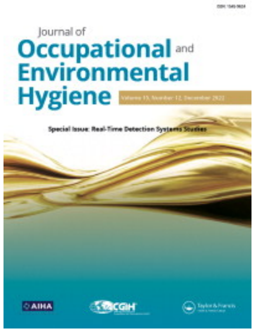

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Benefits and limitations of field-based monitoring approaches for respirable dust and crystalline silica applied in a sandstone quarry

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ABSTRACT

With the advent of new sensing technologies and robust field-deployable analyzers, monitoring approaches can now generate valuable hazard information directly in the workplace. This is the case for monitoring respirable dust and respirable crystalline silica concentration levels. Estimating the quartz amount of a respirable dust sample by nondestructive analysis can be carried out using portable Fourier transform infrared spectroscopy (FTIR) units. Real-time respirable dust monitors, combined with small video cameras, allow advanced assessments using the Helmet-CAM methodology. These two field-based monitoring approaches, developed by the National Institute for Occupational Safety and Health (NIOSH), have been trialed in a sandstone quarry. Twenty-six Helmet-CAM sessions were conducted, and forty-one dust samples were collected around the quarry and analyzed on-site during two events. The generated data generated were used to characterize concentration levels for the monitored areas and workers, to identify good practices, and to illustrate activities that could be improved with additional engineered control technologies. Laboratory analysis of the collected samples complemented the field finding and provided an assessment of the performance of the field-based techniques. Only a fraction of the real-time respirable dust monitoring sessions data could be corrected with laboratory analysis. The average correction factor ratio was 5.0. Nevertheless, Helmet-CAM results provided valuable information for each session. The field-based quartz monitoring approach overestimated the concentration by a factor of 1.8, but it successfully assessed the quartz concentration trends in the quarry. The data collected could be used for the determination of a quarry calibration factor for future events. The quartz content in the dust was found to vary from 14% to 100%, and this indicates the need for multiple techniques in the characterization of respirable dust and quartz concentration and exposure. Overall, this study reports the importance of the adoption of field-based monitoring techniques when combined with a proper understanding and knowledge of the capabilities and limitations of each technique.

KEYWORDS
Direct-reading; quarry; real-time monitors

Introduction

The exposure to respirable dust containing crystalline silica (RCS) is a recognized occupational hazard. Acute and chronic diseases, including chronic obstructive pulmonary disease (COPD), silicosis, and lung cancer, are associated with prolonged exposure to RCS in the workplace (NIOSH 2002; Gamble 2011; Leung et al. 2012; Turci et al. 2016). The generation of airborne dust with variable crystalline silica content is common in mining (Cauda et al. 2013) and is associated with many activities—from drilling and blasting the ore for extraction to transferring, transporting, and unloading the material to crushing, screening, and processing the material into product (NIOSH 2019).

The aggregates industry represents a sector of the mining industry, and quarries are present in every state extracting limestone, sand and gravel, granite, sandstone, and other products. Most quarries typically have 20 or 30 workers on site organized in shifts, and an industrial hygienist or health and safety professional is on-site only periodically. From a hierarchy of controls perspective, dust-free activities are challenging in mining. For this reason, mine operators generally focus on engineering and administrative controls.

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Effective engineering controls have been designed, tested, and implemented in the metal/nonmetal mining industry. Adjustments to the way miners operate to prevent high exposure are also seen as effective, especially as the result of worker empowerment and increased awareness (Haas et al. 2016; NIOSH 2019). Monitoring the exposure of workers and concentration of the hazard in the workplace is essential.

The Mine Safety and Health Administration (MSHA) has a permissible exposure limit (PEL) for respirable dust containing crystalline silica in metal and nonmetal mines. The PEL is adjusted for the presence of RCS by lowering the value as the RCS content increases. Based on the formulaic approach, the resulting RCS Time-weighted Average (TWA) PEL is 100 milligrams of RCS per cubic meter of air (μg/m^3). The National Institute for Occupational Safety and Health (NIOSH) has an established recommended exposure limit (REL) of 50 μg/m^3 time-weighted average for up to 10 hours per day during a 40-hr week (NIOSH 2002). OSHA permissible exposure limits do not apply in mining operations.

In addition to monitoring approaches based on the collection of a representative respirable dust sample and subsequent laboratory analysis, complementary monitoring techniques can be considered by industrial hygienists since they can provide additional layers of information or they can generate results immediately at the worksite, as is the case of field-based approaches. Field-based techniques can use direct-reading methodologies, which can be defined as techniques that can provide in the field a measurement directly when needed, or real-time monitors, that have sensors that can provide time-resolved information on the concentration of a hazard in the workplace; this information is not achievable with methods requiring laboratory analysis.

