.025 mg m^{-3} for crystalline silica, requiring further refinement in engineering controls, administrative controls, or the use of respirators'. Similarly, the researchers of the current study found that the dust controls did not always reduce exposures below the occupational exposure limits of the five tasks observed. Flanagan *et al.* (2003) reported that 43% of silica exposures observed in their study exceeded the protection factor for filtering facepieces (APF 5). The current study observed that 2 of 51 (3.9%) of silica exposures extrapolated to an 8-h shift exceeded the protective capabilities of the filtering facepiece (APF 10) required by the OSHA Table 1 for those tasks (OSHA, 2018).

In considering the findings of Akbar-Khanzadeh *et al.* (2010) and Flanagan *et al.* (2003), the authors propose job rotation. The researchers were informed through employee interviews that tasks were assigned to crews and may remain in place for specific phases of the build. For example, a crew of employees assigned to grinding would perform that task each day, but the location from day-to-day would change based on the progress of the build. However, the workers reported that they would not grind for a full 8-h shift on days when they were postponed by the stage of the build. In these instances, it was common for the workers to be reassigned for the remainder of that day to other tasks. The authors observed that the task reassignments were often other Table 1 silica-generating tasks. OSHA Table 1 requires respiratory protection for some tasks that exceed 4 h, even with controls in place. Table 1 also writes that employees performing more than one Table 1 task during a shift for a combined duration of more than four hours must wear the respiratory protection as prescribed in Table 1 for those tasks. Given the nature of construction sites, respiratory protection should be the last defense against respiratory exposure. This is not only true because of the serious questions about the practicality of respirator use for long periods in the sun, but because respirator assigned protection factors may be unreliable when used in a non-controllable environment such as a construction site. Howie (2005) wrote, 'Respiratory protective equipment performance in the workplace is generally much poorer than suggested by standards or manufacturers' literature'. Weighing the study findings against this knowledge stresses the need for effective control measures beyond PPE. As such, the authors propose job rotation to non-silica generating tasks after performing Table 1 tasks. While there may be barriers to job rotation in some cases, prioritizing the hierarchy of controls and job rotation over respiratory protection when feasible is a better solution for worker protection.

Environmental monitoring

The researchers of the current study classified wind speed into less than or equal to 1 m s^{-1} and greater than 1 m s^{-1}, as did Akbar-Khanzadeh *et al.* (2002). Akbar-Khanzadeh *et al.* (2002) found that respirable silica dust concentrations were significantly lower when wind speed was greater than 1 m s^{-1} and concentrations were higher when wind speed was less than or equal to 1 m s^{-1}. The current study results support the findings from Akbar-Khanzadeh *et al.* (2002) and found that the concentration of silica dust was significantly ($P < 0.01$) lower when wind speed was greater than 1 m s^{-1} as compared to silica dust concentration when wind speed was less than or equal to 1 m s^{-1}. Higher wind speeds aid in the dispersion of silica dust clouds, whereas dust clouds may linger near the breathing zone longer at lower wind speeds. The results of the current study provide further evidence that exposures may be impacted based on the wind velocity during the silica-generating operation.

Location

The current study evaluated location in two categories: outside and partially enclosed. Samples taken in free-flowing open-air were categorized as outside. Samples taken in the water sanitation basins or in buildings that lacked walls, windows, or doors were classified as partially enclosed. The results of the two-sample *t*-test showed that silica dust concentrations were significantly ($P < 0.01$) lower for tasks performed outside than for tasks performed in partially enclosed environments. Location should be considered when assessing exposure potential in accordance with the guidelines found in the OSHA Table 1.

Area air monitoring

In addition to other influences, the current study sought to assess the potential exposure factor of background silica dust. Fifteen of 51 employees were overexposed to silica dust when extrapolated to an 8-h shift, and 14 of those 15 exposures occurred on the 4 days where background silica dust was high enough to be detected by the laboratory. Based on the results of the odds ratio calculations (Table 5), the authors concluded that background RCS levels may contribute to workers' personal RCS exposures while performing construction tasks.

Reed and Organiscak (2006) stated that haul trucks accounted for 78–97% of dust emissions on surface mining sites, and they recognized the potential for a similar hazard in the construction industry. The researchers of the current study observed haul trucks and heavy equipment using unpaved roads throughout the construction site on a regular basis, and these activities could have produced background silica levels that contributed to the measured personal exposures taken during observed construction tasks. In addition, the US EPA (1998) reported that watering haul roads can reduce total suspended particulates by 74% for 3–4 h when water spray is applied at 0.46 gal yd^{-2} (2.1 L m^{-2}) and at 95% for one-half of an hour when water is applied at 0.13 gal yd^{-2}. Frequency of water spray and area coverage appear to be key elements of controlling dust emissions that become dispersed in background air on construction sites. While water spray trucks were observed in use over the 13 sampling days, trucks were not observed wetting unpaved roads and dirt surfaces regularly as this was a job that was only performed when a worker could be spared to perform this activity.

