DISSERTATION

"EXPOSURE TO RESPIRABLE CRYSTALLINE SILICA DURING FIVE OSHA TABLE 1 TASKS AND THE EFFECTIVENESS OF DUST CONTROLS, THE CONTRIBUTION OF BACKGROUND SILICA DUST TO PERSONAL EXPOSURES, AND THE USE OF A PHOTOMETRIC INSTRUMENT TO ASSESS SILICA DUST EXPOSURE IN REAL TIME"

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ABSTRACT

"EXPOSURE TO RESPIRABLE CRYSTALLINE SILICA DURING FIVE OSHA TABLE 1 TASKS AND THE EFFECTIVENESS OF DUST CONTROLS, THE CONTRIBUTION OF BACKGROUND SILICA DUST TO PERSONAL EXPOSURES, AND THE USE OF A PHOTOMETRIC INSTRUMENT TO ASSESS SILICA DUST EXPOSURE IN REAL TIME"

Occupational exposure to respirable crystalline silica (RCS) has become a global public health concern and has been identified as one of the world's most significant causes of occupational disease, with much of the exposures occurring in the construction industry. In 2016, the Occupational Safety and Health Administration (OSHA) enacted a new silica standard for construction with a permissible exposure limit (PEL) of 50 $\mu g/m^3$ and an action level (AL) of 25 $\mu g/m^3$. This new standard also provided the construction industry with the *OSHA Table 1: Specified Exposure Control Methods When Working With Materials Containing Crystalline Silica*, which accommodated employers in the construction industry by offering a guideline to achieving compliance to the standard by using specified dust-control measures and work practices. However, researchers have found that dust controls do not always reduce silica exposure below occupational exposure limits and the current studies confirm this finding.

<u>*Study 1*</u>

Personal silica exposures were measured while construction workers conducted five OSHA Table 1 tasks using dust controls to assess the effectiveness of the dust control measures at reducing silica dust below the PEL. This research was conducted at a northern Colorado construction site during the build of a water sanitation plant (July 2020 – November 2020) and

included personal and area silica air sampling while construction workers performed core drilling, cutting with a walk-behind saw, grinding, dowel drilling, and jackhammering. In addition, environmental conditions (i.e., wind speed, relative humidity, temperature) were recorded every 30 minutes during the personal silica air monitoring so that potential determinants of silica exposure could be evaluated.

Of the construction workers that participated in this study, 24 of 51 (47.1%) had the potential to be exposed over the AL of 25 $\mu g/m^3$ and 15 of 51 (29.4%) had the potential to be exposed over the PEL of 50 $\mu g/m^3$ for an eight-hour time weighted average (TWA) when the silica exposures were extrapolated to eight hours. When the silica exposures were extrapolated to four hours (with an additional four hours of no exposure), then 15 of 51 (29.4%) of workers sampled would have been exposed over the AL and 8 of 51 (15.7%) would have been exposed over the PEL. The mean silica concentration for all tasks was 85 $\mu g/m^3$ (standard deviation [SD] = 176.2) and the mean sample time was 127 minutes. The mean silica concentration for the five tasks included: core drilling 11.2 $\mu g/m^3$ [5.31], cutting with a walk-behind saw 126 $\mu g/m^3$ [115], dowel drilling 99.9 $\mu g/m^3$ [58.7], grinding 172 $\mu g/m^3$ [145], and jackhammering 23.2 $\mu g/m^3$ [5.19]. A multiple regression analysis showed that location ($p < 0.001$), task ($p = 0.001$), and temperature ($p = 0.002$) were significant predictors of silica dust concentrations, but relative humidity was not. A two-sample t-test showed that silica dust concentrations were significantly ($p < 0.01$) higher at wind speeds ≤ 1 m/s compared to wind speeds > 1 m/s. A two-sample t-test also showed that silica dust concentrations were significantly ($p < 0.01$) higher among partially enclosed environments compared to outdoor locations. Based on the results of this study, exposure to hazardous levels of respirable crystalline silica can still occur with the OSHA-mandated controls fully implemented, thus increasing the risk of silica-related illnesses.

Study 2

The goal of this study was to evaluate the contribution of background silica dust to personal silica exposures while employees conducted five OSHA Table 1 tasks and was performed at a northern Colorado construction site. A total of 15 area silica samples were collected over 13 days in tandem with 51 personal task-based silica samples with an average area sampling time of 187 minutes. At least one area sample was collected on each of the 13 sampling days. Of the 15 area samples, only four collected silica masses that were greater than the laboratory's reporting limit of 5,000 ng (5 µg), and included measurable background silica concentrations of 23 $\mu g/m^3$, 5 $\mu g/m^3$, 40 $\mu g/m^3$, and 100 $\mu g/m^3$. Due to data censoring (i.e., non-detects) in the area samples (73.3%), there was not a sufficient number of data points to determine with statistical certainty if silica background concentrations significantly contributed to worker exposure. However, the four measurable background silica samples may have contributed to worker exposure since 14 of 15 of the personal silica samples that exceeded the OSHA PEL occurred on the four days when the background silica levels were measurable. These results suggest a possible correlation between background silica concentrations and the higher personal silica dust exposures.

Study 3

The goal of this study was to evaluate the utility of performing real-time dust monitoring to estimate RCS airborne concentrations during construction tasks. Personal air monitoring using a TSI SidePak AM520 personal aerosol monitor was performed on a northern Colorado construction site during the build of a water sanitation plant during five OSHA Table 1 tasks. Each construction task was sampled once; sample time ranged from 14 minutes to 40 minutes, with a mean sample time of 27 minutes. Prior to task-based air monitoring, the TSI SidePak and an SKC disposable respirable parallel particle impactor (PPI) were co-located on the construction site for 334 minutes to measure the area respirable dust concentration to determine an aerosol-specific correction factor for the TSI SidePak monitoring results. A comparison of respirable dust collected by the SKC PPI to the TSI SidePak AM520 showed that the direct reading instrument was underestimating respirable dust, therefore, the correction factor was applied to the respirable dust sampling results. In addition, bulk material samples were collected during the performance of the five tasks so that the percent silica could be determined for each task-specific material. The adjusted TSI SidePak mean respirable silica dust concentrations ($\mu g/m^3$) (standard deviation [SD]) for the five tasks included: core drilling 12 $\mu g/m^3$ [2.46], grinding 918 $\mu g/m^3$ [1134.08], cutting with a walk-behind saw 36 $\mu g/m^3$ [79.67], jackhammering 27 $\mu g/m^3$ [23.24], and dowel drilling 66 $\mu g/m^3$ [77.65]. While the silica exposure results from this study cannot be directly compared to the OSHA eight-hour TWA silica PEL of 50 $\mu g/m^3$, the data are useful to observe the variability of silica exposures that occur during a task to determine if worker personal behaviors affect exposure and to determine if dust controls are effective. Employing direct-reading instruments to assess exposure also reduces the cost burden on employers by reducing the number of gravimetric samples.

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DEDICATION

For “Mamaw” and “Papaw.” Everything I do is to honor you. We did it!

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LIST OF ACRONYMS

AIHA	American Industrial Hygiene Association
AL	Action Level
APF	Assigned Protection Factor
HEPA	High Efficiency Particulate Air
IARC	International Agency for Research on Cancer
ISO	International Organization for Standardization
LOD	Limit of Detection
MLE	Maximum Likelihood Estimation
MMD	Mass Median Aerodynamic Diameter
NIOSH	National Institute for Occupational Safety and Health
OSHA	Occupational Safety and Health Administration
PEL	Permissible Exposure Limit
PPE	Personal Protective Equipment
PPI	Parallel Particle Impactor
RCS	Respirable Crystalline Silica
SEG	Similar Exposure Group
TLV	Threshold Limit Value
TWA	Time Weighted Average
WOHL	Wisconsin Occupational Health Laboratory

CHAPTER 1

INTRODUCTION

Crystalline silica is one of the most common minerals found in the Earth's crust (OSHA, n.d.). The most common crystalline forms of silica are quartz, cristobalite, and tridymite (United States Department of Health and Human Services, 2016). Of the three, quartz is by far the most prominently encountered in industrial settings. OSHA estimates that of the 2.3 million workers potentially exposed to silica, 2 million (nearly 90%) are employed in the construction industry (OSHA, n.d.; OSHA, 2017a). Common construction materials, such as sand, stone, concrete, and mortar contain an abundance of respirable crystalline silica (RCS) (OSHA, n.d.). However, it is only when this mineral becomes respirable that the dangerous exposure can occur. RCS is a very small particle that is invisible to the naked eye, which allows it to stay airborne for long periods and travel long distances (Texas Department of State Health Services, 2013). Its ability to travel such distances raises concerns for general construction laborers working in proximity to other employees performing silica dust generating tasks. Respirable particulates are typically considered to be about 10 micrometers or less in size, allowing them to deposit deep within the lungs (Brown et al., 2013). Maximum deposition into the gas exchange, or alveolar region occurs at about 2 micrometers (Brown et al., 2013). Workers who are exposed to RCS are at an increased risk of developing silicosis, "an incurable, progressively disabling and sometimes fatal lung disease (National Institute for Occupational Safety and Health, 2015)." Oghiso et al. (1986) studied silica pulmonary deposition in rats and found that initial deposition occurs in alveolar duct bifurcations. Oghiso et al. (1986) also discovered translocation of silica particles into lymphatic tissues after six months of short-term exposures. When RCS exposure occurs in humans, the costs to one's health can be severe. Once deposited in the lung tissue, macrophages are deployed to digest the silica particles provoking a repetitive cycle of inflammation that causes irreparable damage (California Office of Environmental Health Hazard Assessment, 2005). Initial symptoms can include shortness of breath, respiratory irritation, and coughing (National Institute for Occupational Safety and Health, 2015). Ultimately, exposure to RCS can result in many silica-related diagnoses, such as silicosis, emphysema, chronic bronchitis, chronic obstructive pulmonary disease, silicotuberculosis, and lung cancer (California Office of Environmental Health Hazard Assessment, 2005).

A silicosis diagnosis may be placed in one of three different categories: chronic, accelerated, and acute (Greenberg et al., 2007). Chronic silicosis, the most common diagnosis, has a latency period that ranges in the decades after repeated exposure. In some cases, it has taken as long as 45 years for symptoms to develop (Greenberg et al., 2007). Accelerated silicosis has a latency period of five to ten years, and typically occurs when exposures are profound over a shorter term than what is seen in chronic cases (Greenberg et al., 2007). Lastly, acute silicosis may develop when exposures occur in substantial amounts over short periods of time. This is typically found in occupations with known silica induced illnesses (Greenberg et al., 2007).

Occupational RCS exposure has been studied across many industries, but specific task-based RCS exposure data are still needed in the construction industry. In the 2016 final rule on respirable silica dust, OSHA announced the new permissible exposure limit (PEL) of 50 $\mu g/m^3$ and an action limit (AL) of 25 $\mu g/m^3$, averaged over an eight-hour 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 the table was to offer companies a method for achieving OSHA compliance without having to monitor exposures (Occupational Safety and Health Administration, 2016b). Using the assumption that dust controls will reduce RCS exposure below the PEL, the OSHA Table 1 lists specific controls and work practices that should be implemented while performing construction tasks. A comprehensive review of the relevant literature indicated that researchers have identified tasks in which the dust controls could not reduce RCS concentrations below occupational exposure limits (Akbar-Khanzadeh et al., 2010; Flanagan et al., 2003). Further, Echt et al. (2016) warned that while the dust control measures that were identified in their controlled, laboratory study resulted in RCS reductions during dowel drilling, dust controls should be evaluated under actual work conditions to determine effectiveness. Without air monitoring, it is difficult to ascertain when a dust control is no longer operating effectively or has been damaged. The OSHA Table 1 specifies high efficiency particulate air (HEPA) filter vacuums as an acceptable dust control measure for many of the tasks. Further, Shafie (2020) found that 97.1% of the HEPA vacuums evaluated in their silica study operated at less than 75% of their designed airflows and that vacuums of unknown age resulted in the highest predicted RCS exposures.

Silica exposures on construction sites are extremely variable and can be the result of a mixture of many sources. Researchers have evaluated ambient silica dust in proximity to certain industries, such as the pencil slate, agate, and frac sand mining industries, out of concern that ambient air could potentially overexpose nearby residents. However, no researchers have evaluated the concentrations of background silica dust on construction sites and the contribution that background silica may have to personal exposures while performing construction tasks. While silica dust exposure will eventually result in the same illnesses regardless of the source, understanding where silica exposures originate provides valuable information that can be used to control the silica at the sources.

To confirm compliance to the OSHA silica standard, OSHA requires an integrated sampling approach that uses gravimetric analysis. However, silica dust monitoring on construction sites can be time and cost inhibitive. Once gravimetric sampling is conducted to assess dust control effectiveness for a specific task, there is a significant lag time between collecting the samples and receiving the results from the laboratory. This process must be repeated until the exposure is appropriately controlled, which can take weeks to months and potentially leaves construction workers overexposed for extended periods of time. To help remedy the lag time and costs of integrated sampling, direct reading photometric instruments can be used to evaluate silica exposures and to determine dust control effectiveness during dust-generating operations. However, real-time sampling instrument results must be "corrected" by comparing the sampling results to an integrated sample to improve accuracy. Dacunto et al. (2013) and Shafie (2020) suggested that many exposure variables (i.e., mass median aerodynamic diameter, particle size, and silica content in material) can impact the correction factors used to adjust a real-time sampling instrument's results. Supplementing standard gravimetric data with photometric air monitoring as an accurate assessment tool can significantly reduce analysis lag time and costs (TSI, 2018). The goals of the research are summarized below with three specific aims:

Specific Aim 1: Determine RCS exposures among workers performing five OSHA Table 1 tasks (i.e., core drilling, cutting with a walk-behind saw, dowel drilling, grinding, jackhammering) and assess the effectiveness of Table 1 specified dust controls in reducing exposures below the OSHA PEL. The study approach included the use a gravimetric sampler with a personal air sampling pump to perform task-based silica personal air monitoring. The measured silica concentrations were analyzed to determine the percentage of employees that were exposed to RCS concentrations greater than the OSHA AL of 25 μg/m^3 and the PEL of 50 μg/m^3 when the silica exposures were extrapolated to eight-hour shifts. Dust control effectiveness was assessed on the basis of whether or not an employee was overexposed to RCS during task performance.

Specific Aim 2: Determine the contribution of background silica dust to personal exposure during the performance of the five OSHA Table 1 tasks. The study approach included the collection of area silica air samples on the construction site during the same time period that the OSHA Table 1 tasks were performed. The area sampling results were compared to the personal RCS exposures to evaluate the relationship between background silica concentrations and the task-based silica concentrations.

Specific Aim 3: Determine the utility of measuring respirable dust concentrations using a real-time monitoring instrument during the performance of five OSHA Table 1 tasks. The study approach included the use of a TSI SidePak AM520 personal aerosol monitor to measure the respirable dust generated during the five tasks. The real-time sampling results were adjusted based on the sampling results of an integrated, gravimetric sampler and the percent silica present in bulk material samples collected during each task. This approach allowed the examination of real-time silica exposure data to determine the effectiveness of dust controls and the potential for employee work practices to affect silica exposure.

CHAPTER 2

LITERATURE REVIEW

Overview of the Respiratory System (Cleveland Clinic, 2020)

The human respiratory system includes the airways, lungs, and blood vessels, which move oxygen throughout the body and exhaust carbon dioxide. The airways include the mouth and nose, sinuses, pharynx, trachea, and bronchial tubes, which work to deliver air to the lungs. The lungs are two organs that remove oxygen from air and pass it to the bloodstream. The lungs consist of many components, such as alveoli, bronchioles, capillaries, lung lobes, and pleura. Bronchioles are the branches that lead to the alveoli where the exchange of oxygen and carbon dioxide occur. Oxygen and carbon dioxide are moved through the capillaries (blood vessels) in the alveoli. There are sections within the lungs which are called lung lobes and thin sacs (pleura) surround each lung lobe to separate the lungs from the chest wall.

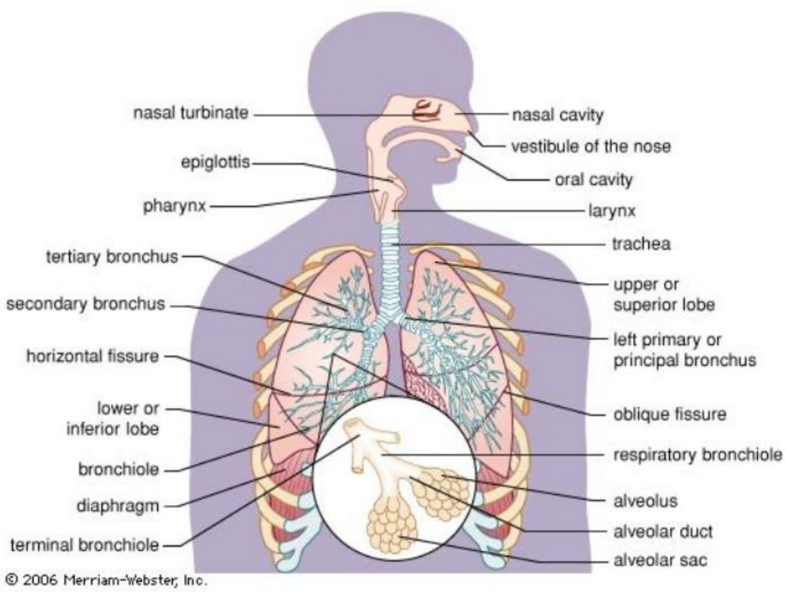

Figure 2.1: Diagram of the human respiratory system (Encyclopaedia Britannica, 2021)

Respirable Crystalline Silica

Crystalline silica is one of the most common minerals found in the Earth's crust and there are many forms, which may be found in sand, stone, and soil (OSHA, n.d.; National Cancer Institute, 2019). The most common crystalline forms of silica are quartz, cristobalite, and tridymite (United States Department of Health and Human Services, 2016). Of the three, quartz is by far the most prominently encountered in industrial settings and is found in almost every type of rock. Cristobalite is rare in nature but found in small amounts in some volcanic rocks and meteorites. However, when quartz is heated at high temperatures cristobalite may form, resulting in the ability for occupational exposures during certain operations that heat quartz (Safe Silica, n.d.). Tridymite is another scarce form of crystalline silica because it is only found in volcanic rocks and meteorites, meaning occupational exposure is unlikely to occur (Safe Silica, n.d.). Non-crystalline (amorphous) silica is found in products, such as glass, silicon carbide, and silicone (Washington Environmental and Occupational Health Sciences, n.d.). However, products containing amorphous silica are much less hazardous for the lungs, placing most of the focus on crystalline forms, particularly quartz. The National Cancer Institute (2019) stated that the primary route of exposure is inhalation for airborne silica.