Real-time respirable dust monitors have been used for occupational health and safety for a few decades. Most monitors use the interaction of a source of light and dust particles to perform the analysis, and they can be called variously: light-scattering monitors, photometers, nephelometers, optical dust monitors, or optical particle counters (NIOSH 1994). The challenges related to the accuracy of the real-time respirable dust monitors for mass concentration measurement have been presented in several studies (Benton-Vitz and Volckens 2008; Soneja et al. 2014; Halterman et al. 2017; Patts et al. 2019; Zuidema et al. 2019), where the measurement can be affected by the characteristics of the dust monitored, environmental conditions, and other factors. On the other hand, these monitors are small, light, and use a relatively simple sensing technology. A recent laboratory study has investigated the effect of different dusts present in mining operations on the factor or ratio needed to calibrate real-time respirable dust monitors (Patts et al. 2019). Among commercially available options, only one real-time respirable dust monitor, the Personal Dust Monitor (PDM3700, Thermo Fisher), employs a direct mass measurement as a sensing technique. The personal dust monitor (Volkwein et al. 2004, 2006; Mischler et al. 2019) has been adopted by MSHA to ensure compliance to a respirable dust rule in coal mines. The cost, size, and weight of this monitor make it infeasible for adoption outside coal mines.

NIOSH started investigating video exposure monitoring (VEM) in combination with real-time dust monitors in the 1980–1990s (Gressel et al. 1988; NIOSH et al. 1992). More recently, with the development of small, portable, and inexpensive video cameras, the NIOSH Mining Program has developed the Helmet-CAM to conduct assessments using a real-time data logging monitor in conjunction with a video camera (NIOSH 2014). In order to combine and analyze the outputs from the monitor and the camera, NIOSH has developed the Enhanced Video Analysis of Dust Exposure (EVADE) software (version 2.4, NIOSH, Pittsburgh, PA). The EVADE software merges the dust and video data and allows the user to utilize multiple analysis tools to identify work areas and specific tasks that were being performed when the worker was exposed to elevated levels of respirable dust. Since 2013, NIOSH has conducted numerous Helmet-CAM studies at mining operations to determine workers' exposures to respirable dust and to identify effective controls to reduce those exposures (Cecala et al. 2013, 2015, 2017; Haas and Cecala 2017). As a result of these studies, several common sources of dust exposure were identified, and several workplace modifications and control technologies were developed.

Currently, efforts are in progress for the development of methodologies that can lead to real-time RCS monitoring (Wei et al. 2017; Zheng et al. 2018). The focus of these efforts has been on improving the sensitivity of analytical techniques employed by the devices and the miniaturization of the sensors and components. To bridge the gap from the laboratory to the field, the NIOSH Mining Program has developed a field-based rapid quartz analysis approach (Miller et al. 2012; Cauda et al. 2016; Chubb and Cauda 2021a): this direct-reading methodology generates RCS concentration data (only in terms of alpha quartz) in the field at the end of a sampling event. This monitoring approach uses a portable FTIR instrument, and the data are analyzed with the NIOSH Field Analysis of Silica Tool (FAST) software (version 1.08, NIOSH, Pittsburgh, PA). The collection of a respirable dust sample can be done with established conventional respirable cyclones (Cauda et al. 2014) and the use of dedicated sampling cassettes (Chubb and Cauda 2021b), which facilitates the analysis of the sample in the field. Since the field-based analysis is nondestructive, the same samples can be also sent to a laboratory for analysis. The results generated by the field-based RCS monitoring approach are well-correlated with the laboratory analysis results (Cauda et al. 2016, 2018; Hart et al. 2018), but the field results can be affected by the presence of other minerals (Cauda et al. 2018; Hart et al. 2018). The creation of a site-specific correction factor has been proposed to address the issue, and this can be developed in the NIOSH FAST software.

This manuscript summarizes the finding of a study aimed to collect field evidence on the benefits and limitations of two field-based monitoring approaches developed by the NIOSH Mining program for respirable dust and crystalline silica, specifically quartz. The objective of the manuscript is to encourage the knowledgeable adoption of the technologies by operators in the mining industry and other workplaces.

Methods

The field data collection was performed in October 2018 and July 2019 at a surface sandstone quarry in Pennsylvania. NIOSH researchers used monitoring approaches for respirable dust and RCS adopting a strategy described below. During the two events, the activities lasted for three shifts over two days and three shifts over three consecutive days, respectively.

Structure of the quarry

The quarry is a typical small operation in the aggregates industry in the United States where ore is excavated from drilling and blasting in an open pit, the material is hauled, crushed, segregated, and processed in a plant, and finally, stockpiles are formed so that material is ready to be loaded into customers' trucks. Three areas of the quarry were identified. The first dry area (area1) included the open pit, the crushers, and transfer points, and the areas where customers' trucks are loaded. The second area (area2) included the wet plant and its control booth. This area is wet and muddy even in the dry season since a water-based chemical solution is first added to the screened material and then removed to separate undesired fine particles from the products. Finally, a third area (area3) included maintenance shops, offices, and the quality control (QC) laboratory, where an analyst analyzed small rock samples. Around 20 people were working at the quarry, including loader and haulage truck operators, press operators, foremen, plant manager, and utility workers.

Helmet-CAM

Each Helmet-CAM package consisted of a factory-calibrated pDR1500 real-time dust monitor (Thermo Fisher Scientific, Waltham, MA), a video camera, and a Camelbak LOBO backpack. The pDR1500 monitor, operated at 1.7 liters per minute (lpm), included a Dorr-Oliver cyclone (Zefon Intl., Ocala, FL) as a preselector for respirable dust. Tubing made of conductive material transferred the respirable dust from the cyclone to the monitor. A new pre-weighed 37-mm, 5-µm pore size polyvinyl chloride (PVC) filter was used inside the pDR1500 filter holder for each session. The real-time monitor was set up to record data with a frequency of 30 data points/minute.

