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Use of the Field-Based Silica Monitoring Technique in a Coal Mine: A Case Study

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Abstract

Exposure to respirable crystalline silica (RCS) can cause serious and irreparable negative health effects, including silicosis and lung cancer. Workers in coal mines have the potential of being exposed to RCS found in dust generated by various mining processes. The silica content of respirable dust in one single mine can vary substantially over both time and location. The current monitoring approach for RCS relies on the use of traditional air sampling followed by laboratory analysis. Results generated using this approach are generally not available for several days to several weeks after sampling, and this delay prevents timely and effective intervention if needed. An alternate analytical method is needed to reduce the time required to quantify the RCS exposure of mine workers. The National Institute for Occupational Safety and Health (NIOSH) has developed a new method using commercially available portable infrared spectrometers for measuring RCS at the end of the sampling shift. This paper will describe the application of the new field-based RCS analytical process for coal mines, including the use of the new method with the existing Coal Mine Dust Personal Sampler Unit. In a case study conducted by NIOSH with a coal mine operator in West Virginia, field-based RCS analysis was completed at a mine site to evaluate the new technique. The RCS analysis results obtained by the field-based method in this case study showed sufficiently strong correlation with results obtained by the MSHA standard laboratory analysis method to allow the mine operator to use the field-based method for evaluating process improvements.

Keywords

Crystalline silica; Respirable dust; Coal mining; Field-based monitoring; FTIR

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Conflict of Interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

1 Introduction

Workers in the US coal mining industry are at risk for exposure to hazardous concentrations of respirable dust, which can lead to a spectrum of respiratory diseases, including coal workers' pneumoconiosis (CWP), and silicosis. These lung diseases are incurable and disabling and can lead to premature death but can be prevented by limiting exposure to harmful dust [1]. Exposure to respirable crystalline silica (RCS), a component often found in respirable coal mine dust, is well established as a risk factor for silicosis and lung cancer [2, 3]. Progression of these diseases can continue even after the exposure to RCS has ended [2, 3]. In coal mines, the presence of crystalline silica has also been implicated as an important contributing factor in the development of rapidly progressive pneumoconiosis [4, 5].

Despite past decreases in CWP incidence, notable clusters of rapidly progressive CWP have been observed in Appalachian regions of Eastern Kentucky and Southwestern Virginia [6, 7]. While total deaths due to CWP have decreased since 1999, much of the decrease can be attributed to the reduced size of the mining workforce; however, per miner, cases are in general now more severe and show more rapid CWP progression [8]. The bulk of this intensification has occurred among miners in the Appalachian region of Eastern Kentucky, Southwestern Virginia, and Southern West Virginia. CWP is approximately four times as common among long-tenured underground coal miners in central Appalachia as compared to long-tenured underground coal miners in the rest of the USA, with 20.6% of long-tenured underground miners in central Appalachia suffering from the disease as of 2017 [9]. Rapid onset of silicosis continues to be observed in relatively young workers [10], further supporting ample historical evidence, such as the 1930 Hawk's Nest Tunnel disaster, that exposure to high concentrations of respirable crystalline silica can lead to acute silicosis [11].

The most common form of crystalline silica is quartz, which is typically found in the immediate roof or floor rock adjacent to the mined coal seam rather than in the seam itself. Over time, mining activities have shifted toward increasingly thinner coal seams as thicker seams have been depleted [12]. Samples from central Appalachia in particular have shown high quartz content and small particle size relative to respirable coal mine dust from other regions [13], both of which are known to be risk factors and suggest a respiratory hazard consistent with the observed clusters of rapidly progressive pneumoconiosis found in that region.

The quartz content of respirable dust in coal mines varies substantially not only from region to region but among different sampling locations in the same mine section. One study found a disparity of 22% on average between duplicate samples spaced several centimeters apart and 42% on average for samples within 6 m [13]. Evidence also suggests considerable variability among sections of the same mine, and from day to day in the same mine section; this is consistent with well-documented variability in dust composition across various mine job tasks [14, 15]. Since the percentage of airborne respirable dust that is composed of crystalline silica can vary widely, the concentration of overall respirable dust is only loosely linked to the concentration of respirable crystalline silica. Therefore, only measuring airborne respirable dust is not sufficient to reliably quantify crystalline silica exposure [16].