Respirable particulates are typically considered to be about 10 micrometers or less in size, allowing them to deposit deep within the lungs with maximum deposition into the gas exchange, or alveolar region occurring at about 2 micrometers (Brown et al., 2013). The National Institute for Occupational Safety and Health (2015) described workers exposed to RCS as having an increased risk of developing silicosis, "an incurable, progressively disabling and sometimes fatal lung disease." Oghiso et al. (1986) found in rats that initial silica deposition occurred in alveolar duct bifurcations and that translocation of silica particles into lymphatic tissues occurred after six months of short-term exposures. In humans, once silica is deposited in the lung tissue it is the beginning of a repetitive cycle of inflammation that causes irreparable damage (California Office of Environmental Health Hazard Assessment, 2005). Initial symptoms can include shortness of breath, respiratory irritation, and coughing (National Institute for Occupational Safety and Health, 2015). Exposure to RCS can result in many silica-related diagnoses, such as silicosis, emphysema, chronic bronchitis, chronic obstructive pulmonary disease, silicotuberculosis, and lung cancer (California Office of Environmental Health Hazard Assessment, 2005).

Medical Examination

An employer must offer a medical exam within the first 30 days of employment, and then every three years after, for employees who are required to wear respirators for at least 30 or more days a year (Occupational Safety and Health Administration, 2018). This frequency can be increased by physician recommendation. The initial medical exam must include a thorough medical and work history, a physical examination, a chest X-ray, a spirometry test for pulmonary function, a latent tuberculosis infection test, and a fit test for respiratory protection (Occupational Safety and Health Administration, 2018). Silica-related illnesses typically occur incrementally and may go unnoticed among employees who do not receive regular medical surveillance examinations until serious illness has already been developed. When diagnosing crystalline silica exposure, the diagnosis is typically placed in one of three categories: chronic, accelerated, or acute (Greenberg et al., 2007). The most common diagnosis, chronic silicosis, has a latency period that ranges in the decades after repeated exposure. Greenberg et al. (2007) noted that in some cases it has taken as long as 45 years for symptoms to develop. Accelerated silicosis, however, has a latency period of five to ten years, and typically occurs when exposures are profound over a shorter term than what is observed in chronic cases. Lastly, a diagnosis of acute silicosis may be determined when exposures occur in substantial amounts over short periods of time and is often found in occupations with known silica-induced illnesses (Greenberg et al., 2007). Typically, the diagnosing physician will order chest X-rays and lung function tests, as well as a sputum test, a bronchoscopy, or a surgical lung biopsy (American Lung Association, 2020). Radiopaedia (2020) provided X-ray and CT scan imagery from patients suffering from silicosis (Figures 2.1 through 2.3). These images illustrate silicosis verified by X-ray or CT scan after chronic exposure, referred to as “classic silicosis.” The two chronic silicosis categories described by Radiopaedia (2020) were simple silicosis (shows small and round opacities) and complicated silicosis (shows large conglomerate opacities).

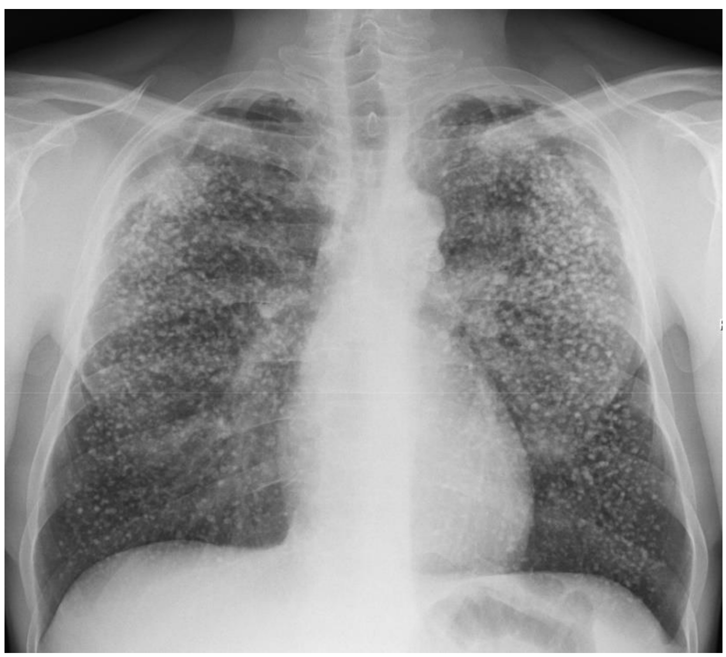

Figure 2.2: X-ray showing silicosis with progressive massive fibrosis (Radiopaedia, 2020)

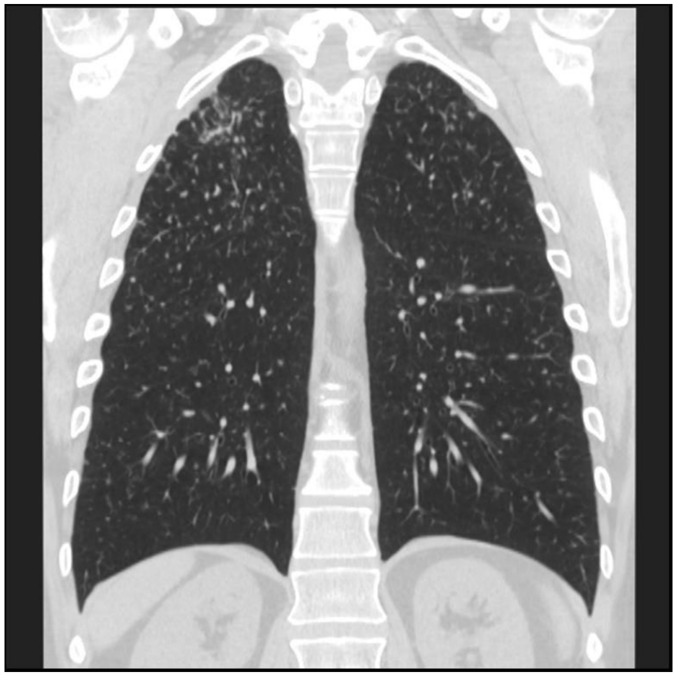

Figure 2.3: CT scan showing classic simple silicosis (Radiopaedia, 2020)

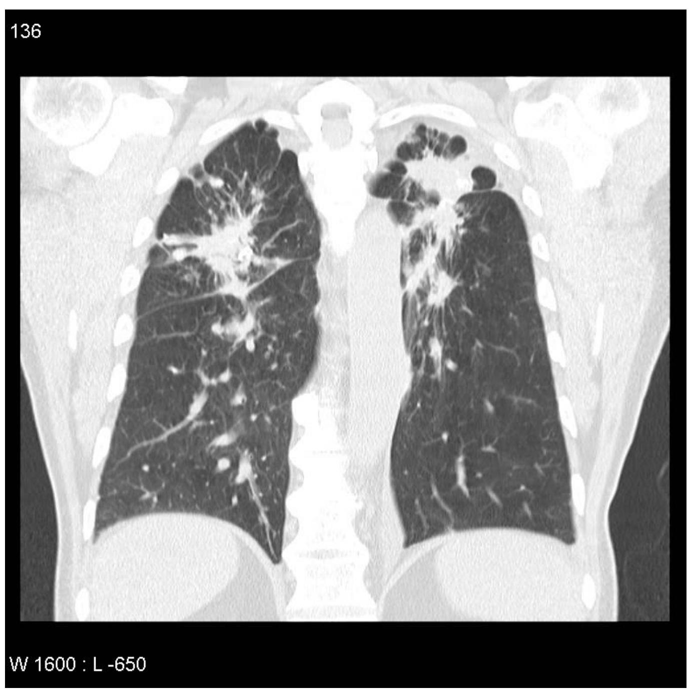

Figure 2.4: CT scan showing classic complicated silicosis with progressive massive fibrosis (Radiopaedia, 2020)

Silica Exposure Regulations and Recommendations

The Occupational Safety and Health Administration (OSHA) is a regulatory agency which ensures safe working conditions from many hazards, including exposure to RCS. In recognition of the hazards of airborne silica exposure, OSHA enacted a new silica action level (AL) of 25 $\mu g/m^3$ and a permissible exposure limit (PEL) of 50 $\mu g/m^3$ as an eight-hour time weighted average (TWA) in 2016. The standard (29 Code of Federal Regulations, 1926.1153) includes the *OSHA Table 1: Specified Exposure Control Methods When Working With Materials Containing Crystalline Silica* which provides task-specific guidance on personal protective equipment (PPE), dust controls and work practices (Occupational Safety and Health Administration, 2016a). The National Institute for Occupational Safety and Health (NIOSH) and the American Conference of Governmental Industrial Hygienists (ACGIH) have also established silica exposure guidelines. The NIOSH recommended exposure limit (REL) for silica is 50 $\mu g/m^3$ for 10 hours of exposure, and the ACGIH threshold limit value (TLV) for silica is 25 $\mu g/m^3$ for an eight-hour TWA. Occupational exposure limits (OELs) are based on silica concentration and exposure duration, however, this assumes that other exposures do not occur outside of that singular occupational setting. The OSHA silica construction standard provides three methods to achieve compliance, the first being dust control. The OSHA (2017a) states that if an employer follows Table 1 and implements the specified dust controls and work practices for all of the required tasks, then they are not subject to the PEL and no further air monitoring is required. If an employer chooses not to implement the Table 1 engineering controls, work practices and respiratory protection then there are two alternative exposure control methods that can be followed, each requiring that employers measure worker exposure to the AL of 25 $\mu g/m^3$. Exposures above the AL will require frequent exposure monitoring and the implementation of dust controls or respiratory protection. In other cases where RCS exposure was reduced after an initial exposure above the AL, these instances may require repeated and continuous air monitoring as well (Occupational Safety and Health Administration, 2017b). Figure 2.5 illustrates the roadmap to achieve OSHA compliance based on the method the employer implements.

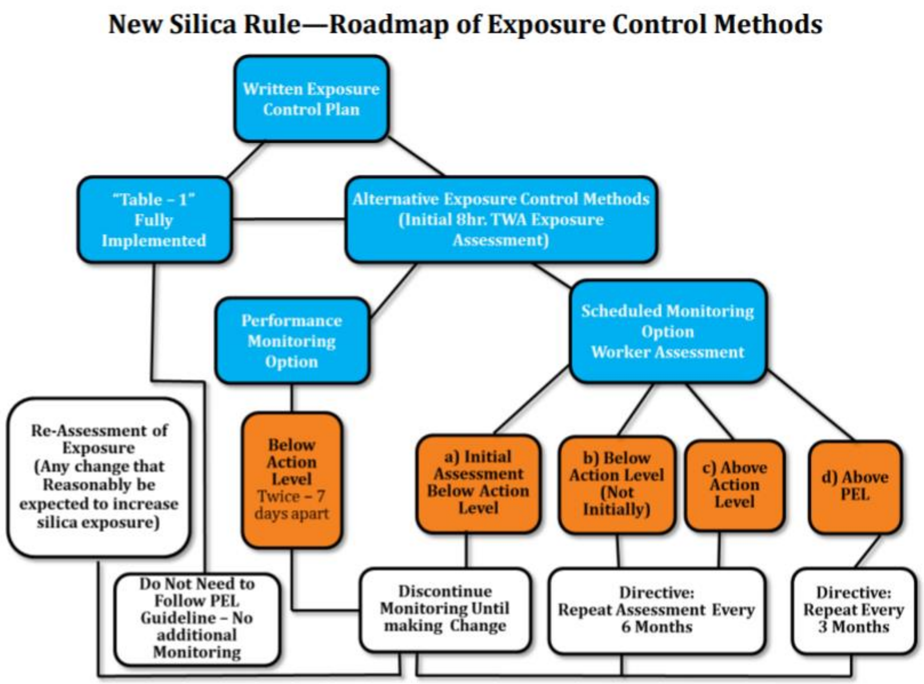

Figure 2.5: Silica exposure control roadmap (TSI, 2018)

<u>Respirable Crystalline Silica Exposure</u>

OSHA estimates that of the 2.3 million workers potentially exposed to silica, 2 million (nearly 90%) are employed in the construction industry (OSHA, n.d.; OSHA, 2017a). Common construction materials, such as sand, stone, concrete, and mortar contain an abundance of respirable crystalline silica (RCS) (OSHA, n.d.). Chen et al. (2012) described occupational silica exposure as a "global public health concern," with more than 23 million workers in China exposed to RCS at work. The NIOSH Director Linda Rosenstock stated, "the human and economic costs of silicosis are unacceptable (National Institute for Occupational Safety and Health, 1996)." Tavakol et al. (2017) studied particles not otherwise specified (PNOS) and silica exposures among construction workers and found that mean pulmonary function parameters (FEV_1% and FVC%) were significantly lower among construction workers compared to a control group. The researchers wrote that that pulmonary status of 51.8% of construction workers showed moderate restriction and 4.70% showed obstruction. Keramydas et al. (2020) evaluated the health implications for construction workers exposed to RCS during outdoor and underground projects and found that underground workers had higher rates of moderate restrictive syndrome and mild obstructive syndrome compared to outdoor workers. In the construction industry, exposure can vary based on multiple parameters, such as tasks performed and location, which was demonstrated by Keramydas et al. (2020). The OSHA Table 1 provides task-specific dust controls that may include: the use of a water delivery system that continuously delivers water to the blade, surface, or point of impact; a dust collector with a filter of 99% or greater efficiency and a filter cleaning mechanism; a high efficiency particulate air (HEPA) filter vacuum, and other task-specific dust controls (Occupational Safety and Health Administration, 2017b). Available data on dust control effectiveness in the construction industry is intermittent and lacks robustness; there are construction tasks in which there is an absence of data to inform exposure potential and dust control effectiveness. Other tasks may only have limited published literature which investigate dust control effectiveness. A comprehensive review of the available literature found that construction workers are still at risk of overexposure to silica dust even when certain controls and protections are in place (Akbar-Khanzadeh et al., 2010; Echt et al., 2016; Flanagan et al., 2003; Shafie, 2020). Akbar-Khanzadeh et al. (2010) evaluated dust control methods for concrete surface grinding and found that no combination of dust controls reduced silica concentrations below the criterion of 25 μg/m^3. Flanagan et al. (2003) assessed silica exposures for eight construction activities and found that dust control measures for surface grinding would not reduce exposures below the threshold limit value (TLV) of 0.05 mg/m^3. Flanagan et al. (2003) also found that dust controls such as sweeping compound, using a box fan for cleanup, ducted fan dilution, and wetted substrate yielded higher silica exposures than the task without dust control. Wet methods to "wet the substrate" were used for four of the five tasks observed in the current study (i.e., core drilling, cutting with a walk-behind saw, grinding, and jackhammering) and high efficiency particulate air (HEPA) filter vacuums were used to control silica dust during core drilling, dowel drilling, and grinding activities. Shafie (2020) evaluated factors that influence HEPA filter vacuum performance on construction sites and found that the age of vacuums and the of date of the last filter change and service, in this order, were the strongest predictors of silica dust exposure. Further, Shafie (2020) found that vacuums of unknown age, which likely represented older vacuums, were expected to perform at 45.3% of the original design airflow, resulting in the highest predicted silica dust exposures, providing evidence that dust control measures, such as HEPA filter vacuums, vary in efficiency.

Tjoe-Nij et al. (2003) found that 55% of workers studied were above the Dutch occupational exposure limit (OEL) of 75 μg/m^3 and the average quartz content in respirable dust was 12 percent (ranging from < 1% to 53%). The researchers found the highest RCS exposures among concrete drillers and grinders, tuck pointers, and demolition workers, with broad exposure ranges and high geometric standard deviations indicating relatively large variability in exposure. Further, the researchers wrote that repeated measures revealed differences (day-to-day variance) between workers was large (Tjoe-Nij et al., 2003). Though few resources are available regarding the determinants of exposure to silica dust, Archer et al. (2002) found that environmental factors such as relative humidity, soil moisture, and windspeed inversely influenced silica dust exposures. Akbar-Khanzadeh et el. (2002) also found silica concentrations to be significantly higher at wind speeds less than or equal to 1 m/s and lower at wind speeds greater than 1 m/s. Further, Echt et al. (2016) suggested that the distribution of dust in air, wind and weather, work practices, and many other factors can impact a construction worker's exposure to silica. Reed and Organiscak (2006) evaluated the exposure potential for drivers following 20 seconds behind the lead haul truck and found that respirable dust concentrations ranged from 750 $\mu g/m^3$ to 2,750 $\mu g/m^3$, with 10% of exposures exceeding 2,750 $\mu g/m^3$. The researchers also evaluated the Mine Safety and Health Administration (MSHA) database for haul truck exposures and found that 10% of drivers following the lead truck and 5% of grade operators were overexposed to silica dust at surface coal mines. The researchers also found that drivers and grade operators were overexposed to silica dust at stone mining sites (5% and 29%). Reed and Organiscak (2006) expressed that construction workers performing tasks in proximity to the dust emissions of haul trucks could be at risk of high exposure to silica dust. The researchers reported data from the EPA which showed that watering haul roads can control total suspended particulates by 74% for three to four hours when water spray is applied at 0.46 gal/yd^2, and at 95% for one-half of an hour when water is applied at 0.13 gal/yd^2.