The video cameras were the point-of-view Contour Roam3 (Contour, LLC). The settings used in this study were 720 pixels (p)/30 frames per second (fps). The camera recorded a stream of images in front of the miner or front of the enclosed cab when strapped on the dashboard of the vehicle.

Time-integrated samples

Time-integrated dust samples were collected uniquely as area samples using GK2.69 cyclones (Mesa Labs, Lakewood, CO) operated at 4.2 lpm (Lee et al. 2010; Stacey et al. 2014). The flow rate during sampling was maintained by SKC AirChek Touch pumps (SKC Inc., Eighty-Four, PA) and verified before and after sampling using a Defender 510 calibrator (Mesa Labs, Lakewood, CO). Respirable dust samples were collected on pre-weighed 37-mm, 5-µm pore size, PVC filter media housed in 4-piece cassettes made of conductive material and optimized for direct-on-filter analysis with portable FTIR (Chubb and Cauda 2021a) (Zefon Intl., Ocala, FL).

Sampling strategy

Helmet-CAM sessions and time-integrated samples were collected around the quarry. Helmet-CAM sessions lasted between 90 min and 4 hr, and time-integrated samples were collected between two hours and 7 hr. Helmet-CAM sessions were conducted inside enclosed cabs of machines (12 sessions), inside the plant control booth (two sessions), or with equipment kits worn by mobile workers (12 sessions). Between three and five Helmet-CAM sessions were conducted for every shift. Time-integrated samplers (41 samples) were deployed as area samples on moving machines outside the enclosed cabs, around the primary crusher, around the wet plant, and inside the QC laboratory. Between 12 and 15 time-integrated samplers were used for every shift. The selection of the location for the time-integrated samplers and the workers for the Helmet-CAM sessions was totally independent and no co-location was pursued. The goal of the study was not a comparison between different monitoring approaches.

Analysis

The RCS mass in the samples collected by the time-integrated samplers was estimated in the field using portable FTIR units. During the first event, samples were analyzed by using a Perkin Elmer Spectrum 2 FTIR (Perkin Elmer, Waltham, MA), while a Nicolet iS 5 FTIR (Thermo Fisher Scientific, Waltham, MA) was used in the second event. The capability of both instruments to provide comparable results has been reported in a recent study (Ashley et al. 2020). The direct-on-filter analysis of RCS in respirable dust samples using a portable FTIR is described in more detail elsewhere (Miller et al. 2012; Cauda et al. 2016, 2018; Chubb and Cauda 2021a). For each sample, the NIOSH FAST software estimated the RCS concentration. The limit of quantification for the field-based analysis is reported to be 13 µg when the GK2.69 cyclone is used (Cauda et al. 2016). The software reports RCS results assuming that alpha quartz is the only crystalline silica polymorph present in the dust. In the field, NIOSH researchers also estimated the RCS in dust samples collected by the filters in the pDR1500 units. The filter samples, still inside the pDR1500 filter holder, were analyzed using portable FTIR units. A 3D printed 37-mm washer, with a central hole 9 mm in diameter, was used to support the PVC filter in the holder. The estimated limitation of quantification for the field-based RCS analysis for samples collected with the pDR1500 is 2 µg.

All filters were conditioned and weighed before and after sampling at NIOSH in a controlled environment kept at $22 \pm 0.7\,^{\circ}C$ and $50 \pm 2\%$ relative humidity using a microbalance (XP6, Mettler Toledo, Columbus, OH) with a precision better than 5 µg. The limit of quantification (LOQ) for the gravimetric analysis was calculated as five times the standard deviation of the laboratory blanks (10% of the entire set). The samples were then analyzed for RCS using the NIOSH 7500 method (NIOSH 1994) at an accredited laboratory (Bureau Veritas North America). To assure proper comparison with the field-based analysis, the dust on the walls of the cassettes was not accounted for in the analysis. The laboratory analysis provided sample-by-sample quantification for respirable dust concentration, RCS concentration, and RCS content (%RCS) in the respirable dust samples.

Each Helmet-CAM session was investigated with the EVADE software. The main results were discussed with the quarry crew in the field. In addition, a systematic analysis of each session was conducted to extract information. The first step of the systematic analysis was the identification of episodes of interest for the session: these episodes were categorized by concentration level higher than 10 times the baseline for the session. There is no reference for the 10 times rationale, but the intention was the identification of episodes characterized by a concentration level substantially higher than the baseline. The rationale is at the discretion of the professional. The second step was the definition of variables of interest to characterize each episode. Three variables were defined: (1) location in the quarry when the episode occurred; (2) whether the worker was inside an environment retrofitted with a ventilation and filtration system; and (3) the specific activity of the worker. The final step of the analysis assigned values to each variable for each specific episode of interest by counting them. The goal of the analysis is to assess the occurrence of episodes characterized by three variables of interest.