In order to protect coal mine workers from the health hazards associated with respirable coal mine dust and respirable crystalline silica, exposure to high concentrations must be prevented. Engineering control technologies can be implemented to reduce the overall respirable dust and RCS exposures from various coal mining tasks [17], and exposure monitoring activities are crucial to verifying the effectiveness of control technologies. Historically, both regulatory compliance sampling and voluntary monitoring for engineering control improvement were conducted by air sampling using the Coal Mine Dust Personal Sampler Unit (CMDPSU). These samples were subsequently analyzed at an external laboratory by gravimetric analysis for respirable dust concentration and then by the MSHA P-7 method for crystalline silica content [18]. The 2014 revised respirable coal mine dust rule required the use of the continuous personal dust monitor (CPDM) for compliance sampling of respirable coal mine dust [19] and can be utilized by the coal mining industry for voluntary monitoring. The CPDM provides an accurate end-of-shift average respirable dust concentration, improving on the days needed to obtain an average concentration with the CMDPSU. It also provides near real-time respirable dust concentration data throughout the shift. The CPDM's method of measurement, however, is not able to differentiate crystalline silica from other contents of the dust [20]. As a result, the CPDM is effective for measuring overall respirable dust concentrations, but a different tool is needed to reliably measure respirable crystalline silica. While the field-based RCS monitoring approach described here does not provide real-time monitoring, it can provide timely direct measurements of respirable crystalline silica, which are not available from CPDM monitoring alone. The focus of this study was to investigate the benefits and limitations of using the field-based RCS monitoring approach in a coal mine for routine monitoring activities for alpha quartz concentration.

2 Methods

2.1 Field-Based Silica Monitoring Approach

The NIOSH Mining Program has developed a field-based respirable crystalline silica monitoring approach with the intent to provide mine operators with a tool for the expedited quantification of crystalline silica in respirable dust samples. In contrast with current methods that require analysis at a laboratory (19, 21–23), the use of a portable analyzer at the mine site is the key component of this monitoring approach. Previous studies have demonstrated that portable Fourier transform infrared (FTIR) spectrometers can be used successfully for direct-on-filter measurement of crystalline silica, using samples collected on coal dust sampling cassettes as well as on other types of sampling cassettes [21–24].

In the field-based approach to RCS monitoring, a respirable dust sample is collected on a cassette using an air sampling system such as the CMDPSU (Dust Sampling Cassette, Non-Regulated, General Purpose, part number 711361, Zefon International, Inc.) in the same way as if the sample were to be used for compliance monitoring. In this manuscript, this method will refer specifically to samples collected on coal dust sampling cassettes, though the method is similar for samples collected on other cassette types. After collection, the sample is returned to the area designated for on-site analysis, generally an aboveground office space. To begin, the instrument operator first analyzes a blank filter as a background measurement to allow for subtraction of the signal from the filter media itself. The blank filter should be from a coal dust sampling cassette that was not used for sampling but from the same production lot as the cassettes used for sampling. The operator then removes the plastic case of the coal dust sampling cassette to be analyzed, places the filter (still contained in its foil housing) into the filter holder, and loads the filter holder into the bracket of the portable FTIR instrument (Fig. 1). After analysis, the operator places the filter back in its plastic case for storage and then repeats the process for any additional samples.

The field-based monitoring approach uses transmission FTIR analysis. Going through the opening in the center of the foil housing, an infrared beam passes through the dust sample and the filter media before reaching a detector inside the portable FTIR. The transmission FTIR measurement is nondestructive and leaves the sample intact after analysis, so samples can be reanalyzed or sent to external laboratories for standard analysis by the MSHA P-7 method, if desired. The sample is analyzed over a spectral range of 4000–400 cm^{-1} at a resolution of 4 cm^{-1}. Crystalline silica and other geologic materials present in the respirable dust sample interact with the infrared beam, generating various signature features in the resulting spectrum. The presence of other minerals can affect the measurement of the crystalline silica signature feature. In general, respirable dust samples from underground coal mines have two constituents of interest: crystalline silica and kaolinite, which is an aluminosilicate [24]. The presence of kaolinite does affect the measurement of crystalline silica, but a correction can be used to mitigate its effect [18, 25].