To the researcher's knowledge there have been no studies that investigated the potential contribution of silica present in the background air to the overall exposure profile on a construction site or the impact it may have in increasing personal exposure for those performing silica-generating tasks. A literature review showed that ambient silica levels have been sampled in residential communities and near select job sites, but none investigated background silica concentrations on the actual job sites. The mean and high estimate of annual ambient silica exposure in the United States was reported by the Environmental Protection Agency (EPA) (1996) to be 3 $\mu g/m^3$ and 8 $\mu g/m^3$. The EPA's National Ambient Air Quality Standards (NAAQS) regulate six common air pollutants, including particulate matter (PM) (Wisconsin Industrial Sand Association, 2013). The EPA does not have an ambient air regulatory standard for silica dust specifically, but it can be extrapolated from the EPA's annual PM10 NAAQS of 50 $\mu g/m^3$ (with a 10% silica fraction), which assumes a maximum annual ambient silica exposure level of 5 $\mu g/m^3$ (Environmental Protection Agency, 1996). Resources regarding ambient silica dust are limited, but Bhagia (2012) reported that the mean 24-hour exposure to RCS in ambient air was approximately 15.28 $\mu g/m^3$ for those in proximity to the agate industry, and 3.03 $\mu g/m^3$ for the control sites. According to Bhagia (2012), ambient air silica concentrations in proximity to the pencil slate and agate industries were above the extrapolated EPA annual exposure limit for silica in ambient air. An investigation conducted by the Environmental Working Group (2014) reported that silica dust present in ambient air near multiple frac sand mines in Wisconsin and Minnesota, could degrade air quality as far as half a mile away from the sand mines. Jenkins Environmental Services (n.d.) stated that fine sized crystalline silica particulates can stay in the air for up to twelve days. Because the EPA lists the construction industry as a major generator for silica dust in ambient air, there is a need for data pertaining to background silica concentrations on construction sites. Reed and Organiscak (2006) confirmed this need for construction background silica data when they wrote that available data to validate exposure potential from dust emissions is almost nonexistent.

Silica Air Monitoring

Before 1984, impingers were used to collect silica air samples, but then the sampling methods evolved once it was discovered that only a fraction of dust collected by the impinger was responsible for silicosis (California Office of Environmental Health Hazard Assessment, 2005). Gravimetric sampling methods (i.e., collecting then weighing the contaminant to determine the mass collected) became standard practice as the apparatus and flow rates were able to discriminate the particle sizes collected on the filter. Presently, the NIOSH method 7500 is a sampling and analytical method that prescribes the acceptable cyclones for silica sampling (with 5 µm PVC membrane filters) and the X-ray diffraction (XRD) analysis method used to measure silica (National Institute for Occupational Safety and Health, 2003). The International Organization for Standardization also harmonizes air sampling methods used in the field by requiring dust samplers that have a 50% cut-point for particles of 4 µm aerodynamic diameter (California Office of Environmental Health Hazard Assessment, 2005). OSHA (2016d) states that silica air monitoring should be performed using accepted integrated sampling methods that use gravimetric analysis, such as the Dorr Oliver 10 mm nylon cyclone or other suitable cyclones operated at specified flow rates. X-ray diffraction is the preferred silica analytical method which identifies primary, secondary, tertiary and quaternary peaks that aid in the elimination of interfering crystalline substances when assessing for quartz (Occupational Safety and Health Administration, 2016d). SKC Incorporated supplied OSHA with data on the new disposable parallel particle impactors (PPI's) with flow rates from 2.0 LPM to 8.0 LPM, which have been shown to conform closely with the International Organization for Standardization (ISO) / European Committee for Standardization (CEN) convention (Dietrich, 2018) (Figure 2.7). These impactors are configurated to scrub out larger particles onto the plates and to collect smaller respirable dust on the pre-weighed PVC filter (Figure 2.6). Gravimetric analysis using NIOSH method 7500 can then be performed to determine the concentration of silica dust collected.

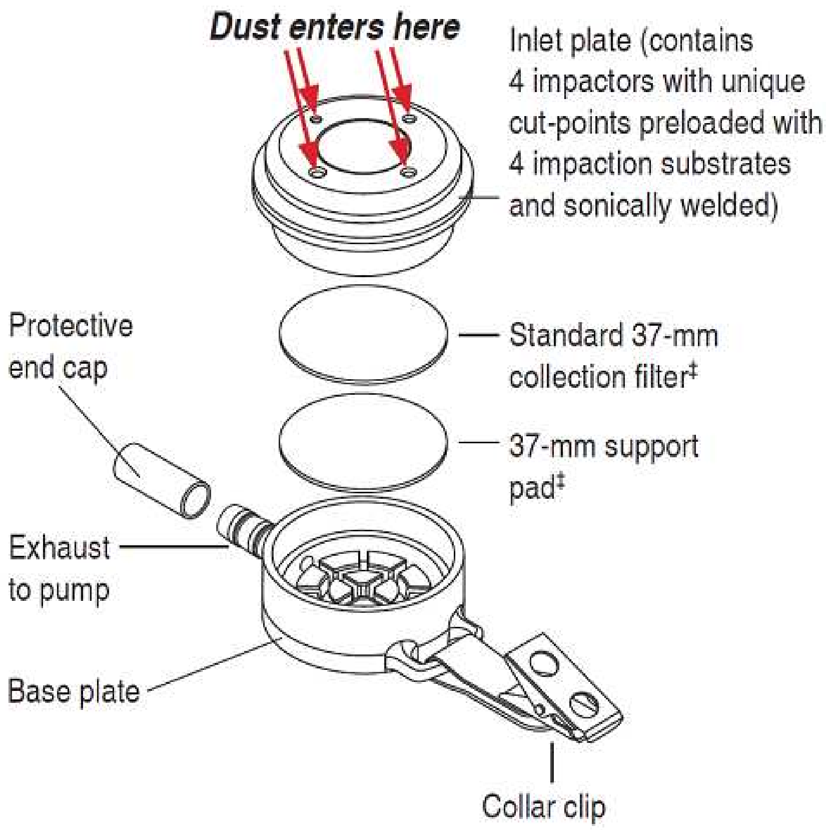

Figure 2.6: Internal Configuration of the SKC 2, 4, and 8 LPM disposable parallel particle impactors (PPI's) (SKC, n.d.)

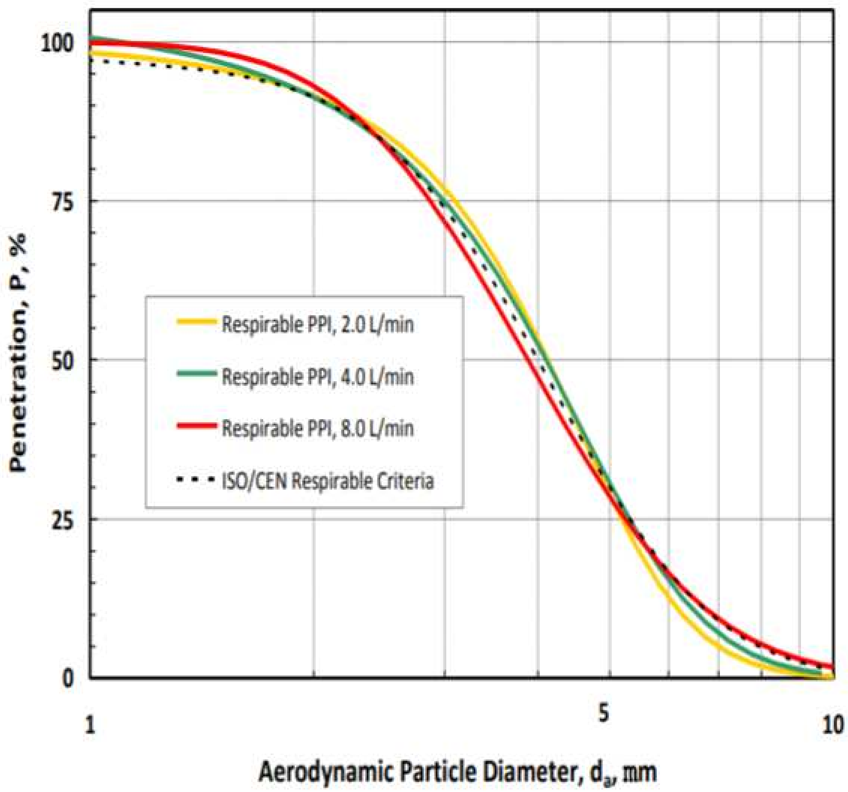

Figure 2.7: Collection efficiency of the 2, 4, and 8 LPM respirable PPI's compared to the ISO/CEN respirable curve (Dietrich, 2018)

A measurement of silica dust referenced in this dissertation includes the eight-hour TWA. The eight-hour TWA is the employees' average airborne exposure over an eight-hour shift of a 40-hour work week.

Gravimetric samplers are required to confirm compliance to the OSHA standard, but new sampling methods have been used to assess the effectiveness of dust controls in reducing RCS exposure. Photometric instruments, such as the TSI SidePak AM520, use light-scattering technology to measure aerosol concentration. Air is drawn into the instrument through an optical chamber where light from a light-emitting diode (LED) laser is scattered by the aerosol, allowing the photo detector to measure the intensity of the scattered light. The instrument instantaneously displays readings which are based on the intensity of light scattered by the same amount of a calibration test dust. However, the instrument cannot differentiate between light scattered by one type of dust to another, meaning a calibration factor must be manually entered for the instrument to display a dust-specific aerosol mass concentration. TSI (2018) assessed five studies with ten samples each and reported a 53% cost savings when using a photometric method to assess exposure, compared to using fully traditional gravimetric methods which require laboratory analysis fees. However, using a photometric instrument to predict RCS exposure requires accurately defining a calibration or correction factor. Pahler et al. (2018) found poor agreement between data from the SidePak and traditional sampling and concluded that a larger sample size with known homogeneous silica content would be necessary to determine a calibration factor that more accurately predicts RCS concentrations. The researchers ultimately concluded that calibration factors could be determined to predict respirable crystalline silica (RCS) concentrations using direct-reading instruments. Shafie (2020) suggested that photometric sampling may not be a suitable exposure assessment method on construction sites due to the variability of silica content among construction materials. The calibration or correction factor must be adjusted for each task monitored based on the silica content of the specific material used.

CHAPTER 3

"THE CHARACTERIZATION OF PERSONAL EXPOSURE TO AIRBORNE SILICA DUST AMONG CONSTRUCTION WORKERS DURING FIVE OSHA TABLE 1 TASKS, THE EFFECTIVENESS OF OSHA-MANDATED SILICA CONTROLS, AND THE CONTRIBUTION OF AMBIENT AIR SILICA DUST TO WORKER EXPOSURE ON CONSTRUCTION SITES"

Summary

In recognition of the hazards of airborne silica exposure, the Occupational Safety and Health Administration (OSHA) enacted a new silica action level (AL) of 25 μg/m^3 and a permissible exposure limit (PEL) of 50 μg/m^3 as an eight-hour time weighted average (TWA) in 2016. Due to a lack of published studies on silica control methods and the new standard, OSHA submitted a request for feedback from safety and health practitioners and individuals working within the construction industry on the new silica standard including the *OSHA Table 1: Specified Exposure Control Methods When Working With Materials Containing Crystalline Silica*. In meeting OSHA's request for data, silica exposure controls need to be evaluated to determine if OSHA-mandated controls are effectively protecting workers from airborne silica exposure. Further, this research is critical to protect the health of workers since the OSHA construction standard does not require air monitoring of employers following the OSHA Table 1 and allows respiratory protection as optional on a task-specific basis when certain guidelines are followed and specific dust control measures are implemented. Current knowledge of silica-related disease informs the occupational health community that workers in the construction

industry are at very high risk for silica-dust overexposure and, consequently, the development of silica-related illnesses. For the current study, construction workers from a northern Colorado construction company participated in personal breathing zone air monitoring during five OSHA Table 1 tasks to determine if they were overexposed to respirable crystalline silica and to evaluate the effectiveness of OSHA-mandated silica controls. Area silica air monitoring was also performed to determine the concentration of silica dust present in background air. To align the results with the OSHA Table 1 distinctions of less than four hours and greater than four hours of exposure for specified tasks, the measured personal exposures were extrapolated into two categories of eight-hour time weighted averages (TWA). During the sampling campaign, there were tasks that could not be sampled for a full eight-hour shift due to the task time. Conversations with workers revealed that there were many tasks such as grinding, core drilling, and dowel drilling that can take place for a full eight-hour shift, whereas jackhammering and cutting with walk-behind saws are not typically performed for eight hours. Therefore, the silica exposure data were extrapolated to eight-hour TWA's assuming that the task continued for a full shift, as well as extrapolated to eight-hour TWA's assuming that the task stopped after four-hours and did not resume for the remainder of the shift (i.e., measured exposures were extrapolated to four hours and assumed no exposure for an additional four hours).

Personal task-based and area silica air monitoring were performed at a northern Colorado construction site during the construction of a water sanitation plant on 13 days over five months (July-November). Fifty-one (51) personal air samples were collected while workers conducted five specific tasks from the OSHA Table 1 with an average task time of 127 minutes (range: 18 to 240 minutes). The mean silica concentration was 85 μg/m^3 (standard deviation [SD] = 176.2) for all samples, with 24 of 51 (47.1%) exposed above the OSHA AL of 25 μg/m^3 and 15 of 51

(29.4%) exposed above the PEL of 50 μg/m^3 when exposures were extrapolated to an eight-hour shift. If the tasks stopped after four hours and did not commence again for the remainder of the shift, then 15 of 51 (29.4%) of workers sampled were exposed over the AL and 8 of 51 (15.7%) were exposed over the PEL. At least one dust control measure, and sometimes a combination of two, were used during all 51 samples collected. The mean silica concentrations for the five tasks were: core drilling 11.2 μg/m^3 [5.31], cutting with a walk-behind saw 126 μg/m^3 [115], dowel drilling 99.9 μg/m^3 [58.7], grinding 172 μg/m^3 [145], and jackhammering 23.2 μg/m^3 [5.19]. Data recorded included: task, location, controls used, respiratory protection, and environmental conditions.

A total of 15 area silica samples were collected in tandem with the personal task-based silica samples with an average sampling time of 187 minutes. At least one area sample was collected on each of the 13 sampling days. The main objective was to determine if background silica levels contributed to personal silica exposures while employees performed the specified OSHA Table 1 construction tasks. Of the 15 area silica samples, only four were greater than the laboratory reporting limit of 5,000 ng (5 μg). The four area silica samples revealed background silica concentrations of 23 μg/m^3, 5 μg/m^3, 40 μg/m^3, and 100 μg/m^3. Due to data censoring (i.e., non-detects) in the area samples (73.3%), there was not a sufficient number of data points to determine with statistical certainty if silica background concentrations significantly contributed to worker exposure. However, the four measurable background silica samples may have contributed to worker exposure since 14 of 15 of the personal samples that exceeded the PEL, when extrapolated to a full eight-hour shift, occurred on the four days when the background silica levels were measurable.

The results of this study suggest that exposure to hazardous levels of respirable crystalline silica may be present even when dust controls, such as wet methods and high efficiency particulate air (HEPA) filter vacuums, are implemented. The current study findings also suggest a possible correlation between background silica concentrations and the higher personal silica dust exposures.

Introduction

There is a long-standing history of respirable crystalline silica (RCS) exposure among workers in certain industries. The Occupational Safety and Health Administration (OSHA) estimates that 2.3 million Americans are exposed to silica dust at work, including two million workers in the construction industry exposed in more than 600,000 workplaces (OSHA, n.d.; OSHA, 2016b). Given these estimates, it is not surprising that silica exposure was identified as one of the world's most significant causes of occupational disease (Institution of Occupational Safety and Health, 2016). According to OSHA, respirable crystalline silica is, "a very small particle, at least 100 times smaller than ordinary sand found on beaches and playgrounds (Occupational Safety and Health Administration, n.d.)." These particulates are nearly impossible to see with the naked eye and it is both the size and shape of this particulate that make it so hazardous for those exposed, especially in occupational settings where chronic exposure may occur. Particulates less than ten micrometers in diameter are considered "respirable" because they have the potential to deposit deep within the lungs (Brown et al., 2013). Maximum deposition into the gas exchange, or alveolar region occurs at about two micrometers (National Institute for Occupational Safety and Health, 2002). Chronic exposure to respirable crystalline silica can have severe implications. Initial symptoms include respiratory irritation, coughing, shortness of breath, and other ailments. Once deposited in the lung tissue, silica particles cannot be digested by the macrophages that the body deploys as a defense mechanism. The inability of macrophages to digest a silica particle perpetuates a repetitive cycle of inflammation long after exposure, known as frustrated phagocytosis (California Office of Environmental Health Hazard Assessment, 2005). The inflammation causes irreparable damage in the form of fibrosis. Ultimately, diseases associated with airborne silica exposure include silicosis, emphysema, chronic bronchitis, chronic obstructive pulmonary disease, silicotuberculosis, 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).