Results

The field review of each Helmet-CAM session allowed the identification of activities and work areas characterized by elevated dust concentration levels. After reviewing the results with the worker, it was possible to document good practices and identify behaviors and engineering controls that could reduce dust exposure. In one case, the Helmet-CAM session of a haul truck driver who delivered ore from the quarry to the primary crusher located at the processing wet plant recorded a reoccurring trend of elevated dust concentration events. It was determined that the truck driver was being exposed to higher levels of dust as

Table 1. Synopsis of the systematic analysis of 122 episodes identified during 26 Helmet-CAM sessions collected during the study.

	Area 1		Area 2		Area 3	
	Inside	Outside	Inside	Outside	Inside	Outside
Dumping	2				5	
Screening					8	
Walking				16	3	1
Washing					2	
Clothing					1	
Door closing			1			
Driving	39		3			
Shoveling	3			1		
Standing	1					
Smoking				11		
Mucking	9					
Typing					1	
Welding				15		
Total	54		47		21	

he entered and left the pit, in the same location each time. After investigating that area and with the help of the truck driver, it was determined that drilling was occurring on a bench near the entrance of the quarry. The driver was most likely exposed to the dust generated from the drilling operations while driving past.

The systematic analysis of the 26 Helmet-CAM sessions, as described in the methodology section, returned 122 episodes of interest for high concentration levels of respirable dust (Table 1). Each episode was analyzed in terms of location in the quarry (area1, area2, and area3), whether the worker was inside a retrofitted environment (inside, outside), and the specific activity of the worker. The data from every episode was aggregated. The episodes occurred in every area of the quarry with a higher prevalence in area1 and area2. Episodes occurred both inside enclosed cabs and environments and outside and during a large variety of activities.

The dataset collected by the 26 Helmet-CAM sessions, 15 sessions for the first sampling event and 11 for the second sampling event, are displayed as a box chart in Figure 1. Investigating the relative Rankit plots (not displayed) for normality, the data for each session have been identified to fit log-normal distributions. For each set, the plot shows the median, the geometric mean, the 25%–75% quartile interval, and the range within 1.5 standard deviations. The label for each set was used to characterize the worker or location associated with the specific session, and the same labels were maintained during both events (for example Driver A). Descriptive statistics on the data relative to the Helmet-CAM sessions are summarized in Table 2. For each session, the arithmetic mean (AM), the geometric mean (GM), and the geometric standard deviation (GSD) for respirable dust concentration have been calculated. The arithmetic means ranged from 0.4 $\mu g/m^3$ to 208.9 $\mu g/m$,^{3} the GM ranged from 0.9 $\mu g/m^3$ to 98.5 $\mu g/m$,^{3} and the geometric standard deviation from 1.5 $\mu g/m^3$to 5.9 $\mu g/m$.^{3}

The samples collected inside the pDR1500 real-time respirable dust monitors were also analyzed in the field for RCS. Ten samples collected during the first event (out of 15 total), and six samples collected during the second event (out of 11 total), showed levels above the LOQ for the analysis with the portable FTIR instrumentation. For these samples, it was also possible to estimate the %RCS in the respirable dust.

The time-integrated samples, collected in different areas of the quarry, were analyzed for RCS concentration using the field-based RCS monitoring approach. For the 18 samples collected during the first event, 11 samples showed quartz levels above LOQ. For the 23 samples collected during the second event, 15 samples were above LOQ for the field-based analysis. A synopsis of the results as they were generated in the field is provided in Table 3. Notably, the RCS concentration levels varied from 17.4 $\mu g/m^3$ to 1726 $\mu g/m^3$ in the first event in October 2018, and from 13.5 $\mu g/m^3$ to 694.5 $\mu g/m^3$ in the second event in July 2019. The results are organized based on the area where the samples were collected and with information on the specific location.

Upon return to the NIOSH laboratories, the samples collected inside the pDR1500 monitors were analyzed to determine the mass collected on the filter. For both events, the LOQ for the gravimetric analysis was determined to be 23 µg. For the first event, 10 samples (out of 15 Helmet-CAM sessions) presented respirable mass above the LOQ. For the second event, three samples (out of 11 Helmet-CAM sessions) presented respirable mass above the LOQ. For the samples above LOQ collected in the second event, the results were corrected with the average field blank result. The average mass for the field blank for the first event was substantially lower than the LOQ and no correction was applied. For all the samples above LOQ, the corresponding average respirable dust mass concentration values were determined and compared with results obtained in the field and a summary of this comparison is presented also in Table 2. For the samples with a gravimetric measurement below LOQ, the concentration result was reported as "less than."