After analyzing the samples using the FTIR instrument, the operator exports the raw data from the instrument’s proprietary software. The mass of crystalline silica on each sample can be estimated by quantifying its signature feature using calibration models previously generated with pure respirable crystalline silica. NIOSH has developed a publicly available PC software, NIOSH FAST (Field Analysis of Silica Tool), that accepts a .csv or .xslx file from the FTIR instrument and completes the required calculations to estimate crystalline silica mass for each sample [26]. With the user inputs of sampling time and pump flow rate, NIOSH FAST calculates RCS concentration.

The field-based transmission FTIR analysis process is substantially similar to that used in the MSHA P-7 and NIOSH 7603 methods, with the notable difference that in the field-based method, the original filter remains intact, while under MSHA P-7 and NIOSH 7603, the original filter is destroyed, and any collected dust is redeposited on a new filter [18, 25]. In both methods, only a small area at the center of the dust sample and filter media interacts with the infrared beam. Because the field-based method uses the original collected filter without evenly redepositing the dust on a clean filter, it requires a quantification model that can predict the crystalline silica present on the unmeasured rest of the filter. Various respirable dusts have been found to deposit predictably on the 37-mm three-piece cassette, and the resulting silica estimation has been shown to be quite accurate as compared with the MSHA P-7 standard method [22, 24]. When a coal dust sampling cassette is used, however, the deposition pattern of crystalline silica is less consistent, which limits the accuracy of the field-based approach to the accuracy of the deposition prediction. Despite this limitation, the coal dust sampling cassette merits consideration for this new application, as the CMDPSU is widely available in coal mines and coal mine safety professionals are familiar with its use.

2.2 West Virginia Coal Mine Case Study

In December 2016, the NIOSH Mining Program began a collaboration with Blackhawk Mining, LLC, a coal mine operator near Charleston, West Virginia, for the purpose of field testing the field-based respirable crystalline silica monitoring approach. The case study was conducted into two parts; for each part, the mining company proposed a question about its workers' potential RCS exposure that it wished to investigate using the field-based approach. Mining company personnel designed and executed the sampling plan for each study, using mining company owned and calibrated sampling equipment, with pre-weighed sampling cassettes supplied by NIOSH. Respirable dust samples were collected using the traditional sampling components of the CMDPSU, with the samplers set up at fixed points to collect area samples. Each CMDPSU used was assembled of the following components: a Dorr-Oliver 10-mm cyclone, a 37-mm coal dust sampling cassette (part number 456243, Zefon International, Inc.), an Escort ELF Personal Sampling Pump (P1-ELF1-1-4-0-0, Zefon International, Inc.) operated at 2.0 l per minute, and brackets and hoses as required. After each sampling event, mining company personnel stored the cassettes in an aboveground training facility at the mine site.

Collected samples were analyzed for crystalline silica by the field-based method at the mine site. After field-based analysis at the mine, NIOSH scientists took custody of the samples and returned them to the NIOSH laboratory at Pittsburgh Mining Research Division (PMRD) in Pittsburgh, PA. Once returned to PMRD, the filters in the coal dust sampling cassettes were post-weighed in the on-site weighing room, the same facility where they had been pre-weighed prior to sample collection, according to the following method. The weighing room is maintained at 22 °C (72 °F) and 50% relative humidity. Filters were placed in the weighing room with plastic case caps removed and allowed to reach equilibrium with chamber conditions overnight; this step is particularly important for weighing samples collected in humid conditions, such as in a mining section where water sprays are used. Following equilibration, each filter was weighed using a Mettler Toledo XP2U microbalance (Mettler-Toledo International Inc.). The filter weight was allowed to stabilize on the microbalance for 60 s, after which the weight of the filter was recorded automatically in a database. A laboratory control filter of well-established mass was weighed before and after sample measurements, and the average net change was −0.001 mg.

From each set of samples, after NIOSH analyses were completed, a subset of samples were sent to an external laboratory (RJ Lee Group, Monroeville, PA) for silica quantification using the standard MSHA P-7 method [18]. The complete set of data generated was further analyzed by NIOSH and then provided to and discussed with the mine company.