In the 2016 final rule on respirable silica dust, OSHA announced the new permissible exposure limit (PEL) of 50 $\mu g/m^3$ and an action limit (AL) of 25 $\mu g/m^3$, averaged over an eight-hour 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 the table was to offer companies a method for achieving OSHA compliance without having to monitor exposures (Occupational Safety and Health Administration, 2016b). To accomplish this, the table lists specific controls and work practices that should be implemented while performing construction tasks. 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, 2016b). The current study evaluates those assumptions so that a determination can be made about the effectiveness of the OSHA Table 1 in protecting construction workers.

To the researchers' knowledge, there are currently no published studies regarding the effectiveness of OSHA Table 1. However, researchers have evaluated the general effectiveness of dust control methods for respirable dust, and found that dust control methods are effective in reducing exposure. While the studied dust controls were shown to be effective and offer a reduction in respirable dust exposure, the "reduction" in dust concentrations were not always below published exposure limits – only that a reduction in concentration occurred. Akbar-Khanzadeh et al. (2010) evaluated dust control methods during concrete surface grinding using an exposure limit criterion of 25 $\mu g/m^3$ and observed that no combination of dust-control methods reduced the eight-hour exposure below the criterion. Echt et al. (2016) evaluated dust control systems on dowel drilling machinery under controlled conditions including conducting the task inside of a tent to eliminate the effects of wind speed. The researchers found that dust control systems on dowel drills could reduce respirable dust concentrations by 93%. However, they warned that the results should not be compared to occupational exposure limits and that that dust control systems should be "evaluated under actual work conditions to determine their effectiveness in reducing worker exposures to crystalline silica below hazardous levels." Further, Echt et al. (2016) suggested that many factors can influence personal exposure, such as the effects of wind and weather, work practices, the non-uniform distribution of dust in the air, and other factors.

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. In addition, they found that exposures were higher for controls such as sweeping, using a box fan for cleanup, ducted fan dilution, and wetted substrate. The researchers found that dust control reductions for surface grinding would not reduce exposures below the American Conference of Governmental Industrial Hygienist's (ACGIH) threshold limit value (TLV) and that respiratory protection and engineering controls were often ineffective. The authors suggested that more research assessing the effectiveness of available controls was needed to assist the construction industry in identifying effective controls and methods to reduce exposure.

The OSHA (n.d.) specified that RCS can be created through, "cutting, sawing, grinding drilling, and crushing stone, rock, concrete, or mortar," of which all are common activities in construction. Researchers have found elevated silica exposures generated during construction tasks and have also found instances where workers were overexposed to RCS while using dust control measures during task performance (Akbar-Khanzadeh et al., 2010; Echt et al., 2016; Flanagan et al., 2003). Silica dust may also be generated on construction sites by other means, such as haul trucks used for transporting materials and heavy equipment. The Environmental Protection Agency (1998) reported that haul trucks were responsible for 78% to 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 laborers and the general public.

To the researchers' knowledge, there are no published studies that have investigated the potential contribution of airborne, background 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). Wisconsin Industrial Sand Association (2013) quoted an EPA finding that approximately 90% of silica dust comes from fugitive dust sources, with unpaved roads and construction among the four sources that contribute the most. The Environmental Working Group (2014) reviewed ambient silica dust concentrations near multiple fracking sand mining sites in Wisconsin and Minnesota and concluded that silica dust particulates can degrade air quality up to a half a mile away from the sand mines. In addition, Jenkins Environmental Services (n.d.) reported that fine-sized crystalline silica particulates can linger in the air for up to twelve days. Hence, construction workers may not only be exposed to silica generated throughout the work-shift, but may also be exposed to silica generated from activities in the days prior and to ambient silica typically present in the air as reported by the EPA (1996). Therefore, research is needed to evaluate the potential contribution of background silica exposure to construction workers engaged in silica-generating tasks.

The current study was performed at a northern Colorado wastewater treatment plant construction site. As construction workers performed their usual tasks, environmental data (e.g., wind speed, humidity, temperature) were collected as well as personal and area air monitoring for airborne silica dust. The aims of this study were to 1) characterize personal exposure to silica dust among construction workers during five OSHA Table 1 tasks and determine the effectiveness of dust controls, and 2) assess the contribution of background air silica dust to worker exposure on construction sites.

Methods

The study was conducted in the summer and fall of 2020 at a northern Colorado construction site during the build of a water sanitation plant. Participants in this study included nineteen construction workers who were male and 18 years of age or older. Fifty-one 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. The models and manufacturers of construction equipment and dust controls could not be inspected by the researchers and therefore were not recorded due to the research rules of engagement that were approved for operation during the COVID-19 pandemic. The study was performed in compliance with a human subjects study protocol approved by Colorado State University's Institutional Review Board.

Personal Air Monitoring

An observational approach was used to define similar exposure groups (SEGs), as has been recognized as a standard approach (Jahn et al., 2015). The observational approach was also necessary as the researchers aimed to investigate exposure by task from the OSHA Table 1. A total of 51 silica dust personal breathing zone air samples were collected during five OSHA Table 1 tasks from July 2020 to November 2020. All five tasks 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 air samples were collected for each of the tasks, except for core drilling where eleven samples were collected. While the initial goal was to collect four-hour samples, this was not always possible to achieve due to task length. The sampling periods ranged from 18 minutes to 240 minutes, with the average sample time of 127 minutes.

The SKC (Eighty Four, PA) disposable 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 liters per minute to conform to the International Organization for Standardization's (ISO) standard 7708 particle collection efficiency curve criteria with a cut point (D_{50}) of 4 µm. The pumps were attached to the workers' waists and the PPI's were secured to the workers' collars within the breathing zone. 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. Calibration was performed using 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 samples were taken, 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 minutes to 240 minutes, with an average sample time of 187 minutes.

Sample Analysis

All sample analysis was performed by the Wisconsin Occupational Health Laboratory (WOHL), an American Industrial Hygiene Association (AIHA) accredited laboratory. The laboratory used the National Institute for Occupational Safety and Health (NIOSH) Method 7500 for respirable crystalline silica (all forms), and NIOSH Method 0600 for respirable dust.

Environmental Monitoring

Environmental data were collected every 30 minutes throughout the sampling period on each sampling day so that exposures could be evaluated against windspeed, relative humidity and temperature. 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

In order to focus specifically on the exposures generated from the five OSHA Table 1 tasks, a qualitative or observational approach was used in defining similar exposure groups (SEGs) for the subjects. Observation can include defining a SEG by task, job description, the process, exposure, and controls used (Chemscape Safety Technologies, 2019). A Welch's ANOVA and a Games-Howell Post Hoc Test were conducted to test for difference of means between the five tasks, or observed SEG's. While core drilling was identified to have a significant difference from three tasks, none of the other pairwise comparisons were found to be different by a statistically significant margin, due to the relatively large variability of the mean differences. Therefore, in the current study the observational approach to defining SEGs was determined to be the most appropriate for task-based assessments for exposure.

Of the 51 personal breathing zone silica samples collected, 8 of 51 (15.7%) were below the laboratory's reporting limit of 5,000 ng (5 µg), indicating that the true value for these samples was between 0 µg and 5 µg. Of the area samples, 11 of 15 (73.3%) were below the laboratory's reporting limit. Therefore, the airborne concentrations for the left-censored personal samples were estimated using the LOD/√2 method, which is standard practice for datasets with less than 20% censored data points (Army Public Health Center, 2015). The censored data were managed with the substitution method before descriptive statistics were computed and statistical analysis performed. Because of severe censoring in the area samples and small sample size, no method could be used to account for the censored data. This prohibited statistical analysis from being performed to compare personal exposures to area samples using a regression model.

SAS JMP Pro 15, Microsoft Excel (2013), and IH Stat (2021) were used to compute descriptive statistics among SEGs and designate the percentage of construction workers potentially overexposed to respirable silica using the OSHA PEL of 50 $\mu g/m^3$ and the AL of 25 $\mu g/m^3$. Pivot tables were used in Microsoft Excel to summarize multiple variables. A log-transformation (Log_{10}) was applied to improve the distribution of the positively skewed personal air sampling data. Microsoft Excel was used to perform a multiple linear regression using log-transformed silica concentrations as the outcome variable and temperature, relative humidity, task, and location as predictor variables. The regression was used to determine the effect of the predictor variables on the response variable. A two-sample t-test is a statistical test that determines whether the means of two groups are equal or not. The two-sample t-test was used to analyze the log-transformed mean silica concentrations in two categories of wind speed (i.e., wind speed less than or equal to 1 m/s and wind speed greater than 1 m/s). The two-sample t-test was also used to analyze the log-transformed mean silica concentrations between two location categories of partially-enclosed and outdoors.

Results

Similar Exposure Groups

The results of the Welch's ANOVA for the log-transformed air sampling data indicated that a portion of the pairwise comparisons were statistically significant ($p < 0.01$). However, a Games-Howell Post Hoc Test showed that the majority of the pairwise comparisons were not different by a statistically significant margin (Figures 1.1 and 1.2). Because of the relatively large variability between the sample means, the observational approach was used to define the SEGs, as has been recognized as a standard approach (Jahn et al., 2015). The observational approach was also necessary as the researchers aimed to investigate exposure by task from the OSHA Table 1.

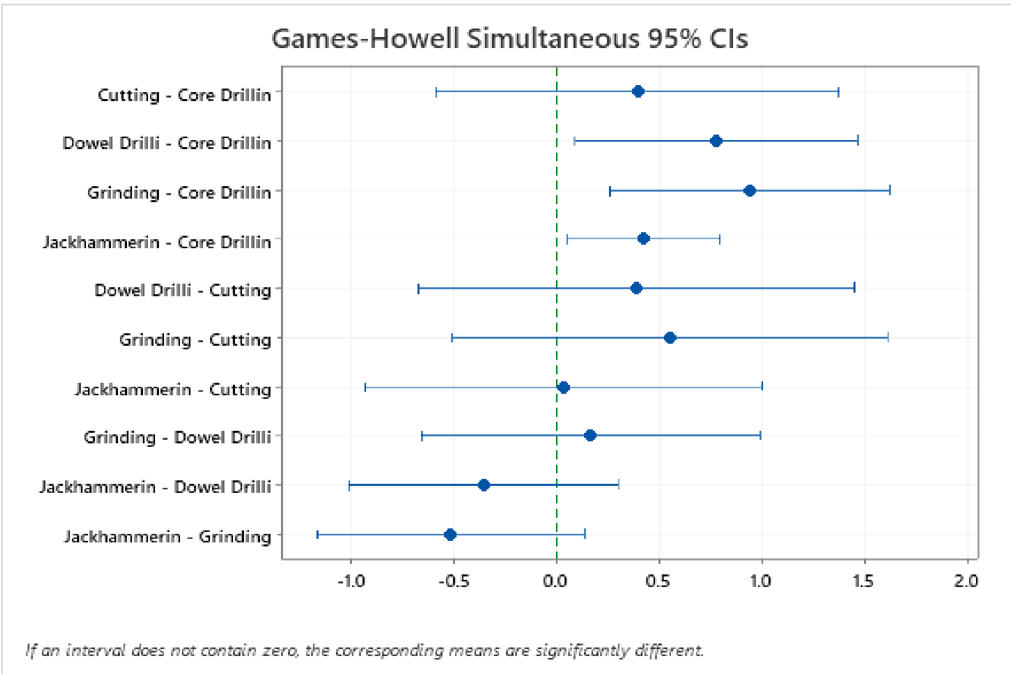

Figure 3.1 Games-Howell Simultaneous 95% Confidence Intervals on Pairwise Comparisons

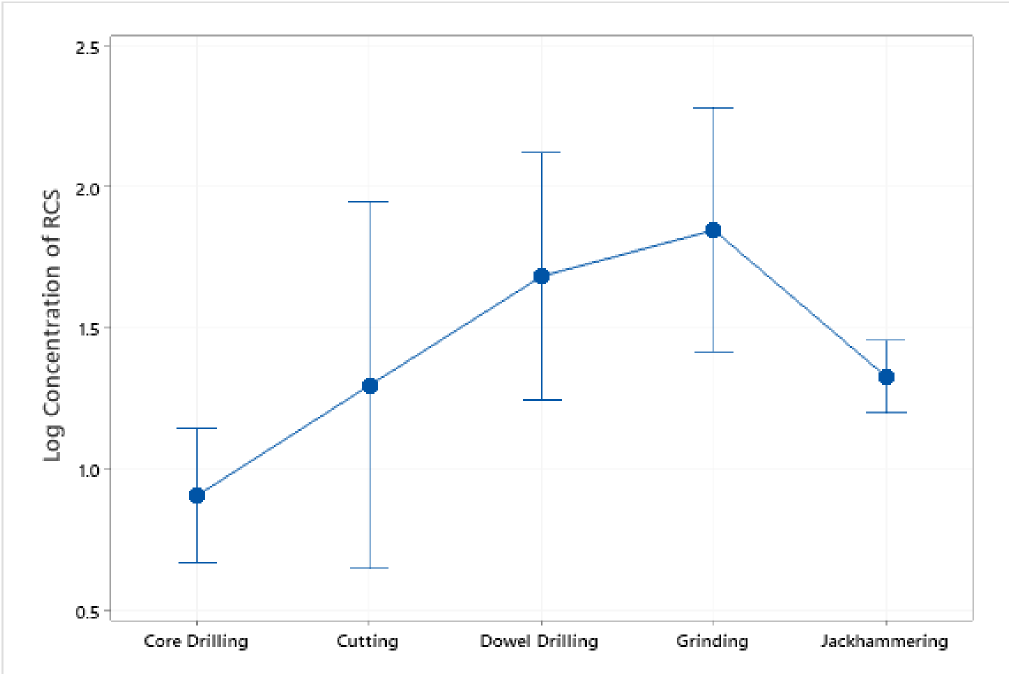

Figure 3.2 Confidence Interval Plot on Log-Transformed Data for Five Tasks

Personal Air Monitoring

A total of 51 personal silica samples were collected during five OSHA Table 1 construction tasks. Of the employees monitored, 24 of 51 (47.1%) had the potential to be exposed at or above the OSHA AL of 25 μg/m^3, and 15 of 51 (29.4%) had the potential to be exposed at or above the OSHA PEL of 50 μg/m^3 based on an eight-hour TWA assuming that the task was performed for an eight-hour shift. Extrapolating the measured exposure to a four-hour shift (with zero exposure for the remainder of the shift) resulted in 15 of 51 (29.4%) of subjects exposed at or above the AL, and 8 of 51 (15.7%) subjects exposed at or above the PEL. Dust controls such as wet methods, shrouds, and HEPA filtration vacuums were implemented throughout the duration of every task monitored (Table 3.1).

Table 3.1: Dust Controls Implemented by Task

Task	Dust Control Methods	Implementation by Employees
Core Drilling	Wet Methods and HEPA Filtration Wet/Dry Vacuum in Combination	10/11
	Wet Methods	1/11
Cutting with a Walk-Behind Saw	Wet Methods	10/10
Dowel Drilling	Shroud and HEPA Filtration Vacuum Dust Collection System	10/10
Grinding	Wet Methods and HEPA Filtration Wet/Dry Vacuum in Combination	6/10
	Shroud and HEPA Filtration Vacuum Dust Collection System	4/10
Jackhammering	Wet Methods	10/10

The OSHA Table 1 uses two categories for work: less than four hours and greater than four hours. The worst-case exposure scenario for workers conducting tasks over an eight-hour shift is presented in Table 3.2. Based on the descriptive statistics for each of the five tasks, the mean RCS concentrations ranged from 11.2 $\mu g/m^3$ for core drilling to 172 $\mu g/m^3$ for grinding. The results suggest that dust controls were inadequate for cutting with a walk-behind saw (126 $\mu g/m^3$), dowel drilling (99.9 $\mu g/m^3$), and grinding (172 $\mu g/m^3$) when compared to the OSHA PEL of 50 $\mu g/m^3$. Core drilling (11.2 $\mu g/m^3$) and jackhammering (23.3 $\mu g/m^3$) were below the OSHA AL of 25 $\mu g/m^3$, which suggests that dust control measures were effective for these tasks. 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.

Table 3.2: Descriptive Statistics of Non-Log$_{10}$ Silica Concentrations by SEG for Tasks Conducted for Full 8-Hour Shift

	Core Drilling	Cutting	Dowel Drilling	Grinding	Jackhammering
Number of Samples (*n*)	11	10	10	10	10
Range	3-37	3.54-670	3.54-380	5-950	11-48
Mean (μg/m^3)	11.2	126	99.9	172	23.2
CI for the Mean (μg/m^3)	(4.16-18.27)	(-38.79-290.60)	(15.89-183.96)	(-35.45-379.20)	(15.51-30.75)
Median (μg/m^3)	7	7	42.5	70	20.5
Standard Deviation (s) (μg/m^3)	10.6	230	118	290	10.6
Geometric Mean (μg/m^3)	8.04	20.1	48.2	70.6	21.4
Geometric Standard Deviation (μg/m^3)	2.31	8.02	4.09	4.01	1.51
Percent Above AL (25 μg/m^3)	9.1%	40.0%	70.0%	90.0%	30.0%
Percent Above PEL (50 μg/m^3)	0.0%	40.0%	40.0%	80.0%	0.0%

The descriptive statistics presented in Table 3.3 illustrate exposure data that would categorize into the OSHA Table 1 category of tasks performed for less than four hours. Based on the descriptive statistics for each of the five tasks, the mean RCS concentrations ranged from 5.73 μg/m^3 for core drilling to 86 μg/m^3 for grinding. The results 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. 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.