All the respirable dust samples collected were sent to an accredited laboratory (Bureau Veritas North America, Inc., Novi, MI) for the quantification of RCS with the NIOSH 7500 method. Out of 41 area samples collected with GK2.69 cyclones, 18 samples had RCS

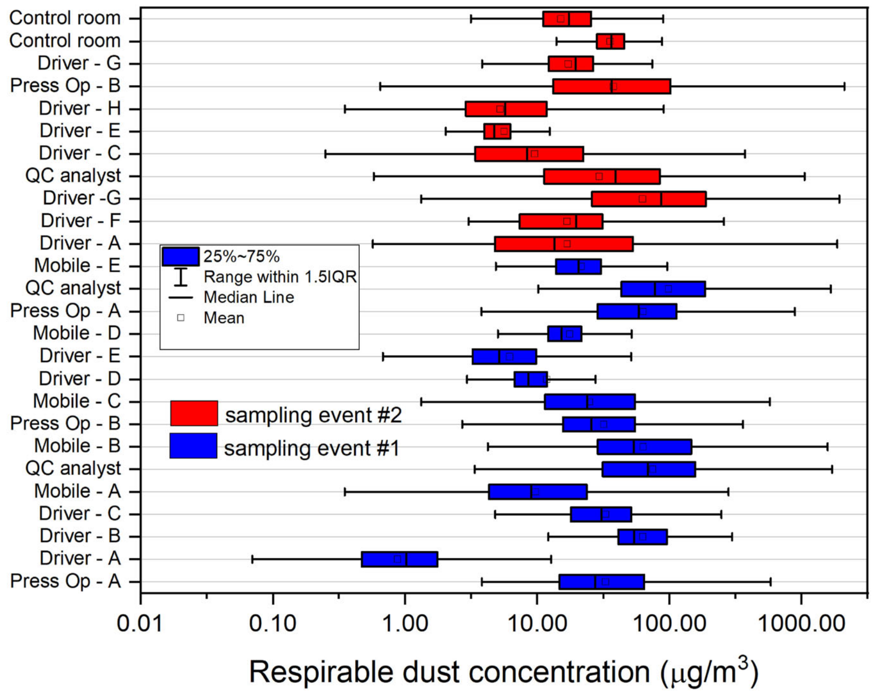

Figure 1. Statistical values for each Helmet-CAM session: median (empty box), geometric mean (line), 25%–75% quartile interval (box), and 1.5 standard deviation (whiskers).

Table 2. Summary of the descriptive statistical data for respirable dust concentration collected with the 26 Helmet-CAM sessions in both sampling events.

	Helmet-CAM session	Arithmetic mean, μg/m^3	Geometric mean, μg/m^3	Geometric Standard Deviation	RCS Concentration, μg/m^3	RCS content, %	Concentration from gravimetric analysis, μg/m^3	Ratio pDR/grav
October 2018	Press Op – A	97.3	33.0	3.0	40.3	41	117.2	1.2
	Driver – A	0.4	0.9	3.5	<LOQ	–	< 128	–
	Driver – B	75.7	62.9	1.8	<LOQ	–	219.0	2.9
	Driver – C	48.0	32.9	2.2	<LOQ	–	< 128	–
	Mobile – A	18.3	9.7	3.3	5.9	32	< 84	–
	QC analyst	174.4	74.9	3.4	15.0	9	265.2	1.5
	Mobile – B	113.0	63.5	2.8	7.3	6	144.0	1.3
	Press Op – B	62.3	31.9	2.8	44.6	72	< 340	–
	Mobile – C	51.7	25.0	3.1	27.5	53	459.2	8.9
	Driver – D	75.1	11.8	3.3	<LOQ	–	218.8	2.9
	Driver – E	13.3	6.2	2.5	<LOQ	–	< 120	–
	Mobile – D	23.9	17.6	1.9	18.6	78	213.8	8.9
	Press Op – A	165.1	63.5	3.3	78.6	48	287.1	1.7
	QC analyst	208.9	98.5	3.0	87.2	42	647.9	3.1
	Mobile – E	27.3	21.5	1.8	18.9	69	166.1	6.1
July 2019	Driver – A	7.1	16.9	4.1	<LOQ	–	< 131	–
	Driver – F	24.3	16.8	2.3	<LOQ	–	< 121	–
	Driver -G	67.2	62.7	4.3	25.4	38	294.0	4.4
	QC analyst	54.8	29.4	5.4	56.1	103	266.0	4.9
	Driver – C	28.9	9.6	3.8	10.2	35	< 243	–
	Driver – E	7.2	5.6	1.8	<LOQ		< 106	–
	Driver – H	8.5	5.3	3.2	7.7	92	< 130	–
	Press Op – B	116.9	37.8	5.9	<LOQ	–	< 114	–
	Driver – G	19.8	17.2	1.8	<LOQ	–	< 79	–
	Control room	38.2	35.6	1.5	20.6	54	670.9	17.5
	Control room	19.2	15.1	2.3	9.1	47	< 51	–

amounts above the laboratory LOQ. Out of 26 samples collected with pDR1500 monitors, none had an RCS amount greater than the laboratory LOQ. The results of the NIOSH 7500 analysis on samples above LOQ were compared to the field-based method (Figure 2) and Table 3.

Table 3. RCS results generated by the field-based monitoring approach during both sampling events.