2.2.1 Case Study, Part 1: Testing Surfactant Water Spray Additive in Continuous Miner Section—The first part of the case study, conducted in December 2016 through February 2017, employed the field-based monitoring approach in the evaluation of a commercially available surfactant additive to the onboard water spray control technology used by a continuous miner machine in an underground coal mine. The mine company was already using onboard water sprays as a means of controlling the concentration of respirable dust during continuous miner activity, and it was interested in testing the benefit of adding a chemical surfactant to the water specifically to reduce respirable crystalline silica.

Testing was conducted on two underground Mechanized Mining Units, operating on split air sections of the same coal seam within one organization. Each section was ventilated by the same shared fresh air intake upstream of the continuous miner. Respirable dust samples were collected on each section while the continuous miner was operating. For each section, one sampler was worn by the miner operating the continuous miner, and the other was positioned in the return (downstream from the continuous miner), for a total of four samples per sampling event. Each test was conducted for an equivalent amount of mining progress to allow comparison of the results in terms of work milestones: respirable dust samples were collected, while each continuous miner performed exactly two cuts, and onboard water sprays were active. The experimental variable was the presence of the chemical surfactant in the water used by the water spray system: four levels of chemical surfactant were tested (100% dissolve rate, 75%, 50%, and 0%). For each condition, four sampling events were conducted, for a total of 16 sampling events, yielding 63 samples collected on coal dust sampling cassettes (1 sample was discarded due to physical damage during sampling).

After sampling by mine safety professionals had concluded, NIOSH scientists traveled to an aboveground training structure at the mine in February 2017 with two portable FTIR instruments (Bruker Corp. model Alpha and Thermo Fisher Scientific Inc. model Nicolet iS5N), as well as two laptop computers loaded with each manufacturer’s proprietary analysis software. There, the NIOSH scientists demonstrated the field-based analysis method and used it to analyze the collected respirable dust samples for crystalline silica. All 63 samples were returned to NIOSH laboratories for gravimetric analysis, and these samples were subsequently sent to the external laboratory RJ Lee Group for analysis by the MSHA P-7 method.

2.2.2 Case Study, Part 2: Comparing Respirable Crystalline Silica Exposure Across Occupations—

The second part of the case study, conducted in September 2017 through November 2017, employed the field-based monitoring approach to compare the differences in potential respirable crystalline silica exposure for workers assigned to various mine occupations. The mine company was interested in comparing relative exposures across occupations in order to best prioritize the application of control measures.

For this second part of the case study, NIOSH scientists traveled to the mine in September 2017 with a portable FTIR instrument (Thermo Fisher Scientific Inc. Nicolet iS5N), as well as a laptop computer loaded with the manufacturer’s proprietary analysis software and NIOSH FAST software. NIOSH scientists set up the equipment at an aboveground mine training structure and trained mine company safety professionals on the use of the field-based analysis method.

Testing was conducted on 11 underground Mechanized Mining Units, operating across four closely located coal seams within one organization, by 4 teams of mine safety professionals conducting sampling separately. On each section, area samples were collected to represent the potential exposure at five occupation positions (continuous miner, roof bolter, scoop, center shuttle car, and outside shuttle car), as well as ventilation air at intake (upstream) and return (downstream), for a total of seven samples per sampling event. One sampling event was completed at each of the 11 sections. Area samples were measured to identify section-to-section consistency and to prevent any possible confusion with personal compliance sampling. A sampling duration of 540 min was used on all sections and represented the average portal-to-portal exposure of the equipment operators.

The mine company safety professionals collected a total of 77 samples over a 12-week period and analyzed the samples by the field-based method for crystalline silica. Field-based analysis of each sample was performed by the mine safety professional who had collected that sample, and analysis was completed throughout the period as the samples were collected. About 72 of these samples were collected on coal dust sampling cassettes and are included in this analysis.

For all 77 samples, after post-weighing at PMRD as described above, NIOSH scientists repeated the field-based analysis at PMRD to ensure consistent adherence to the method; the measurements taken by mine safety professionals were not considered for analysis and were used for training only. A subset of 35 samples were selected to be representative of the full set and were subsequently analyzed by MSHA P-7 method by the external laboratory RJ Lee Group. Those samples found to be below the limit of quantification for the field-based method, 16-μg crystalline silica mass [24], were not sent for external laboratory analysis.