Table 3.3: Descriptive Statistics of Non-Log$_{10}$ Silica Concentrations by SEG for Tasks Conducted for Half of 8-Hour Shift

	Core Drilling	Cutting	Dowel Drilling	Grinding	Jackhammering
Number of Samples (*n*)	11	10	10	10	10
Range	2-19	2-335	2-190	2-475	6-24
Mean (μg/m^3)	5.73	63	50	86	11.6
CI for the Mean (μg/m^3)	(2.08-9.13)	(-19.39-145.30)	(7.94-91.98)	(-17.71-189.60)	(7.75-15.38)
Median (μg/m^3)	4	3	21.5	35	10.5
Standard Deviation (s) (μg/m^3)	5.31	115	58.7	145	5.19
Geometric Mean (μg/m^3)	4.24	10.2	24.4	34.7	10.8
Geometric Standard Deviation (μg/m^3)	2.17	7.82	4.01	4.20	1.48
Percent Above AL (25 μg/m^3)	0.0%	40.0%	40.0%	70.0%	0.0%
Percent Above PEL (50 μg/m^3)	0.0%	20.0%	40.0%	20.0%	0.0%

Environmental Data

The mean wind velocity ranged from 0.52 m/s for core drilling to 1.45 m/s for jackhammering, and the mean relative humidity ranged from 23.52% for grinding to 35.50% for jackhammering. Further, the mean temperature ranged from 58.5°F for dowel drilling to 72.8°F for grinding (Table 3.4).

Table 3.4: Mean Wind Velocity, Relative Humidity, and Temperature Collected During 5 Tasks

	Core Drilling	Cutting	Dowel Drilling	Grinding	Jackhammering
Mean Wind Velocity (m/s)	0.52 m/s	1.07 m/s	0.59 m/s	0.54 m/s	1.45 m/s
Mean Relative Humidity (%)	34.20 %	33.30 %	31.35 %	23.52 %	35.50 %
Mean Temperature (°F)	69.3 °F	63.92 °F	58.5 °F	72.8 °F	60.0 °F

Wind velocity was categorized into two groups: wind speeds less than or equal to 1 m/s (74.5%), and wind speeds greater than 1 m/s (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 different. The test was statistically significant ($p < 0.01$) and showed that the mean silica dust concentration (Mean[SD] 1.54 $\mu g/m^3$ [0.67]) at wind speeds less than or equal to 1 m/s was greater than the mean silica dust concentration (Mean[SD] 1.01 $\mu g/m^3$ [0.41]) at wind speeds greater than 1 m/s (Table 3.5). While statistical analysis could not be performed on the silica area samples, the researchers observed that the four area silica air samples that were above the laboratory reporting limit all occurred at windspeeds less than or equal to 1 m/s. Observationally, this suggests a similar outcome where the personal silica sample concentrations were greater at windspeeds less than or equal to 1 m/s.

Table 3.5: Log Transformed Respirable Crystalline Silica Exposure by Wind Velocity

	Silica Concentration µg/m³ (Wind Speed ≤ 1 m/s)	**Silica Concentration µg/m³ (Wind Speed > 1 m/s)**
n	38	13
Mean ± SD	1.54 ± 0.67	1.01 ± 0.41
Range	0.54 – 2.98	0.55 – 1.68
Median	1.56	0.99
GM ± GSD	34.67 ± 4.68	10.23 ± 2.57

*Silica concentrations represented in this table are log transformed (Log_{10})
*Inverse log transformation was computed to obtain the GM and GSD (e.g., 10^1.54 = 34.67)

Location

A two-sample t-test was performed on log-transformed silica concentrations to determine if the means were different between two sampling locations (i.e., outside, and partially enclosed). The test revealed a significant difference ($p < 0.01$) between the mean of silica concentrations (Mean[SD] 1.10 µg/m^3 [0.44]) outside and the 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 3.6).

Table 3.6: Log Transformed Respirable Crystalline Silica Exposure by Location

	Silica Concentration µg/m³ (Outside)	**Silica Concentration µg/m³ (Partially Enclosed)**
n	21	30
Mean ± SD	1.10 ± 0.44	1.62 ± 0.70
Range	0.55 – 1.89	0.54 – 2.83
Median	1.19	1.60
GM ± GSD	12.59 ± 2.75	41.69 ± 5.01

*Silica concentrations represented in this table are log transformed (Log_{10})
*Inverse log transformation was computed to obtain the GM and GSD (e.g., 10^1.10 = 12.59)

A multiple linear regression was performed to assess whether a relationship existed between silica dust concentrations (dependent variable) and the predictor variables location, task, temperature, and relative humidity. The regression showed that relative humidity was not statistically significant ($p > 0.05$) but location, task, and temperature were statistically significant ($p < 0.05$). Table 3.7 presents the summary of regression results.

Table 3.7: Summary of Regression Results with Log-Transformed (Log_{10}) RCS as the Response and Location, Task, Temperature, and Relative Humidity as Predictors

	Coefficients	Standard Error	t	P Value
Intercept	-0.277	0.849	-0.327	0.745
Location	0.651	0.143	4.558	<0.001
Tasks	0.186	0.050	3.738	0.001
Mean Temperature (°F)	-0.019	0.006	-3.321	0.002
Mean Relative Humidity (%)	0.001	0.007	0.085	0.932
Residual	10.371 (48 DF)			
Standard Error	0.475			
Multiple R^2	0.715			
Adjusted R^2	0.512			
Equation	0.469			

Area Air Monitoring

Silica dust exposure for workers conducting tasks over an eight-hour shift and background silica dust concentrations associated with each task are presented in Table 3.8. Of particular note is that 14 of the 15 personal RCS exposures that exceeded the OSHA PEL occurred on the four sampling days where background silica concentrations were detected by the laboratory.

Table 3.8: Background Silica Concentrations (µg/m³) and Personal Silica Exposure (µg/m³)

Date	Task	Dust Controls Used	Extrapolated 8-hr TWA (µg/m³) for Continuous Work	Background Silica Concentration (µg/m³)
7/7/2020	Grinding	Shroud and HEPA Filtration Vacuum	5	< 5
7/8/2020	Grinding	Shroud and HEPA Filtration Vacuum	35	< 5
7/23/2020	Cutting	Wet Methods	7	< 5
	Core Drilling	Wet Methods and HEPA Filtration Wet/Dry Vacuum	3.54	
	Cutting	Wet Methods	3.54	
7/30/2020	Dow Drilling	Shroud and HEPA Filtration Vacuum	15	< 5
	Core Drilling	Wet Methods and HEPA Filtration Wet/Dry Vacuum	7	
	Core Drilling	Wet Methods and HEPA Filtration Wet/Dry Vacuum	12	
	Dow Drilling	Shroud and HEPA Filtration Vacuum	20	
8/31/2020	Jackhammering	Wet Methods	33	< 5
	Jackhammering	Wet Methods	22	
	Core Drilling	Wet Methods and HEPA Filtration Wet/Dry Vacuum	3.54	
	Core Drilling	Wet Methods and HEPA Filtration Wet/Dry Vacuum	3	
9/1/2020	Core Drilling	Wet Methods and HEPA Filtration Wet/Dry Vacuum	10	< 5
	Core Drilling	Wet Methods and HEPA Filtration Wet/Dry Vacuum	3.54	
	Jackhammering	Wet Methods	21	
	Jackhammering	Wet Methods	20	
9/29/2020	Grinding	Wet Methods and HEPA Filtration Wet/Dry Vacuum	50	< 5

	Grinding	Wet Methods and HEPA Filtration Wet/Dry Vacuum	38	
10/8/2020	Grinding	Wet Methods and HEPA Filtration Wet/Dry Vacuum	69	23
	Grinding	Wet Methods Inconsistently and HEPA Filtration Wet/Dry Vacuum	950	
	Cutting	Wet Methods	78	
	Cutting	Wet Methods	64	
	Core Drilling	Wet Methods and HEPA Filtration Wet/Dry Vacuum	37	
	Core Drilling	Wet Methods and HEPA Filtration Wet/Dry Vacuum	24	
	Grinding	Wet Methods and HEPA Filtration Wet/Dry Vacuum	350	
	Grinding	Wet Methods and HEPA Filtration Wet/Dry Vacuum	75	
10/15/2020	Core Drilling	Wet Methods	7	5
	Grinding	Shroud and HEPA Filtration Vacuum	76	
	Grinding	Shroud and HEPA Filtration Vacuum	71	
	Dow Drilling	Shroud and HEPA Filtration Vacuum	3.54	
	Core Drilling	Wet Methods	13	
	Dow Drilling	Shroud and HEPA Filtration Vacuum	25	
10/29/2020	Jackhammering	Wet Methods	48	< 5
	Jackhammering	Wet Methods	19	
	Cutting	Wet Methods	3.54	
	Cutting	Wet Methods	3.54	
	Jackhammering	Wet Methods	16	
	Jackhammering	Wet Methods	26	
11/2/2020	Jackhammering	Wet Methods	11	< 5
	Jackhammering	Wet Methods	16	
	Cutting	Wet Methods	3.54	
	Cutting	Wet Methods	7	

11/13/2020	Dow Drilling	Wet Methods	41	40
	Dow Drilling	Wet Methods	130	
	Dow Drilling	Wet Methods	44	
	Dow Drilling	Wet Methods	380	
11/18/2020	Cutting	Wet Methods and HEPA Filtration Wet/Dry Vacuum	420	100
	Cutting	Wet Methods and HEPA Filtration Wet/Dry Vacuum	670	
	Dow Drilling	Shroud and HEPA Filtration Vacuum	170	
	Dow Drilling	Shroud and HEPA Filtration Vacuum	170	

*Extrapolated silica concentrations for personal eight-hour TWA include eight data points that were corrected using the LOD/√2 method.

Figure 3.3 graphically demonstrates RCS exposures when compared to background silica concentrations, illustrating elevated RCS concentrations above the PEL occurring on days where background silica dust was detected.

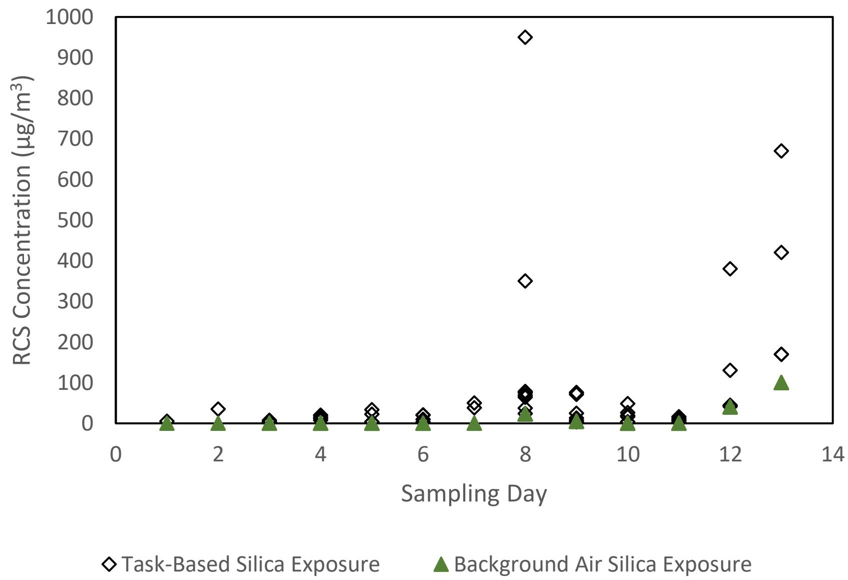

Figure 3.3: Background Air Silica Concentrations (µg/m³) Compared to Task-Based Silica Concentrations (µg/m³)

Discussion

Similar Exposure Groups

Two approaches can be used when defining similar exposure groups (SEGs); an observational approach, or a statistical approach. Using the statistical approach can be more robust, but when there are limited monitoring resources and the dataset lacks a large number of random measurements, with multiples of those measurements repeated on an individual worker, Jahn et al. (2015) suggests that the observational approach is acceptable as a standard practice. Defining SEGs by task was used by Flanagan et al. (2013) to investigate the exposures of eight construction tasks and Archer et al. (2002) to investigate silica exposure by agricultural activities. The statistical approach to defining SEG's was initially investigated by computing a Welch's ANOVA and a Games-Howell Post Hoc Test on log-transformed data. While a portion of the pairwise comparisons were statistically significant, the majority were not different from one another by a statistically significant margin. One reason for the lack of significance could be due to the large variability relative to the mean difference and small sample size. Therefore, the observational approach was used in the current study to define SEG's based on task. However, one limitation with the observational approach is the expected similarity of exposure within SEGs, which can lead to the misclassification of individual exposures (Jahn et al., 2015). Future research in silica exposure assessments should examine the exposures for congruity within SEGs by accumulating large sample sizes and refining exposure classifications as appropriate using statistical analysis.

Personal Air Monitoring

As presented in Table 3.2, the worst-case scenario (i.e., eight-hour extrapolated exposure) is important to highlight because construction tasks may take eight hours 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 eight-hour shifts for weeks to months at a time whereas the grinding tasks observed in the current study averaged 217 minutes. As a construction project evolves and components of the build are completed, then tasks such as grinding may be reduced and other tasks, such as core drilling will begin. Construction projects are an ever-evolving process and the tasks a construction worker performs may change from day-to-day. For example, an employee may use a grinder for two hours on one shift and then eight hours on the next shift. Because of the varying task times it is important to examine the potential exposure data for different shift lengths as presented in Tables 3.2 and 3.3.

As noted in the results section, 15 of 51 (29.4%) of the silica samples exceeded the OSHA PEL of 50 $\mu g/m^3$ when extrapolated over an eight-hour shift. Further, when considering the “best case” scenario, that is if the tasks were performed for only four hours with another four hours of zero silica exposure, 8 of 51 (15.7%) of construction workers were predicted to be overexposed to the OSHA PEL while conducting OSHA Table 1 tasks and using dust control methods. 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 saws performed by these guidelines 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 eight-hour 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), even if dust control methods are used. This requirement seems appropriate since 40% of the workers sampled in this SEG had the potential to be exposed above the PEL for tasks conducted over an eight-hour shift. All grinding activities that were sampled in the current study were conducted 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 researchers' greatest concern with the OSHA Table 1 controls. Eight of 10 (80%) employees sampled had the potential to be exposed above the PEL for grinding conducted for an eight-hour shift. In reference to jackhammering, the OSHA Table 1 specifies that respiratory protection, such as a filtering facepiece with an assigned protection factor (APF 10), must be used when jackhammering outside if the task exceeds four hours, even while using wet methods. Since zero of 10 (0.0%) of employees monitored had the potential to be overexposed while jackhammering for a full eight-hour shift, it appears that the dust control methods for jackhammering in OSHA Table 1 were effective at protecting workers.

The five tasks observed in this study and the specified OSHA controls are found in Table 3.9.

Table 3.9: Five Tasks from the OSHA Table 1 "Specified Exposure Control Methods When Working With Materials Containing Crystalline Silica"

Equipment / Task	Engineering and Work Practice Control Methods	Required Respiratory Protection and Minimum Assigned Protection Factor (APF)	
		≤ 4 hours / shift	> 4 hours / shift
(iv) Walk-behind saws	Use saw equipped with integrated water delivery system that continuously feeds water to the blade. Operate and maintain tool in accordance with manufacturer's instructions to minimize dust emissions. -When used outdoors. -When used indoors or in an enclosed area.	None APF 10	None APF 10
(vi) Rig-mounted core saws or drills	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.	None	None
(viii) Dowel drilling rigs for concrete	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. Use a HEPA-filtered vacuum when cleaning holes.	APF 10	APF 10
(x) Jackhammers and handheld powered chipping tools	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.	None APF 10 None APF 10	APF 10 APF 10 APF 10 APF 10
(xii) Handheld grinders for uses other than mortar removal	For tasks performed outdoors only: Use grinder equipped with integrated water delivery system that continuously feeds water to the grinding surface. Operate and maintain tool in accordance with manufacturer's instructions to minimize dust emissions. OR	 None	 None

	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. -When used outdoors. -When used indoors or in an enclosed area.	None None	None APF 10

Akbar-Khanzadeh et al. (2010) wrote that in regard to concrete surface grinding, "No combination of control methods reduced an 8-hour 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 eight-hour shift exceeded the protective capabilities of the filtering facepiece (APF 10) required by the OSHA Table 1 for those tasks.

Environmental Monitoring

The results of the multiple linear regression in the current study showed that relative humidity was not statistically significant. However, RCS concentrations were shown to be significantly ($p = 0.002$) higher at cooler temperatures and lower at warmer temperatures. Typically, the reverse would be expected; these results may be a product of sample size as more samples were collected during the cooler months than the warmer months. Location and task were also shown to be significant ($p < 0.001$; $p = 0.001$). The R^2 value shown Table 3.7 suggests that only 51% of the variation in RCS concentrations is explained by location, task, and temperature. Archer et al. (2002) reported results that conflict with this study's findings on temperature as a determinant of respirable dust exposure. Further, Archer et al. (2002) found that relative humidity, soil moisture, and wind speed were all significantly associated with having an inverse relationship with respirable crystalline silica exposures. One determinant on which the current study and Archer et al. (2002) agree is wind speed. The researchers of the current study classified wind speed into less than or equal to 1 m/s and greater than 1 m/s, 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 and concentrations were higher when wind speed was less than or equal to 1 m/s. 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 as compared to silica dust concentration when wind speed was less than or equal to 1 m/s. 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 since there are no published studies evaluating this exposure factor. However, due to the relatively high number of non-detects for the area samples, the authors of the current study can only speculate observationally about the potential relationship between the background silica dust concentrations and the personal silica samples.