	Area	Specific location	RCS Field, μg/m^3	NIOSH 7500, μg/m^3	RCS, %
October 2018	Pit-crusher	Outside haulage truck	17.4	<LOQ	-
	Pit-crusher	Outside loader	22.6	<LOQ	-
	Pit-crusher	Primary crusher rail	118.8	59.6	60.4
	QC lab	Laboratory	34.3	16.1	14.8
	QC lab	Office	27.9	14.8	16.3
	Wet plant	Outside control tower	18.4	<LOQ	-
	Wet plant	Outside control tower	16.9	<LOQ	-
	Wet plant	shop base level	114.2	48.8	47.3
	Wet plant	2nd level mezzanine	143.0	71.9	55.3
	Wet plant	1st level mezzanine	1726.1	1051.1	75.5
	Wet plant	Press mezzanine	41.0	19.3	43.7
July 2019	Pit-crusher	Primary crusher rail	145.7	75.4	104.6
	Pit-crusher	Primary crusher rail	166.8	128.9	67.0
	Pit-crusher	Primary crusher rail	143.5	73.5	54.2
	Pit-crusher	Outside loader	234.6	252.9	49.0
	Pit-crusher	Outside loader	61.2	36.1	29.8
	Pit-crusher	Outside loader	154.5	106.5	35.2
	Pit-crusher	Outside loader	30.9	18.0	24.5
	Pit-crusher	Outside breaker	694.5	459.9	75.8
	Pit-crusher	Outside haulage truck	47.0	25.2	32.1
	Pit-crusher	Outside haulage truck	142.3	86.7	30.5
	QC lab	Office	15.3	<LOQ	-
	QC lab	Laboratory	56.7	<LOQ	-
	QC lab	Laboratory	17.8	<LOQ	-
	QC lab	Laboratory	21.7	<LOQ	-
	Wet plant	Outside control tower	13.5	<LOQ	-

The results in the table are relative only to area time-integrated samples.

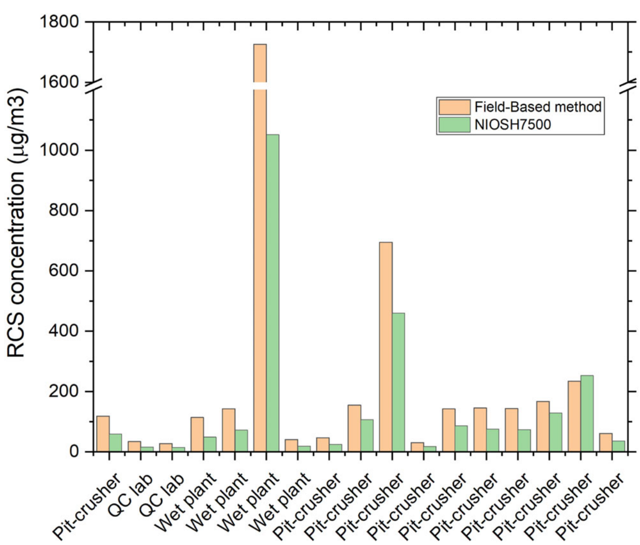

Figure 2. RCS concentration results for time-integrated samples as measured by the field-based monitoring approach and the NIOSH 7500 method.

Discussion

As a result of conducting Helmet-CAM assessments, it was determined that the QC lab operator had one the highest exposure levels out of all sessions collected in the quarry. The combined analysis of the video files in EVADE showed that exposures for the QC lab operator occurred while conducting typical QC tasks of analyzing quarry samples. This additional layer of information is one of the benefits of using the Helmet-CAM strategy. Similarly, it was determined that the haul truck drivers were experiencing elevated levels of respirable dust concentrations while entering and leaving the quarry pit. The higher dust exposures in this area of the mine were a result of drilling near the entrance of the pit. Being able to identify exactly where the mine workers were and what tasks they were performing allowed for the identification of these high-exposure events, as in the case of the QC lab operator, or to identify trends and patterns, as in the case of the haul truck drivers.

The Helmet-CAM assessments can also be beneficial when evaluating the effectiveness of in-place engineering controls and can facilitate the decision-making process to either implement or improve engineering controls to reduce workers' dust exposures. For example, it was determined that some haul truck and equipment operators would open their windows while operating their mobile equipment. Through a series of small tests with haulage truck operators (not reported), researchers and workers observed directly that leaving the windows closed allows the filtration system to operate efficiently and significantly reduces the operators' exposures. The challenge of windows and doors opening in enclosed cabs was already documented in a study on percussion rock-drilling rigs (Tharr and Zimmer 1997).

The distribution of the data points for a single session of a real-time respirable dust monitor can be analyzed, and this analysis can be more interesting when multiple sessions are compared (Figure 1). The comparison can provide valuable information about the variability of the concentration levels within and between sessions, even for the same environment and worker. The comparison can be helpful to identify and prioritize interventions, engineering controls, or changes to work practices. Each data point for a session is not an independent measurement, and for this reason, a user should refrain from using standard statistical analyses for comparing sessions as groups (O'Shaughnessy and Cavanaugh 2015; NIOSH 2022). Still, for each dataset, the analysis of both geometric mean and arithmetic mean, can indicate the distribution of the data. The geometric standard deviation can be an appropriate metric to assess variability (Nicas et al. 1991); that is, variability can be of interest for exposure monitoring between shifts and within a single shift. This information is only available using time-resolved monitoring approaches. An activity, task, or location with higher temporal variability can pose a serious challenge from a risk management perspective, and the geometric standard deviation provides information in this regard.