3 Results and Discussion

3.1 Comparison of Field-Based and MSHA P-7 Analysis Methods

The results of the field-based FTIR, MSHA P-7, and gravimetric analyses generated for each sample were collected into a single database for each part of the case study, along with information on the sampling conditions for each sample. Data from each part of the case study was analyzed to compare the results generated by the field-based versus MSHA P-7 methods and to provide information with which the mine company could address its operational questions. This section will focus primarily on the comparison of the field-based and MSHA P-7 methods.

3.1.1 Case Study, Part 1—Data was expressed in terms of respirable crystalline silica mass and grouped by surfactant condition. Each surfactant condition was composed of 16 samples (the “50%” condition has 15 due to cassette damage). Figure 2a shows results of the field-based analysis, while Fig. 2b shows results of the MSHA P-7 analysis performed on the same samples by the external laboratory. Both analysis methods visually suggest that, in general, the presence of the surfactant chemical compound did not reduce the amount of respirable crystalline silica generated in the continuous miner sections tested.

The results obtained by MSHA P-7 method were compared by linear regression to the results obtained by the field-based method (Fig. 3). Examination of a plot of residuals against predicted values suggested that the assumption of constant variance of residuals was not met. When this assumption is violated, the ordinary least squares (OLS) solution does not provide the optimal estimate of the true regression equation. The purpose of the weighted least squares (WLS) regression is to give more weight to observations where the variance of residuals is smallest, and less weight to observations where the variance of residuals is largest. The ideal weight is the reciprocal of the variance of residuals for each value of the predictor variable; because the ideal weight is not known, it must be estimated. In this case, ideal weights were estimated using the weight estimation procedure in Statistical Package for the Social Sciences (SPSS), an iterative procedure that tests a range of powers of the weight variable and identifies the power that best approximates the ideal weight. Levene's test of homogeneity applied to the weighted residuals returned nonsignificant results, providing evidence that the assumption of constant variance of residuals was met. Examination of the weighted residuals by quantile-quantile plot showed slight deviation from linearity, but sufficiently close to support the assumption of normality in the absence of contrary evidence.

The paired measurements show strong linear correlation, with a correlation coefficient of 0.92. This strong relative relationship offers evidence that the field-based measurements are sufficient to draw reliable conclusions about the underlying relative respirable crystalline silica conditions among the observations made in Part 1. The 95% confidence interval for the regression coefficient, [0.69, 0.80] for Part 1, suggests that the field-based method generated absolute results that were consistent with but in general larger than the MSHA P-7 values. The 95% confidence interval for the regression intercept, [0.9, 10.5], suggests that the regression coefficient estimated may not fully describe the true regression, which would be expected to pass through the origin. Alternatively, the field-based method as applied in Part 1 could have resulted in a small subtractive systematic error as compared to MSHA P-7. Such an error could arise from a loss of dust in handling, though this explanation seems unlikely in this case as no statistically significant error was found for the Part 2 samples that were subjected to greater handling.

3.1.2 Case Study, Part 2—Data from Part 2 was grouped by mine occupation and expressed in terms of respirable crystalline silica concentration, as sampling times were available for this data set. Figure 4a compares results of the field-based analysis conducted by NIOSH scientists at PMRD with Fig. 4b, which shows results of the MSHA P-7 analysis performed on the same samples by the external laboratory. The results from Case Study Part 2 likewise suggest consistent findings between the field-based and MSHA P-7 analytic methods.

In the same way as the Part 1 data set, the results obtained by field-based method versus MSHA P-7 method for Part 2 were compared by linear regression (Fig. 5). Examination of a plot of residuals against predicted values suggested that the assumption of constant variance of residuals was not met, so the WLS solution to the regression was again selected and was calculated in the same way as in Part 1. Levene's test of homogeneity applied to the weighted residuals returned nonsignificant results, providing evidence that the assumption of constant variance of residuals was met. Examination of the weighted residuals by quantile-quantile plot showed them to be very closely linear, providing evidence that the assumption of normality was met.

The paired measurements show strong linear correlation, with a correlation coefficient of 0.90. This strong relative relationship offers evidence that the field-based measurements are sufficient to draw reliable conclusions about the underlying relative respirable crystalline silica conditions among the observations made in Part 2. The 95% confidence interval for the regression coefficient, [0.81, 1.02] for Part 2, suggests that the field-based method generated absolute results that are likely to provide a reasonable estimate of the MSHA P-7 values, though the best fit regression again suggests a mild tendency to overestimate. As would be expected in the absence of a systematic error, the 95% confidence interval for the regression intercept, [−1.9, 8.7], includes the origin.