Fifteen of 51 employees were overexposed to silica dust when extrapolated to an eight-hour shift, and 14 of those 15 exposures all occurred on the four days where background silica dust was high enough to be detected by the laboratory. Reed and Organiscak (2006) stated that haul trucks accounted for 78% to 97% of dust emissions on surface mining sites, and they recognized the potential for a similar hazard in the construction industry. The researchers evaluated the exposure potential for drivers following 20 seconds behind the lead haul truck and found that respirable dust concentrations ranged from 750 μg/m^3 to 2,750 μg/m^3, with 10% of exposures exceeding 2,750 μg/m^3. The researchers also evaluated the Mine Safety and Health Administration (MSHA) database for haul truck exposures and found that 10% of drivers following the lead truck and 5% of grade operators were overexposed to silica dust at surface coal mines. The researchers also found that drivers and grade operators were overexposed to silica dust at stone mining sites (5% and 29%). The researchers suggested that construction workers performing tasks in proximity to the dust emissions of haul trucks could be at risk of high exposure to silica dust. 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 EPA (1998) reported that watering haul roads can control total suspended particulates by 74% for three to four hours when water spray is applied at 0.46 gal/yd^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. The researchers of the current study observed the use of the following OSHA-mandated dust controls: water delivery systems that continuously fed water to the blade, material surface, or point of contact; commercial dust collection systems; high efficiency particulate air (HEPA) filter vacuums; dust shrouds around drill bits and grinders; and water spray trucks. 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 real-time, task-based, data in the field. Personal and area samples could only be collected while workers performed the five OSHA Table 1 tasks. The researchers collected samples in this manner to ensure the results of both types of air monitoring were task focused. Many obstacles, such as worker injury or changes to the build schedule, prevented the researchers from capturing a minimum of four-hour samples for each task and area sample. Full-shift standard exceedances may be overestimated when sample periods do not span a full eight-hour shift.

Another limitation was the collection of low sample volumes, which result 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 this 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 (SEGs). 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. Due to this limitation, the area samples could only be evaluated against the task-based air samples through observation. 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, large variability was present among RCS exposures within SEGs 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 differences (day-to-day variance) between workers was large. Throughout the project, there were tasks performed at many locations on the construction site. The researchers observed variability in exposure among workers conducting the same task with the only observable difference being their location and sampling day. This observation caused reason to believe that location could substantially impact exposure. 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 a simple 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 water sanitation basin was at low risk of overexposure because they were working in "open air" outdoors. But perhaps just slight differences in wind velocity through an area can result in substantial differences in employee exposure. This further supports the observation that wind speeds less than or equal to 1 m/s resulted in higher silica concentrations compared to wind speeds greater than 1 m/s. 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 within SEGs 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 in the construction industry may feel a false sense of security regarding silica exposure as long as the controls and work practices are implemented. 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 provides an observation of the impact of background silica dust to personal task-based exposures on construction sites. The results indicate that exposure to hazardous levels of respirable crystalline silica can still occur with the OSHA-mandated controls fully implemented, and that exposure to respirable crystalline silica may have been exacerbated for employees conducting tasks on the four days where background silica concentrations were detected by the laboratory. 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 and the impact it may have as a determinant of exposure.

Future construction task-based silica exposure researchers should attempt to reduce exposure variability within SEGs, such as limiting air monitoring by task, location, and environmental conditions. For future studies, it is also recommended that high flow samplers (e.g., SKC PPI's that operate at 4 or 8 LPM), be used for sample collection to reduce the number of non-detects. 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, such as wet methods and high efficiency particulate air (HEPA) filters. However, attempts to reduce background silica concentrations should be considered through a combination of task-based and site controls. 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.

CHAPTER 4

"A TEMPORAL EVALUATION OF RESPIRABLE CRYSTALLINE SILICA EXPOSURE FOR CONSTRUCTION TASKS"

Summary

Personal air monitoring using a TSI SidePak AM520 personal aerosol monitor was performed on a northern Colorado construction site during five tasks from the *OSHA Table 1: Specified Exposure Control Methods When Working With Materials Containing Crystalline Silica* to analyze silica dust concentrations in real time. Each task was sampled once; sample time ranged from 14 minutes to 40 minutes, with a mean sample time of 27 minutes. Prior to task-based air monitoring, the TSI SidePak AM520 with a Dorr Oliver cyclone (operated at 1.7 LPM) and a Zefon Escort ELF personal air sampling pump with an SKC disposable respirable parallel particle impactor (PPI) (operated at 4.0 LPM) were co-located on the construction site for 334 minutes to capture the area respirable dust concentration. The SKC PPI was co-located with the TSI SidePak AM520 to determine an aerosol-specific correction factor (2.48) by applying the results of the integrated sampling device to the direct reading instrument. A comparison of respirable dust collected by the SKC PPI to the TSI SidePak AM520 showed that the direct reading instrument underestimated the respirable dust concentration when the factor was employed. Bulk material samples were collected during the performance of the five tasks so that the percent silica could be determined in the material. The mean silica dust concentrations (μg/m^3) (standard deviation [SD]) for the five tasks computed from the TSI SidePak AM520 respirable dust measurements included: core drilling 12 μg/m^3 [2.46], grinding 918 μg/m^3

[1134.08], cutting with a walk-behind saw 36 μg/m^3 [79.67], jackhammering 27 μg/m^3 [23.24], and dowel drilling 66 μg/m^3 [77.65]. Currently, there are no direct reading air sampling instruments that monitor for respirable silica dust specifically. The main objective of this pilot study was to assess the ability of the TSI SidePak AM520 to be used as a method for observing silica dust exposure in real time. While there are several limitations to using a direct reading instrument that was not designed for the specific purpose of silica dust measurement, the data can be used to observe the variability of exposure that occurs within a task and identify potentially ineffective dust controls. The results of the current study suggest that the TSI SidePak AM520 can be used as an exposure assessment tool to aid researchers and those in the construction industry in better understanding exposure spikes throughout task performance, which can be compared to other observations such as employee posturing (i.e., the employee kneeling down or hovering over the equipment producing dust) or other dust generating activities in proximity to identify root causes for the sudden spike in respirable crystalline silica (RCS). Implementing photometric instruments to assess exposure also reduces the burden of cost on employers and construction company owners by reducing the number of gravimetric samples needed, and thus reducing laboratory analysis fees. However, this method of assessing silica dust exposure should only be used as an exposure assessment tool to enhance knowledge of exposure and should not be used to determine OSHA compliance.

Introduction

Activities within the construction industry can generate high concentrations of dust, including respirable crystalline silica (RCS). Because of the nature of the work and the materials needed, OSHA estimates that of the 2.3 million workers potentially exposed to silica, 2 million (nearly 90%) are employed in the construction industry (OSHA, n.d.; OSHA, 2017a). Chronic silica exposure is known to cause silicosis, which is characterized by “histologically unique silicotic nodules and by fibrotic scarring of the lung (California Office of Environmental Health Hazard Assessment, 2005).” Tavakol et al. (2017) evaluated construction workers exposed to respirable particles not otherwise specified (PNOS) and silica dust and reported that the mean pulmonary function parameters (FEV_1% and FVC%) among construction workers were significantly lower than a control group. In addition, the researchers described a significant negative correlation between cumulative RCS exposure and the respiratory parameter (FVC). Of the construction workers’ pulmonary results, 51.8% showed moderate restriction and 4.70% showed obstruction (Tavakol et al., 2017). Greenberg et al. (2007) reported that the construction industry had the highest mortality rates from silicosis (1990 – 1999) as compared to other industries. Further, one third of all silicosis cases from 1990 to 1999 were attributed to the construction and mining industries alone (Greenberg et al. (2007). Silicosis is an incurable disease, meaning prevention is the only course of action to protect the health of construction workers.

The Occupational Safety and Health Administration (OSHA) enacted a new permissible exposure limit (PEL) of 50 $\mu g/m^3$and an action level (AL) of 25 $\mu g/m^3$for silica dust in the construction industry in 2017. The standard provided construction companies with the OSHA Table 1, a guideline that allows employers to forego air monitoring if they implement task-specific dust control measures and work practices from the Table 1. The construction company in the current study followed the OSHA Table 1 by implementing dust controls for each of the five tasks monitored. Dust control methods were evaluated by Akbar-Khanzadeh et al. (2010) for concrete surface grinding using a criterion of 25 $\mu g/m^3$. The researchers found that the dust controls, in any combination, did not decrease dust levels below the criterion level.

Comparatively, in an assessment of eight construction activities Flanagan et al. (2003) found that surface grinding dust control measures would not reduce silica exposures below the threshold limit value (TLV) of 0.05 mg/m^3. The authors also listed several dust controls (e.g., sweeping compound, using a box fan for cleanup, ducted fan dilution, and wetted substrate) that were found to generate higher silica concentrations compared to the same task without dust control. Wet methods to "wet the substrate" were used both independently and in combination with other controls for a large portion (72.5%) of the activities observed in the current study. Various models of high efficiency particulate air (HEPA) filter vacuums were also used to control silica dust for 58.8% of activities. In an evaluation of the factors that influence HEPA filter vacuum performance on construction sites, Shafie (2020) found that the strongest predictors of silica dust exposure were vacuum age and the date of the last filter change and service. Further, the author wrote that the expected performance for vacuums of unknown age was 45.3% of the original design airflow, which resulted in the highest predicted silica dust exposures. The findings from Shafie (2020) suggest that dust control measures, such as HEPA filter vacuums, vary in efficiency. The need for continuous, real-time air monitoring to verify the effectiveness of dust controls and to identify equipment that may no longer be operating appropriately is supported by the silica control results from Akbar-Khanzadeh et al. (2010), Flanagan et al. (2003), and Shafie (2020).

OSHA requires that silica samples be collected over the duration of a work shift or task to estimate the TWA. Integrated sampling using gravimetric analysis is one method that can be employed to compare silica exposures to the OSHA PEL. However, gravimetric methods present employers with two potential barriers: expense and length of time to evaluate exposure. Gravimetric sampling can take weeks, even months, to complete a sampling campaign. Next, samples must be sent to an accredited laboratory to conduct the analysis, where turnaround times vary. After finally receiving the gravimetric sampling results, the employees may have potentially been overexposed to silica dust for months before any data were provided to inform the need for changes in controls or personal protective equipment (PPE). Further, the process would repeat again until the exposure was controlled, extending the length of time required for employers to achieve compliance.

Photometric sampling eliminates lag time by producing instantaneous exposure data, allowing employers to act in real-time to protect their workers. Once an initial gravimetric sample has been collected, photometric monitoring can be performed to adjust controls. While a final gravimetric sample is needed to confirm compliance, using photometric monitoring to assess and adjust controls significantly reduces the time it would otherwise require to achieve compliance.

TSI (2018) reviewed five studies in which photometric methods were used to assess exposure and reported a 53% cost savings as a result. However, there is discussion about whether or not calibration factors can be accurately determined to predict respirable crystalline silica (RCS) concentrations using real-time monitors. In an evaluation of the relationship between particulate matter recorded by photometric instruments and silica dust measured by standard gravimetric samplers, Pahler et al. (2018) found poor agreement between data from the SidePak and traditional sampling. To achieve a calibration factor that more accurately predicts RCS concentrations the authors stated that a larger sample size with a known silica content would be necessary. However, the researchers ultimately concluded that calibration factors could be determined to predict respirable crystalline silica (RCS) concentrations using direct-reading instruments. Radnoff et al. (2014) found a relationship between airborne RCS and respirable dust, however, they found no correlation between airborne RCS concentrations and the percentage of silica in respirable dust. This finding is concerning since the silica content is an important factor in the method for deriving RCS concentrations from respirable dust. Due to the variability of silica content among construction materials, Shafie (2020) suggested that photometric sampling may not be a suitable exposure assessment method on construction sites. Because of the diverse nature of construction materials, the author concluded that a calibration factor must be adjusted for each task monitored based on the silica content of the specific material used. The current study collected bulk material samples for each of the five tasks monitored to ensure that the variable silica content in the materials were adjusted for in the calculations to derive RCS from respirable dust concentrations for each task. The current study used a different approach than Shafie (2020) and Pahler et al. (2018). Shafie (2020) performed a lab simulation by using a vacuum to collect 10 kg of dolomite lime, which was used as a substitute for RCS. The author measured respirable dust during the vacuuming and vacuum emptying process with a SidePak AM510 and an SKC PPI operated at 8 LPM with a Legacy Leland personal air sampling pump. Data collected by the co-located photometric instrument and gravimetric sampler were used to determine a calibration factor (3.91) using an equation provided by TSI Incorporated (2018). Once a calibration factor is determined it can be entered into the SidePak so that the instrument applies the new calibration factor to the aerosol concentration readings, displaying readings more representative of RCS. Therefore, the method discussed by Shafie (2020) implemented the calibration factor prior to further sampling so that the instrument displays readings depictive of RCS rather than respirable dust. Pahler et al. (2018) co-located gravimetric samplers and photometric instruments (i.e., SidePak and DustTrak) and performed a linear regression using the measured respirable dust concentrations to provide an equation to predict RCS concentrations using direct reading instruments. The current study used a co-located gravimetric sampler and photometric instrument to measure respirable dust in the background air on the construction site. The photometric instrument was then used to monitor respirable dust during the performance of five tasks. No calibration factor was used prior to performing task-based monitoring. After all data were collected, the co-located sampling data were used to define a correction factor using the equation provided by TSI Incorporated (2018). The correction factor (2.48) was then applied to each respirable dust data point, from which percent silica for material used during that task was applied to derive RCS concentrations.

Methods

Area Monitoring

The TSI SidePak AM520 (Shoreview, MN) with a Dorr Oliver 10 mm nylon cyclone (operated at 1.7 LPM) was co-located on the construction site with an SKC disposable respirable parallel particle impactor (PPI) (Eighty Four, PA) and a Zefon Escort ELF (Ocala, FL) personal air sampling pump (operated at 4.0 LPM). The gravimetric sampler was co-located with the photometric sampler so that results of the gravimetric area sample could be applied to the photometric sampling results to define a correction factor (Equation 1):

$$PCF = \frac{Reference\ Concentration}{Data\ Log\ Concentration} \times 1.0 \qquad \textbf{Equation 1}$$

Where,

PCF = Photometric Calibration Factor

Reference = Gravimetric Average Concentration

Data Log = AM520 Average Concentration

ECF = Existing Calibration Factor of Real-Time Instrument (factory default calibration is 1.0)

The area monitoring (PPI) was performed for 334 minutes. One field blank was handled for quality control. Pre- and post-calibration of the SidePak and the Escort ELF personal air sampling pump were conducted immediately before and after the sampling day. Escort ELF calibration was performed using a Mesa Labs (Lakewood, CO) DryCal Defender Series primary gas flow calibrator and an SKC (Eighty Four, PA) calibration adapter for the PPI. SidePak calibration was performed using a Mesa Labs (Lakewood, CO) DryCal Defender Series primary gas flow calibrator and a Zefon (Ocala, FL) calibration jar which housed the Dorr Oliver 10 mm nylon cyclone. The blank inlet was installed in the SidePak for the area air monitoring. Prior to use, the SidePak zero filter was attached for 60 seconds to zero calibrate the equipment. The SidePak took a sample every second and was set to log the data every minute.

Task-Specific Personal Air Monitoring

The TSI SidePak AM520 (Shoreview, MN) and Dorr Oliver 10 mm nylon cyclone (operated at 1.7 LPM) were used to conduct air monitoring while workers performed five OSHA Table 1 tasks. The SidePak was attached to the worker's belt and the cyclone was attached to the worker's collar in the breathing zone. Pre- and post-calibration were performed immediately before and after the sampling day using the same methods for area sampling. The PM_{10} inlet with an impactor disc was used to perform air monitoring during the five tasks. The SidePak took a sample every second and was set to log the data every minute.

Bulk Material Samples

Concrete dust mounds were created as each task was performed. Bulk material samples were collected and secured in a plastic sample bag for each of the five tasks so that the percentage of silica content could be determined from the material.

Environmental Data

Environmental conditions, such as wind velocity, relative humidity, and temperature were recorded every 30 minutes during the sampling day. 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.

Laboratory Analysis

The gravimetric area and bulk samples were analyzed by the Wisconsin Occupational Health Laboratory (WOHL), an American Industrial Hygiene Association (AIHA) accredited laboratory. The laboratory used the National Institute for Occupational Safety and Health (NIOSH) method 7500 for RCS (all forms) and NIOSH method 0600 for respirable dust. NIOSH method 7500 was also used to determine percent silica in the bulk samples.

Correcting for RCS Concentrations

The respirable dust concentration from the gravimetric area sample was compared to the mean SidePak respirable dust area air sampling data to derive a correction factor, which accounted for the SidePak underestimating respirable dust by a factor of 2.48. The correction factor was then multiplied by every respirable dust data point logged by the SidePak for each of the five tasks, resulting in the "corrected respirable dust" data. The percent silica from the bulk samples was multiplied by each corrected respirable dust concentration which resulted in a compilation of RCS concentrations for each task in real-time.