The distribution of the respirable dust concentrations as assessed by the Helmet-CAM sessions (Figure 1) does not show a substantial difference between the two events, October 2018 and July 2019. Notably, the dust concentration detected when the Helmet-CAM was used inside a haulage truck (Driver A) was extremely low during the first sampling event. An assessment of the enclosed cab indicated the presence of a new and highly efficient filtration-pressurization system which was demonstrated to greatly reduce in-cab concentrations (NIOSH 2018). When the Helmet-CAM was used in the same haulage truck during the second event, the average concentration was substantially higher. While the causes of this variability are not clear, this finding supports the need for multiple sessions for the evaluation of an area or a control technology.

The information generated right in the field (Figure 1 and Table 2) indicates that the Quality Control (QC) analyst (average of the sessions GM 67 μg/m^3) and the press operators (average GM 41 μg/m^3) work in environments subject to respirable dust concentrations higher than the average workers (overall average GM 31 μg/m^3). For haulage truck and loader operators, there is higher variability in terms of average respirable dust concentration but, on average, a lower geometric standard deviation which indicates more consistent conditions within the session.

To verify the findings generated in the field and to correct the results of the field-based technique, laboratory analysis was conducted on the respirable dust samples collected inside each pDR1500 monitor. Several samples showed a mass below the LOQ, and it was not possible to correct the corresponding average respirable dust concentration value detected by the pDR1500monitor (Table 2). The collection of samples with mass below the LOQ is the product of the length of the Helmet-CAM sessions and the respirable dust mass concentration levels. Some generalizable considerations for the adoption of this monitoring approach by professionals can be drawn. If verifying and correcting the results from the field is desired, an operator should conduct Helmet-CAM sessions for a period adequate to collect enough dust for gravimetric analysis. Helmet-CAM sessions using real-time respirable dust monitors rarely extend to a full shift. This is due to the burden for the workers and the prohibitively large size of the video files (Haas and Cecala 2017). A related issue entails reporting the average concentrations for sessions characterized by low collected mass. The gravimetric analysis is characterized by a constant LOQ, in this case, 23 μg. The respirable dust concentration value associated with each sample with a mass below LOQ is different since the sampling time was different. An ad-hoc "less than LOQ" value can be determined for these sessions. In the case of a sampling session of 2 hr, for example, the reported average respirable dust concentration should be less than 112 μg/m^3 (as LOQ 23 μg/(120 min $\times$ 1.7 lpm)). A more sensitive gravimetric analysis can help to minimize the problem. Alternatively, a real-time monitor capable of operating at a high flow rate should be considered to ensure the collection of a greater amount of mass in the same amount of time.

For the sample with a mass above the LOQ, the results from the Helmet-CAM sessions and the laboratory results were compared (Table 1). The laboratory analysis reported respirable dust concentration values higher than the pDR1500 monitors detected in the field. The difference between the two datasets was not consistent and the ratio values varied from 1.2 to 17.5 with an average of 5.0 (Table 2). Due to this ratio, it is evident that the Helmet-CAM approach cannot be used as a substitute for compliance monitoring. As proposed, it can be a very powerful complementary approach for more comprehensive monitoring. Different characteristics of the monitored dust can justify this variability (Wang et al. 2016; Patts et al. 2019; Tryner et al. 2019). From the perspective of adopting this technology in the field, such variability in the ratio indicates also that the determination of a single correction factor could be challenging. While this variability can present a concern, the conclusions reached in the field are confirmed by the laboratory results, such as the identification of the QC analyst with the highest concentration level.

The sample filters inside the pDR1500 monitors were also analyzed for RCS in the field (Table 2). This was done by adding a washer to concentrate the sampled dust onto the center of the filter, which is also the FTIR analytical area; this increases the overall sensitivity of the analysis for these samples by a factor of almost 10. In addition, the use of the washer minimizes the issues of the analysis related to dust pattern deposition. The addition of the washer does not impact the ability of the samples to be analyzed at the laboratory. The capability to estimate RCS in the collected samples with a pDR1500 can enhance the benefit of the Helmet-CAM technology. The RCS concentration levels detected were never above 100 µg/m,[3] but in some cases exceeded 50 µg/m,[3] which can be adopted as an action limit; this was the case for the QC analyst and the press operators. The RCS concentration levels showed all quite low numbers for the samples collected inside the enclosed cabs of trucks and loaders. The estimated %RCS in the collected samples inside the pDR1500 monitors (Table 2) was quite variable but indicates a high content of RCS in the respirable dust. The %RCS values should be considered estimates since they have been calculated by combining the information of two field-based monitoring techniques.

The results of the RCS field-based analysis on time-integrated samples (Table 3) provide information on the variability of RCS concentration in the quarry. The atmospheres in the open pit and primary crusher showed relatively low levels of RCS during the first event and much higher levels during the second event. The production activities for the quarry were much more intense during the second event. On the other hand, the RCS concentration in different points of the wet plant was much higher for 2 days of the first event but, except for one sample, not quantifiable during the second event. The wet plant is not considered a dusty environment for the quarry, and some abnormalities in the operation, such as an issue with the chemical agent, might have caused the elevated levels in 2018. This finding reinforces the necessity of collecting multiple samples from different events to fully characterize the conditions of the workplace.