To demonstrate the operational use of the study, the complete Part 2 sample set is shown in Fig. 6. These results suggest that a difference in potential respirable crystalline silica exposure was observed across the mine occupations tested.

3.2 Implications of Deposition Pattern

The analysis in this case study uses the standard quantification model developed by Miller et al. [21] for use with direct-on-filter analysis of three-piece cassettes. This model uses the measured signature features from the center of the filter to estimate the contents of the unmeasured remainder of the filter and has been shown to provide a consistently accurate quantification of respirable crystalline silica mass for samples collected on three-piece cassettes [21, 24]. On the coal dust sampling cassette, differences in dust composition are suspected to result in differing dust deposition patterns; in contrast, three-piece cassettes are observed to have a well-characterized predictable deposition pattern regardless of dust composition. A quantification model for the signal from the unmeasured part of the filter specific to the coal dust sampling cassette has not been developed, and it is known that the model designed for the three-piece cassette does not fully account for this behavior of the coal dust sampling cassette. As a result, the field-based measurements taken from coal dust sampling cassettes will show some systematic difference from their MSHA P-7 values. A few individual samples from each part of the case study show a relatively large (around 100%) deviation from their respective predicted values on the regression line, a further indication that any single field-based measurement on a coal dust sampling cassette can be meaningfully different from its true value as best determined by the MSHA P-7 method.

In a 2013 study, Miller et al. [22] explicitly measured the crystalline silica and kaolinite signature features at several points along the radius of the filters of three-piece, two-piece, and coal dust sampling cassettes. Miller et al. found that for three-piece and two-piece cassettes collected using a Dorr-Oliver cyclone, the relative peak area measured from each signature feature follows a consistent pattern across the radial points that is independent of the quantity and composition of dust on the filter, where the heaviest loading occurs in the center of the filter and decreases along an empirically determined bell-shaped distribution toward the edges. Miller et al. disassembled coal dust sampling cassettes and found by the same method that those cassettes showed a deposition of approximately uniform magnitude across the filter, with comparatively large random variation but no discernible pattern. All three cassette types showed deposition patterns that were generally radially symmetric.

In their study, Miller et al. used an older model of the coal dust sampling cassette in which the filter was supported by a perforated backing pad. This case study used current model coal dust sampling cassettes, which no longer have a backing pad and instead use a metal ring for this function. Subsequent to all field-based analysis as described above, but prior to MSHA P-7 analysis, each filter collected in this case study was disassembled from its aluminum cone and analyzed by transmission FTIR a total of six times at five unique points across its diameter, using a method materially similar to that used by Miller et al. This data, as well as other preliminary NIOSH work, suggests that the current model coal dust sampling cassettes show a discernible deposition pattern that is not explained by random variation. The underlying cause of this varying deposition pattern is not well understood; current data suggests that it may vary with the relative content of crystalline silica versus other constituents. While it is possible to avoid this uncertainty of the deposition pattern by measuring multiple radial points for each filter and determining the deposition curve empirically, this approach requires the disassembly of the filter from its aluminum cone, thus reintroducing the need for more time and a controlled environment and negating much of the benefit of the field-based method.

It is important to note that an FTIR-compatible four-piece 37-mm cassette exists and is commercially available (Zefon International, Inc.). The four-piece 37-mm cassette is a user-friendly modification of the three-piece cassette used by Miller et al. [21] that has shown consistent deposition of crystalline silica. The resulting estimations of crystalline silica using this cassette can be less variable than those made using coal dust sampling cassettes.

3.3 Variability of Crystalline Silica Content

To assess the variability of the silica content in the respirable dust collected for this case study, the results of crystalline silica analysis by MSHA P-7 method (Fig. 2b and 4b) were combined with gravimetric data to determine the composition of the collected respirable dust in terms of percent crystalline silica by mass. As expected, percent RCS was found to be variable, ranging from 2.7% to 28.9% of the total respirable dust (Fig. 7a and b). The range is large from an analytic perspective but is consistent with previously reported retrospective analysis of MSHA compliance measurements [27] and with other studies that show high variability even among samples from the same mine [13, 14]. Furthermore, the high variability of crystalline silica content indicates that for this mining operation, there is not a straightforward relationship between respirable dust and respirable crystalline silica, and advanced respirable dust monitors alone, such as the CPDM, would not be sufficient to characterize respirable crystalline silica exposures. This finding supports the need for innovative field-based monitoring approaches specific to respirable crystalline silica, such as the field-based crystalline silica monitoring approach described in this manuscript.