Statistical Analysis

Descriptive statistics (i.e., sample time, percent silica, mean, standard deviation, and range for both RCS and corrected respirable dust concentrations) for each of the five tasks were computed using Microsoft Excel 2013; plotted graphs were also created using Microsoft Excel 2013.

Results

The airborne concentrations of respirable dust measured by the co-located gravimetric and photometric samplers showed disagreement between the two sampling methods. The photometric instrument underestimated respirable dust by a factor of 2.48 compared to the gravimetric sampler (Table 4.1).

Table 4.1: Correction Factor Derived from Co-Located Gravimetric and Photometric Respirable Dust Concentrations

Gravimetric Sampling Respirable Dust Concentration (µg/m^3)	Photometric Sampling Mean Respirable Dust Concentration (µg/m^3)	Correction Factor
300	121	2.48

Based on the descriptive statistics for each of the five tasks (Table 4.2), the mean RCS concentrations ranged from 12 $\mu g/m^3$ for core drilling to 918 $\mu g/m^3$ for grinding. Although not directly comparable to the eight-hour OSHA PEL of 50 $\mu g/m^3$, the results suggest that dust controls were inadequate for grinding (918 $\mu g/m^3$) and dowel drilling (66 $\mu g/m^3$) if the OSHA PEL is used as a reference concentration for dust control performance. Further, jackhammering (27 $\mu g/m^3$) and cutting with a walk-behind saw (36 $\mu g/m^3$) were below the PEL when used as a reference for dust control performance, but both exceeded the OSHA AL of 25 $\mu g/m^3$. For employers who do not implement the OSHA Table 1, any tasks that are expected to generate silica exposures at or above the AL are required to be identified (Occupational Safety and Health Administration, 2017b). The results of the current study potentially identified silica exposures above the AL during four out of five tasks while using dust controls. The corrected respirable dust concentrations are included in Table 4.2 to demonstrate the significant concentration differences between respirable dust and RCS.

Table 4.2: RCS and Corrected Respirable Dust by Task

	Core Drilling	Grinding	Cutting with a Walk-Behind Saw	Jackhammering	Dowel Drilling
Sample Time (minutes)	14	40	24	30	26
% Silica	12	33	12	12	23
Mean RCS Concentration (μg/m^3)	12	918	36	27	66
Standard Deviation RCS Concentration (μg/m^3)	2.46	1,134.08	79.67	23.24	77.65
Range RCS	10 - 20	116 – 6,416	6 – 393	6 - 92	13 - 406
Mean Corrected Respirable Dust (μg/m^3)	98	2,782	302	227	288
Standard Deviation Corrected Respirable Dust (μg/m^3)	20.49	3,436.59	663.91	193.68	337.62
Range Respirable Dust	82-166	352 - 19,443	52 - 3,274	47 - 764	57 – 1,763

Real-time RCS concentrations were plotted to demonstrate the variability of exposure during task performance. Figures 4.1 through 4.5 show evident fluctuations in silica exposure, which may be due to human factors (e.g., hovering closely over the tool while performing the task) or other dust generating sources in proximity. Figure 4.1 illustrates a relatively constant exposure for core drilling with only one spike in RCS at the start of the task. Figure 4.2 suggests extremely variable exposures for grinding with one peak exceeding 6,416 μg/m^{3}and the lowest measurement at 116 μg/m^3; the lowest detected RCS concentration was still more than double the OSHA PEL when used as a reference value. The silica airborne concentrations measured during cutting with a walk-behind saw (Figure 4.3) was relatively constant with only four peaks above the mean RCS concentration. RCS exposure from jackhammering (Figure 4.4) was perhaps the most variable of all the tasks and was likely due to the stop and go nature of the task. The employee would frequently use the jackhammer and then stop to reposition or stretch his fingers. The plotted RCS concentrations for dowel drilling (Figure 4.5) show one major peak in RCS exposure which may have occurred when the employee was observed kneeling over the dowel drill.

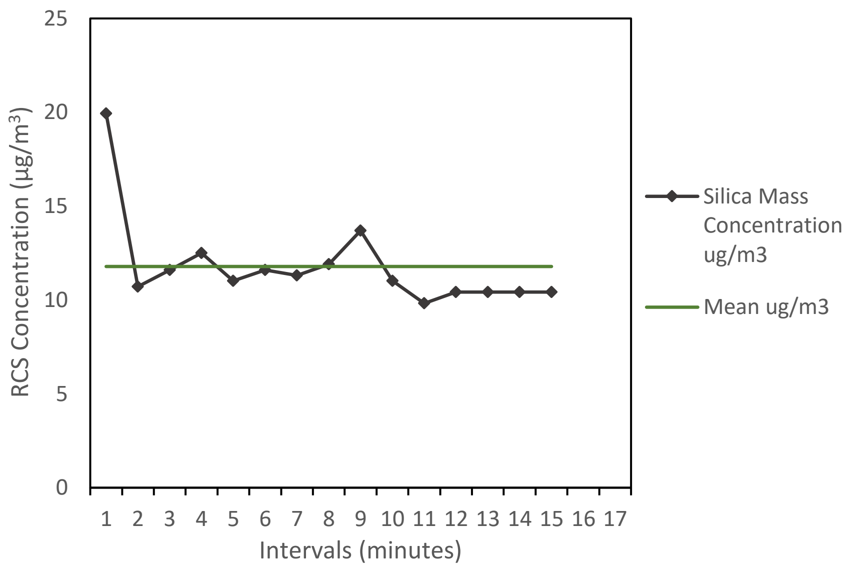

Figure 4.1: RCS Concentration (µg/m^3) in Real Time During Core Drilling Activity

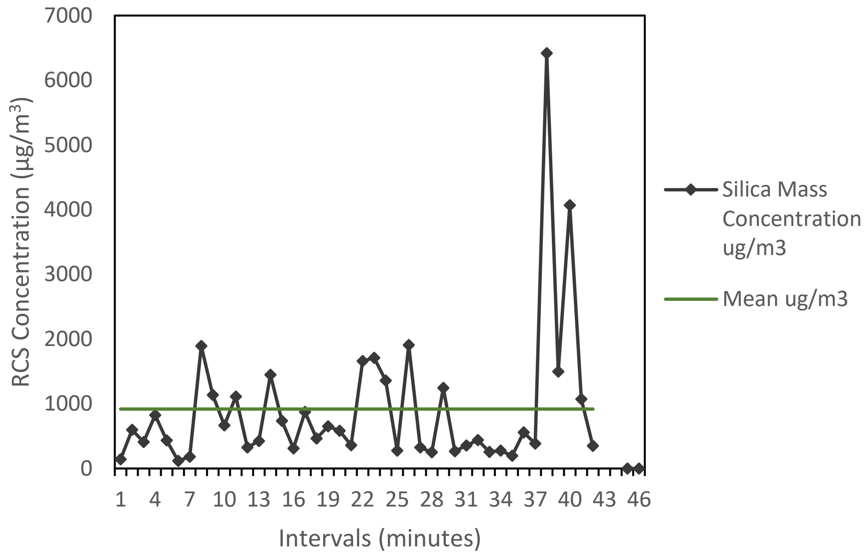

Figure 4.2: RCS Concentration (µg/m^3) in Real Time During Grinding Activity

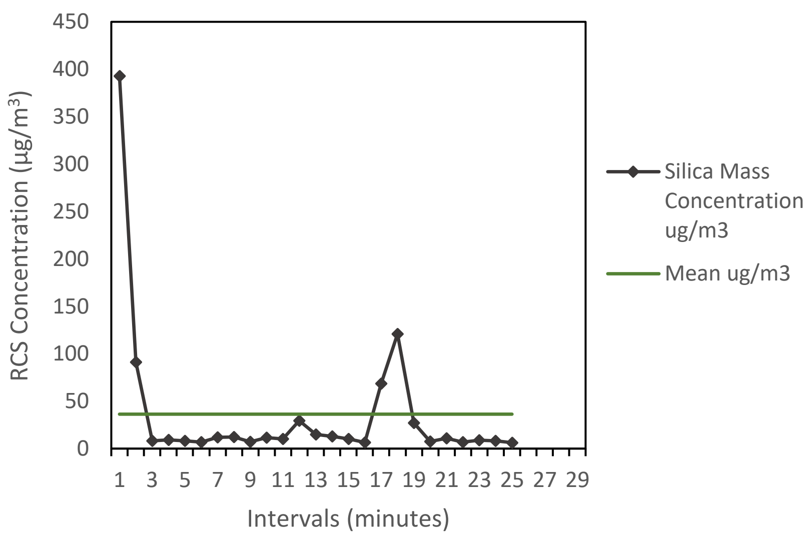

Table 4.3: RCS Concentration (µg/m^3) in Real Time During Cutting Activity

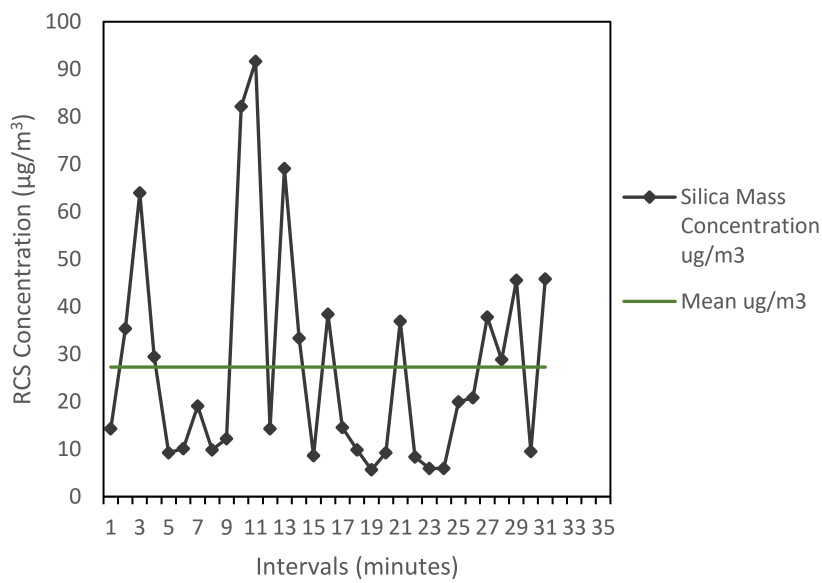

Figure 4.4: RCS Concentration (µg/m^3) in Real Time During Jackhammering Activity

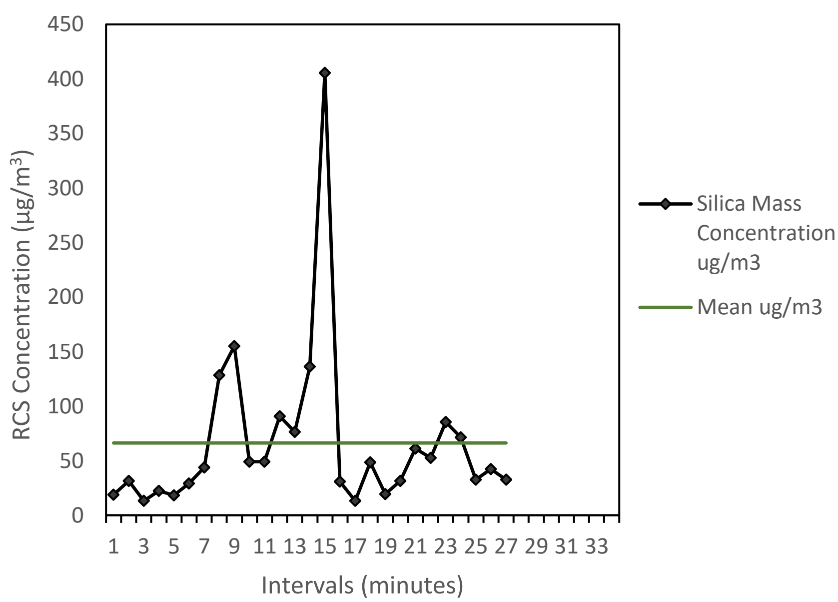

Figure 4.5: RCS Concentration (µg/m^3) in Real Time During Dowel Drilling Activity

Environmental conditions including wind speed, temperature, and relative humidity were recorded during the silica air sampling so that silica dust concentrations could be evaluated against environmental conditions. The temperature ranged from 71°F to 85°F and relative humidity from 23.20% to 40.15%. Core drilling and grinding were performed with wind speed conditions less than 1 m/s while cutting, jackhammering, and dowel drilling were performed at wind speeds greater 1 m/s.

Table 4.3: Environmental Conditions by Task

	Mean Wind Speed (m/s)	Mean Temperature (°F)	Mean Relative Humidity (%)
Core Drilling	0.34	71	40.15
Grinding	0.10	83	31.00
Cutting with a Walk-Behind Saw	1.01	85	24.45
Jackhammering	1.50	80	28.45
Dowel Drilling	1.74	82	23.20

Discussion

Area Monitoring

As presented in Table 4.1, the SidePak AM520 underestimated respirable dust concentration (mean = 121 $\mu g/m^3$) compared to the SKC PPI (300 $\mu g/m^3$). A correction factor of 2.48 was derived and applied to each respirable dust data point logged by the SidePak to account for this difference. Pahler et al. (2018) found that prediction of RCS was not similar for identical instruments, suggesting variability among samplers. The TSI SidePak AM520 is calibrated against a gravimetric reference using the respirable fraction of standard International Organization for Standardization (ISO) 12103-1, A1 test dust, which is representative of a wide variety of ambient aerosols (TSI, 2012). For a specific aerosol reading, TSI (2012) writes that the

SidePak must be adjusted according to a calibration factor for the predominate aerosol. It appears that calibration factors are situational and circumstance specific. Dacunto et al. (2013) found that mass median aerodynamic diameter (MMD), density and particle size influenced the magnitude of the correction factors used for indoor $PM_{2.5}$ sources in their study. For indoor sources, the authors found that as aerosol MMD increased so did the correction factor, and for ambient sources with MMD's below 1 um the correction factor decreased. Dacunto et al. (2013) concluded that the SidePak overestimated concentrations for indoor $PM_{2.5}$ sources if not corrected, and that correction factors increased when the aerosol MMD increased. The current study measured respirable dust using a SidePak with a PM_{10} inlet, compared to Dacunto et al. (2013) who used a $PM_{2.5}$ inlet to measure smaller particle sizes. The differences in particle sizes and MMD's collected by the photometric instruments between the two studies, may be suggestive of the reason why the current study's correction factor is larger than the range of correction factors (0.32-0.70) used in the Dacunto et al. (2013) study. Further, Shafie (2020) calculated a relatively large calibration factor (3.91) which was used for dolomite lime, indicating that calibration factors should not be compared across industries, aerosols and locations as the variability is substantial.

It is possible that some of the disagreement between the SKC PPI and SidePak dust area samples was due to the use of a PPI for the gravimetric method as opposed to a Dorr Oliver 10 mm nylon cyclone as recommended by TSI (2018), since the Dorr Oliver 10 mm nylon cyclone is used with the SidePak. As done in the current study, Shafie (2020) compared the SidePak to the SKC PPI but operated the PPI at a flow rate of 8.0 LPM as compared to the flow rate of 4.0 LPM used in the current study. The authors of the current study selected the SKC PPI, operated at a flow rate of 4.0 LPM, to collect a relatively large sample volume to reduce the risk of nondetectable samples. However, comparing different instruments at different flow rates can introduce bias, which may have led to disagreement between the instruments' respirable dust results.

Task-Specific Personal Air Monitoring

The computed RCS concentrations were derived from the corrected respirable dust concentrations for each task by multiplying the percentage of silica by the respirable dust concentration. Shafie (2020) expressed concern that the SidePak may not be a viable tool for monitoring silica dust in the construction industry due to the variability of silica content among materials. Rather than use a single silica percentage across all tasks, such as the 19% silica found in the gravimetric area sample, the researchers of the current study collected bulk material samples for each task so that percent silica used in the calculation was accurate for that material. The assertion made by Shafie (2020) was found to be true based on the results of the bulk material samples which showed a range of percent silica (12% to 33%). As illustrated in Figures 4.1 through 4.5, the plotted silica concentrations for each of the five tasks showed fluctuations in silica dust levels in real time. Silica concentrations for grinding, jackhammering and dowel drilling were relatively extremely variable throughout the sampling period, while silica concentrations from core drilling and cutting were relatively more constant. The 40-minute grinding airborne silica concentrations revealed a mean RCS concentration of 918 $\mu g/m^3$, nearly 19 times the PEL when used as a reference value. The mean RCS concentration for dowel drilling was also larger than the PEL when used as a reference value. Further, all tasks except for core drilling were above the AL when used as a reference value. As indicated earlier, photometric methods should not be used to determine OSHA compliance, however, the information can be used by employers to identify temporal spikes in exposure and to evaluate the performance of control methods. The grinding activity monitored in the current study was conducted while using OSHA Table 1 dust controls. The grinder was equipped with a shroud which was attached to the HEPA filter vacuum hose. Shafie (2020) found that 97.1% of vacuums sampled operated at less than 75% of their designed airflow and that vacuums of unknown age resulted in the highest predicted RCS exposures. The SidePak may be a potential tool for employers to use to identify controls that are no longer operating effectively.