The analysis of the results of the NIOSH 7500 method for RCS provided additional information about the samples collected and the monitoring techniques. The first finding was the absence of another crystalline silica polymorph in the samples—alpha quartz was the only crystalline silica polymorph. The field-based RCS data follow the same trend as the results reported by the NIOSH 7500 method, and this confirms the finding of previous studies (Cauda et al. 2018; Hart et al. 2018; Figure 2). The field-based analysis consistently overestimated the RCS concentration, providing results on average 1.8 times higher. The overestimation can be caused by the presence of other minerals in the respirable dust (Cauda et al. 2018; Hart et al. 2018; Walker et al. 2021). In its current state, the field-based method addresses only the presence of kaolinite when analyzing samples collected in coal mines (Miller et al. 2012). The method does not directly address the interference of other minerals for the quantification of RCS. The results from this case study could be used to derive a correction factor for this quarry and to minimize the bias for future samples (Cauda et al. 2018; Hart et al. 2018; Chubb and Cauda 2021a). The 17 samples with values from FAST and the NIOSH 7500 method (Table 3) were used to generate the correction factor for this quarry. The reference values (NIOSH7500) and the estimations from FAST were correlated with an R^2 of 0.996. The correction factor was found to be 0.612, and it could be used in that quarry in the future. The use of a correction factor can be effective if the minerals present in the respirable dust remain consistent. The comparison with the NIOSH 7500 results (Figure 2) indicates that the field-based analysis could detect RCS in the respirable dust samples, and it provided valuable information about the variability of RCS concentration. In other words, the field-based analysis could assess different relative levels of RCS concentration around the quarry. The ability of a field-based method to provide timely estimates on a hazard concentration is an asset for an industrial hygienist or the health and safety staff.

The %RCS in the respirable dust samples can be determined using the NIOSH 7500 results and the gravimetric analysis of the samples (Table 3). The %RCS varied from 14% to 100% with an average of 48%. This is an indication that the content of RCS in the respirable dust present in the quarry can be extremely variable.

The objective of the study was not to conduct the characterization of the respirable dust and RCS concentrations in the quarry or to conduct an exposure assessment study for this environment. The study was designed to collect evidence of the benefits and limitations of using field-based monitoring approaches for respirable dust and RCS. The areas and tasks for sampling and monitoring were selected for their known presence of respirable dust and RCS. Every sample was collected for a period shorter than 8 hr or a full shift. For these reasons, the information collected in this study cannot be extrapolated to describe actual comprehensive exposures at this sandstone quarry or any quarry in general.

The Helmet-CAM sessions inside the enclosed cabs were set up by strapping the backpack on the back of a seat with the respirable cyclone attached to the shoulder strap of the backpack. This approach is effective for monitoring the conditions inside the enclosed cabs of machines. From an industrial hygiene perspective, though, these sessions cannot be considered personal monitoring since they were not conducted within the personal breathing zones of workers.

Conclusions

The field-based monitoring approaches presented in this manuscript can provide valuable information even right at the workplace at the end of the monitoring session. This information can be complementary to what is generated by non-field-based approaches. The rapid quartz analysis monitoring approach, using a portable FTIR, can estimate right in the field the quartz concentration levels in different areas of the workplace by analyzing dust samples collected with respirable samplers. The possibility of analyzing the samples in the field can facilitate the identification and characterization of areas of concern by the professional industrial hygienist. Real-time respirable dust monitors can provide time series values that cannot be obtained from the collection of an integrated dust sample. The distribution of the data during a session can inform the professional about the variability of the dust concentration levels in time and space. The combination of the real-time respirable dust monitor data and video camera footage, used for Helmet-CAM assessments, add another layer of information. Several activities are facilitated: the identification of tasks with high and variable exposure to respirable dust and RCS, the comparison of multiple tasks and the same task for repeated sessions, and the development and evaluation of engineering control technologies and work practices. A systematic analysis of Helmet-CAM sessions should be considered a powerful tool, despite the time needed to process all the data.

The limitations of the field-based monitoring techniques also need highlighting. The agreement between the results generated in the field by the real-time respirable dust monitors as arithmetic average concentrations and the laboratory results can be quite variable, as indicated by the ratios or correction factors (1.2 to 17.5). Caution should be taken to consider the real-time respirable dust monitors' data as accurate or that a correction factor can be determined for every workplace. Correcting the field-based data from real-time respirable dust monitors is not always possible due to the low mass collected for gravimetric analysis, particularly with short-duration samples. The data on quartz concentration associated with collected samples generated in the field by a portable FTIR and verified by the laboratory analysis indicates that the field-based monitoring approach can be used in an environment like this quarry to assess relative concentration levels in the quarry. The accuracy of the field-based monitoring might be improved by establishing a site-specific correction factor. For both field-based monitoring approaches described, an additional limitation is the time and resources needed to adopt and implement the approaches. Professionals should consider the benefits and limitations associated with these complementary approaches.

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Disclaimer

The findings and conclusions in this paper are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute an endorsement by NIOSH.

Data availability

The data that support the findings of this study are available from the corresponding author, EC, upon reasonable request.

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