Study limitations

One important limitation in this study was the difficulty associated with collecting a minimum of 4-h samples for the five OSHA Table 1 tasks. The sampling time was based on the actual task time and therefore, the exposure extrapolations to 4 and 8-h shifts may be under or overestimated.

Another limitation was the collection of low sample volumes, which resulted in left-censored datasets. Eight of 51 (15.7%) personal breathing zone silica samples and 11 of 15 (73.3%) area silica samples were below the laboratory's reporting limit of 5 µg. Censored data can negatively impact statistical power and result in bias when interpreting the results. In addition, the methods used to adjust for these censored data may lead to bias. The Army Public Health Center (2015) reported that the LOD/√2 method provides adequate estimates for making exposure-based judgements in similar exposure groups. However, since 15.7% of the personal silica exposure data in this study were censored, it is important to acknowledge that the LOD/√2 method, like others, can diminish data representativeness. When non-detects are treated as actual observed values by using a substitution method that inputs a constant variable into the dataset, the statistical results can be misinterpreted (Shoari *et al.*, 2017). While acknowledging the risk of statistical bias, the researchers of the current study believe that the LOD/√2 method was appropriate for the degree of censoring in the personal air samples, but not appropriate for the area samples given the relatively large number of non-detects. The authors considered maximum likelihood estimation (MLE) for the area silica samples since it is often considered the 'gold standard' when accounting for highly censored datasets (Army Public Health Center, 2015). However, the authors concluded that the MLE method was not appropriate considering the small sample size of the area air monitoring data. For future task-based and area sampling conducted in the construction industry, equipment such as the higher flow rate SKC PPI's (i.e. 4 or 8 LPM) would collect a larger sample volume and reduce the number of non-detects.

Based on the results of the current study, relatively large variability was observed among RCS exposures within tasks and within the dataset itself. The reason for this observed variance is speculative but could likely be due to the differences in location and sampling day. Tjoe-Nij *et al.* (2003) found broad exposure ranges and high geometric standard deviations among concrete drillers and grinders, tuck pointers, and demolition workers, indicating relatively large variability in exposure. Further, the researchers wrote that repeated measures revealed relatively large differences (day-to-day variance) between workers. In the current study, variability in exposure was observed among workers conducting the same task with the only observable differences being their location and sampling day. To investigate the impact of location on exposure, the current study classified tasks into two groups (i.e. outside and partially enclosed). A two-sample *t*-test showed that silica concentrations outside were significantly ($P < 0.01$) lower than silica concentrations in partially enclosed environments. The OSHA Table 1 specifies only two classifications: outdoor work and indoor work. The findings from this study suggest that this dichotomy describing the environmental work conditions may not be adequate when applied to actual practice. For example, management for a construction project may believe that an employee grinding in an open-air concrete basin is at low risk of overexposure because they are working in 'open air' outdoors. However, a partial enclosure may affect wind velocity and may result in substantial differences in employee exposure, such as observed in the current study. Locations that prohibit frequent and consistent air flow result in dust particulates remaining suspended in the workers' breathing zones. Future task-based sampling should restrict monitoring during tasks to similar locations and environmental conditions to reduce the significant exposure variability that occurred during this study.

Because the OSHA Table 1 does not require exposure monitoring for those tasks that employ the required dust controls and work practices, managers and employees may assume that they will not be overexposed to silica while employing the mandated dust controls. However, the results of this study suggest that even with the implementation of dust controls and work practices, employees may still be at risk of silica exposure above the OSHA AL and PEL.

Conclusions

This study provides an evaluation of the effectiveness of silica controls and work practices that are mandated in the OSHA Table 1 and presents the potential impact of background silica dust to personal task-based exposures on construction sites. The results indicate that exposure to hazardous levels of RCS can still occur with the OSHA-mandated controls fully implemented and that exposure to RCS may have been exacerbated from background silica concentrations. Future research is recommended to examine the 13 remaining tasks found in OSHA Table 1 and to further analyze the contribution of background silica to the overall exposure profile on construction sites.

Currently, the OSHA Table 1 focus is to reduce silica exposures on construction sites by better controlling task-based silica exposures through the use of dust control methods. However, from the industrial hygienist's perspective, attempts to reduce task-specific and background silica concentrations should be considered through a combination of task-based and site controls by considering the hierarchy of controls including engineering controls (e.g. ventilation and wet methods, including water application on roads), administrative controls (e.g. employee rotation and training), and lastly personal protective equipment. In addition, management and workers should consider voluntary use of respiratory protection for certain tasks, even when controls are implemented and respiratory protection is not required by OSHA. Although air monitoring may not be required of employers complying with OSHA Table 1, the results of this study suggest that air monitoring may still be warranted to identify employees who are at an increased risk of silica exposure.

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This section should be in a separate FUNDING section. NIOSH should be changed to National Institute for Occupational Safety and Health.

Conflict of interest

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Data Availability

The data underlying this article will be shared on reasonable request to the corresponding author.

Supplementary Data

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

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