In summary, these findings indicate that the field-based crystalline silica monitoring approach can be used to identify trends and patterns in respirable crystalline silica exposure with a level of reliability that would not be available from CPDM monitoring alone. A set of samples considered as a group can be expected to show similar results whether analyzed by the field-based or MSHA P-7 method. Miller et al. reported that results from direct-on-filter FTIR analysis in the laboratory setting correlate closely with results from MSHA P-7 analysis [20]; the findings reported here are consistent with Miller et al., and each set of field-based estimations shows a similarly close correlation with its respective results from MSHA P-7 analysis. Due to issues specific to the coal dust sampling cassette, individual measurements made by the field-based method on a coal dust sampling cassette can deviate by up to around 100% from the expected value measured by the MSHA P-7 method. The field-based method allows for simpler, more rapid analysis and faster turnaround time as compared with the standard MSHA P-7 method, which may allow mine operators to make use of results from sampling on a more operationally relevant timescale.

4 Conclusions

The field-based respirable crystalline silica monitoring approach uses a portable FTIR instrument to create a new opportunity for mine operators to generate reliable measurements at the mine site and in a timeframe that is suitable for operational interventions. Prior research has shown that the accuracy of field-based RCS analysis for samples collected on three-piece cassettes approaches that of the standard MSHA P-7 method, and this study suggests that the field-based method is also practical for use with the CMDPSU. The findings from the case study suggest that the accuracy of the field-based method using the coal dust sampling cassettes is quite variable, sample by sample. Nevertheless, the good correlation between the aggregated results generated by the field-based method and the MSHA P-7 method supports the use of the proposed method for reliable assessment of trends in respirable crystalline silica conditions. Overall, the field-based method can be useful for the type of engineering and process improvement purposes attempted in the case study. Due to the high variability of crystalline silica content in respirable coal mine dust, implementation of field-based crystalline silica monitoring in addition to a program of advanced total respirable dust monitoring could provide more accurate information on potential respirable crystalline silica exposure in a faster timeframe and at lower cost as compared to standard MSHA P-7 analysis.

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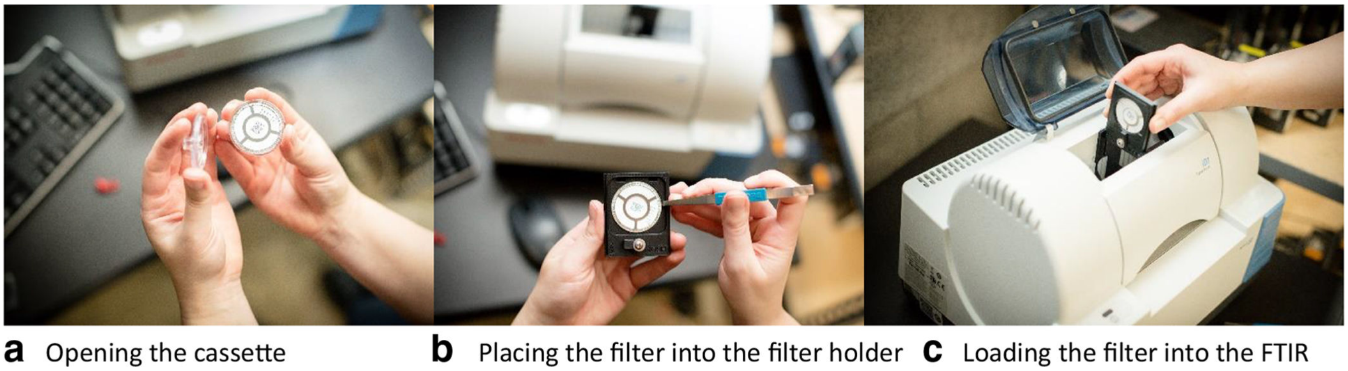

Fig. 1.