The exposure profile on a construction site may change rapidly, which makes it difficult for employers to rely on integrated samplers for all of their data. By the time laboratory analysis turn around is complete, the exposure of interest may have passed. Employers require a method of investigating exposure that can target exposure potential in real time, allowing time-sensitive mitigative actions to be implemented at once. There are currently no direct reading instruments designed to monitor silica dust specifically. However, TSI, the manufacturer of the SidePak AM520, furnished a report which states that photometric monitoring for silica dust can be effective. While OSHA requires integrated sampling methods using gravimetric analysis to confirm compliance to the standard (Occupational Safety and Health Administration, 2016d), TSI (2018) suggested that photometric monitoring grants employers a cost-effective and time-effective means to assess exposure and act quickly. It should also be recognized that employers may have difficulty in collecting bulk samples for each material to determine the silica content. This poses barriers to using photometric instruments on construction sites where so many initial gravimetric or bulk samples would be required to accurately calculate RCS concentrations from respirable dust concentrations logged by the instrument. Employers applying a single correction factor and silica percentage to the calculations could grossly over or underestimate RCS from different materials.

Environmental Conditions

Statistical analysis could not be performed due to small sample size (each task was only monitored once). Akbar-Khanzadeh et al. (2002) found that that the concentration of silica dust was significantly ($p < 0.01$) lower when wind speed was greater than 1 m/s as compared to silica dust concentration when wind speed was less than or equal to 1 m/s. An observation of the mean silica concentrations among the five tasks showed wind speeds less than or equal to 1 m/s for core drilling and grinding and greater than 1 m/s for cutting, jackhammering and dowel drilling. While grinding concentrations were extremely high and occurred at wind speeds less than 1 m/s, dowel drilling concentrations were also above the PEL and occurred at wind speeds greater than 1 m/s which do not support the position of Akbar-Khanzadeh et al. (2002). However, when observing only one sample per task it is nearly impossible to suggest how environmental factors could have impacted the results.

Study Limitations

As noted by Shafie (2020) and Pahler et al. (2018) large sample sizes enhance the accuracy of the derived correction factor and the current study defined the correction factor from area monitoring performed once by co-locating a photometric instrument and gravimetric sampler. Another study limitation was the use of samplers with two different cut points. Rose and Cohrssen (2011) found that while the Dorr Oliver 10 mm nylon cylone initially had a 50% cut-point of 4.0 µm, as the sample period progressed to three hours the 50% cut-point changed to 3.5 µm. The SKC PPI has a 50% cut-point of 4 µm that closely fits the ISO standard 7708 particle collection efficiency curve. The SidePak and Dorr Oliver cyclone were co-located with the SKC PPI for 334 minutes, nearly double the three-hour sampling time that Rose and Cohrssen (2011) found the Dorr Oliver would depart from the curve. If 50% of the 3.5 µm sized particles penetrated the cyclone and 50% of the 4 μm sized particles penetrated the impactor (PPI), then the potential impact of this on the current study would be the under collection of 4 μm sized silica particles by the Dorr Oliver cyclone. Future studies should compare co-located methods by using a Dorr Oliver 10 mm nylon cyclone attached to both the SidePak and the personal air monitoring pump at the same flow rates to achieve a more reliable sample.

Conclusions

This study evaluated RCS exposure on a construction site during the performance of five OSHA Table 1 tasks by using a SidePak AM520 direct-reading instrument. The current study provides additional evidence that direct reading instruments can be useful in illustrating the variability of silica exposure over the task duration; and provide information relevant to the task and exposure potential in a manner that is more time effective than integrated sampling methods which require substantial turnaround time for results. The authors found that the plotted concentrations of silica dust as it fluctuates over the sample period may allow the observer to identify peaks in exposure and relate those RCS concentrations to worker behaviors or environmental conditions that may have contributed to the peak exposures.

It is recommended that future research collect more co-located gravimetric and photometric samples so that correction factors can be more accurately defined. In an effort to identify dust controls that are not effectively reducing RCS exposure, employers in the construction industry should consider implementing photometric air monitoring as a means of detection and exposure assessment to ensure workers are protected. The authors of the current study also believe that to date no methods have been created that are more effective or accurate at gauging exposure than gravimetric sampling methods, which should be implemented as the final confirmation of compliance.

CHAPTER 5

SUMMARY

Major Findings

This research was the first to assess the effectiveness of OSHA Table 1 specified dust controls in protecting construction workers from overexposure to RCS while conducting five tasks (i.e., core drilling, cutting with a walk-behind saw, grinding, dowel drilling, jackhammering). The investigation included personal silica air sampling to determine the RCS levels to which the construction workers were exposed and area silica air sampling to determine the contribution of background silica dust to personal exposure while performing the five OSHA Table 1 tasks. The 2016 silica standard for construction eliminates the requirement for employers to conduct silica air monitoring to determine compliance to the standard if they are implementing the specified dust controls and work practices. The typical gravimetric sampling method required by OSHA to assess exposure and confirm dust control effectiveness requires time-consuming and cost-inhibiting industrial hygiene sampling to be performed. Therefore, the researchers also aimed to evaluate a cost- and time-effective method for assessing RCS exposures and dust control effectiveness in real-time using a TSI SidePak AM520.

Specific Aim 1

The first objective of this study was to determine the RCS exposure of construction workers performing five OSHA Table 1 tasks at a northern Colorado construction site and to assess dust control effectiveness in reducing exposures below the OSHA AL and PEL. SKC PPI's were used to estimate exposure and the silica exposure measurements were analyzed to determine if workers were exposed to silica dust above the OSHA AL of 25 μg/$m^3$and the PEL of 50 μg/m^3.

Results

To compare the silica sampling results to the OSHA Table 1 distinctions of less than four hours and greater than four hours of exposure for specified tasks, the measured exposures were extrapolated into two categories of eight-hour time weighted averages (TWA): 1) eight-hour TWA's assuming that the task continued for a full shift (i.e., measured exposures were extrapolated to eight hours), and 2) eight-hour TWA's assuming that the task were to stop after four hours (i.e., measured exposures were extrapolated to four hours and assumed no exposure for an additional four hours). Of the construction workers sampled, 47.1% were exposed over the AL of 25 μg/m^3 and 29.4% were exposed over the PEL of 50 μg/m^3 for an eight-hour TWA if the task were performed for eight hours. If the tasks stopped after four hours and did not commence again for the remainder of the shift, then 29.4% of workers sampled were exposed over the AL and 15.7% were exposed over the PEL. Workers overexposed to RCS may be at an increased risk of developing respiratory issues and other serious silica-related illnesses. A total of 51 personal air monitoring silica samples were collected over a period of 13 days (July 2020 – November 2020), with an average sample time of 127 minutes (range: 18 minutes to 240 minutes). The mean silica concentration for all samples was 85 μg/m^3 (standard deviation [SD] = 176.2). The mean silica concentration for the five tasks include: core drilling 11.2 μg/m^3 [5.31], cutting with a walk-behind saw 126 μg/m^3 [115], dowel drilling 99.9 μg/m^3 [58.7], grinding 172 μg/m^3 [145], and jackhammering 23.2 μg/m^3 [5.19]. Factors recorded included: task, location, controls used, respiratory protection, and environmental data. Wind speeds were assessed to determine if silica concentrations were influenced by this environmental condition. A two-sample t-test on log-transformed RCS concentrations showed that the mean silica dust concentration (Mean[SD] 1.54 $\mu g/m^3$ [0.67]) at wind speeds less than or equal to 1 m/s was significantly ($p < 0.01$) greater than the mean silica dust concentration (Mean[SD] 1.01 $\mu g/m^3$ [0.41]) at wind speeds greater than 1 m/s. Further, a two-sample t-test was also performed to assess the significance of location on RCS concentrations, which revealed a significant difference ($p < 0.01$) between the mean of silica concentrations (Mean[SD] 1.10 $\mu g/m^3$ [0.44]) outside and the mean of silica concentrations (1.62 $\mu g/m^3$ [0.70]) in partially enclosed environments. Lastly, a multiple linear regression was performed to assess whether a relationship existed between silica dust concentrations and the predictor variables location, task, temperature, and relative humidity. The regression showed that relative humidity was not statistically significant ($p > 0.05$) but temperature ($p = 0.002$) was, and that RCS concentrations were higher during the cooler months and lower during the warmer months. The regression also showed a significant relationship between RCS and location ($p < 0.001$) and task ($p = 0.001$).

Specific Aim 2

The second objective of this research was to determine if background silica dust contributed to personal RCS exposure during the five OSHA Table 1 tasks. Overexposure to RCS while using dust controls has been identified by past research. The researchers of the current study aimed to investigate background silica dust as a potential contributing factor that increases personal RCS exposure above the PEL. A total of 15 area silica samples were collected in tandem with the personal task-based silica samples with an average sampling time of 187 minutes. At least one area sample was collected on each of the 13 sampling days. SKC PPI's and Zefon Escort ELF personal air sampling pumps were positioned on the construction site to collect area silica samples.

Results

Of the 15 area silica samples, only four were greater than the laboratory reporting limit of 5,000 ng (5 μg). The four area silica samples revealed background silica concentrations of 23 $\mu g/m^3$, 5 $\mu g/m^3$, 40 $\mu g/m^3$, and 100 $\mu g/m^3$. Due to data censoring (i.e., non-detects) in the area samples (73.3%), there was not a sufficient number of data points to determine with statistical certainty if silica background concentrations significantly contributed to worker exposure. However, the four measurable background silica samples may have contributed to worker exposure since 14 of the 15 personal samples that exceeded the PEL occurred on the four days when the background silica levels were measurable.

Specific Aim 3

The third objective of this study was to assess RCS concentrations in real time using the TSI SidePak AM520. Task-based direct air monitoring using a TSI SidePak AM520 personal aerosol monitor was performed on the northern Colorado construction site during five tasks from the OSHA Table 1. Each task was sampled once; sample time ranged from 14 minutes to 40 minutes, with a mean sample time of 27 minutes. Prior to task-based air monitoring, the TSI SidePak AM520 with a Dorr Oliver 10 mm nylon cyclone (operated at 1.7 LPM) and a Zefon Escort ELF personal air sampling pump with an SKC PPI (operated at 4.0 LPM) were co-located on the construction site for 334 minutes to measure the area respirable dust concentration. The SKC PPI was co-located with the TSI SidePak AM520 so that an aerosol-specific correction factor (2.48) could be determined by applying the results from the integrated sampling device (i.e., PPI) to the TSI SidePak results. Bulk material samples were collected during the performance of the five tasks so that percent silica could be determined in the material. The calculated RCS concentrations from the corrected TSI SidePak results were plotted so that exposure fluctuations could be viewed graphically. The purpose of measuring RCS concentrations with the SidePak was to observe the silica concentrations variability that occurs within a task and to determine the effectiveness of dust controls.

Results

A comparison of respirable dust collected by the SKC PPI to the TSI SidePak AM520 showed that the direct reading instrument underestimated the concentration of respirable dust, which was corrected using the calculated correction factor (2.48). The mean silica dust concentrations (μg/m^3) (standard deviation [SD]) for the five tasks computed from the SidePak respirable dust concentrations include: core drilling 12 μg/m^3 [2.46], grinding 918 μg/m^3 [1134.08], cutting with a walk-behind saw 36 μg/m^3 [79.67], jackhammering 27 μg/m^3 [23.24], and dowel drilling 66 μg/m^3 [77.65]. The results of the direct reading TSI SidePak sampling suggest that dust controls for grinding and dowel drilling were ineffective in controlling RCS exposure. The large standard deviations also confirmed that RCS concentrations were variable throughout task performance.

Limitations

Personal air monitoring was limited to the number of pre-scheduled sampling dates that the construction company could host from July 2020 to November 2020, which resulted in a small sample size. The study was also limited by the length of time the tasks were performed, resulting in non-detects within the dataset. Ideally, larger sample sizes and full-shift eight-hour sample periods would increase the power of the statistics, as well as reduce the number of non-detects that bias the results. A major limitation was extrapolating exposures to an eight-hour shift when none of the samples were monitored for more than four hours. When comparing to an eight-hour occupational exposure limit, it is best practice to capture full-shift samples. Collecting small sample volumes was a limitation due to the use of SKC PPI's that operated at a flow rate of 2.0 LPM. Using higher flow PPI's at 4 or 8 LPM would have better accommodated the short sampling times and increased the mass of contaminant in the samples. Employees that were monitored more than once in one sampling day for different tasks also introduces bias. Further, variability within similar exposure groups, likely due to differences in location, controls used, and environmental conditions, contributes to bias in the descriptive statistics.

Similarly, the area samples were collected using SKC PPI's that operated at flowrates of 2.0 LPM, resulting in 73.3% non-detects. High flow samplers would have been more effective at capturing additional silica mass when performing area silica monitoring. Small sample size inhibited the researchers from using a statistical model such as maximum likelihood estimation (MLE) to account for the censored data. This resulted in the greatest limitation, which was the inability to perform statistical analysis, but rather rely on observations to assess the contribution of background silica dust to personal RCS exposure while employees performed the five OSHA Table 1 tasks.

A limitation of the SidePak RCS analysis was due to the different samplers used. TSI Incorporated recommends that a Dorr Oliver 10 mm nylon cyclone be used for both the SidePak and with the personal air sampling pump for the co-located air monitoring. Instead, an SKC PPI was used and operated at a flow rate of 4.0 LPM compared to the Dorr Oliver cyclone which was operated at 1.7 LPM. Rose and Cohrssen (2011) indicated that the Dorr Oliver cyclone deviates from the ISO standard 7708 particle collection efficiency curve as the sampling period continues, resulting in a 3.5 μm cut-point as opposed to a 4 μm cut-point. The potential differences in the cut-points between the the Dorr Oliver cyclone and the SKC PPI could result in the cyclone undercollecting silica particles larger than 3.5 μm. Another potential limitation is that co-located sampling was only performed once. While TSI Incorporated does not indicate that multiple co-located samples are required, a larger sample size would increase the accuracy of the derived correction factor.

Contribution to the Field

This research identified an area of concern in the construction industry. Employers following the OSHA Table 1 specified dust control measures and work practices are not required to conduct silica air monitoring to confirm compliance to the OSHA silica construction standard. Foregoing air monitoring to determine RCS exposure ignores the potential for faulty equipment and dust control measures that would otherwise be identified through sampling. The results of the personal air monitoring RCS concentrations extrapolated to an eight-hour shift revealed that 15 of 51 employees monitored had the potential to be exposed above the OSHA PEL. Even when extrapolating the personal air monitoring RCS concentrations to a four-hour period (using the assumption that the no further exposure occurred for the remaining four hours of the shift) eight of 51 employees monitored had the potential to be exposed above the OSHA PEL. The identification of these potentially overexposed construction workers suggest that silica air monitoring is still necessary to identify ineffective dust controls and inform the need for respiratory protection.

Future Research Opportunities

The results from this research suggest that dust controls were not always effective at preventing overexposure to RCS. Previous researchers have conducted task-based silica air sampling, but typically these studies are focused on one specific task and the study is conducted in a controlled environment. Field analysis presents many sampling difficulties, but there is a major gap in silica exposure research regarding field studies and the personal exposures observed during construction activities. Further, there are still 13 remaining OSHA Table 1 tasks that should be studied to determine the exposure potential for employees conducting those tasks. Future research should collect larger sample sizes and control for variability among different locations and environmental conditions. Researchers conducting task-based air sampling should consider high flow samplers to reduce non-detects in the dataset. A more comprehensive dataset could include more observations about surrounding sources of dust generation (i.e., track haul trucks and heavy equipment moving on the construction site, and nearby workers performing other dust generating tasks) and a detailed investigation into the dust control measures used (i.e., document HEPA filter vacuum age, condition, and airflow; assess water flow from wet methods to determine if enough water is being used to adequately wet the substrate). More research should be conducted using photometric instruments to better assess their effectiveness as a tool for measuring RCS in the construction industry. Dust controls must be assessed to determine efficiency and future studies using photometric instruments to assess controls could further validate or disprove this method as an acceptable exposure monitoring tool for the construction industry.

Perhaps the most needed research is the collection of sampling data regarding background silica dust concentrations and whether it significantly contributes to personal exposure while workers perform Table 1 tasks. Can background silica dust concentrations contribute to personal exposures significantly enough that it has the potential to drive exposures above the OSHA PEL? There are still many unknowns. Task-specific dust controls cannot account for silica dust present in the background air, potentially leaving a source of exposure completely uncontrolled.

Conclusions

It is estimated that two million workers in the construction industry are exposed to RCS. The 2016 OSHA silica standard for construction eliminates the requirement for employers to perform air monitoring if specified dust controls and work practices are implemented, which may now make it difficult to identify workers at an increased risk of developing silica-related illnesses. Conversations with construction workers in the current study revealed that many had been working in the industry since their teenage years, which could result in the genesis of negative health outcomes at an earlier age. Of participants in the current study, 47.1% were exposed to RCS above the AL and 29.4% were exposed to RCS above the PEL when samples were extrapolated to a full eight-hour shift. While dust controls were used for each task in this study, these sampling results suggest that a reliance upon dust controls measures to reduce RCS exposure effectively in all cases is unreasonable.

The researchers' investigation into RCS exposure variability throughout a sample period using a photometric instrument showed that dust concentrations fluctuate significantly throughout task performance. Future researchers should study peaks in exposure and determine root causes by comparing the time of the peak exposure to other factors (i.e., employee leaning closer to the equipment, haul trucks passing by, poor wind activity, etc.) The SidePak data further confirmed the need for more research into the effectiveness of dust controls, as grinding and dowel drilling RCS concentrations (918 $\mu g/m^3$ and 66 $\mu g/m^3$) were above the OSHA PEL when used as a reference. This finding may create a difficult choice for employers in the construction industry as air monitoring can be a cost and time inhibitive requirement. However, it is necessary in identifying high risk groups in multi-variable construction environments.

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