Measuring a sample collected on a coal dust sampling cassette using a portable FTIR instrument for the field-based method. (**a**) Opening the cassette, (**b**) placing the filter into the filter holder, (**c**) loading the filter into the FTIR

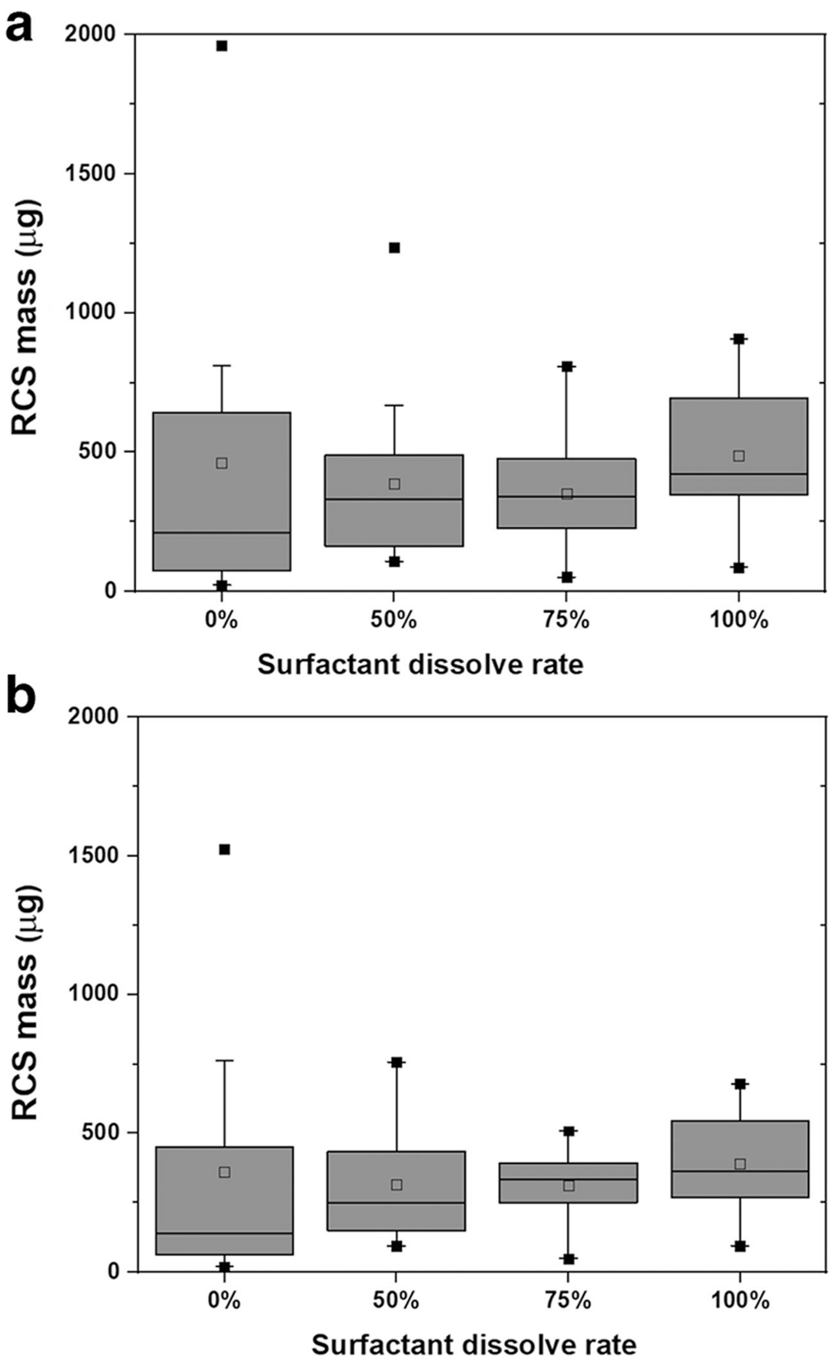

Fig. 2.

Respirable crystalline silica mass by surfactant condition, Case Study Part 1, as measured by field-based method and MSHA P-7 method. Each box represents the range 25%–75% of the data. The line is the median, the empty symbol the mean, and the black symbols the minimum and maximum. The whiskers indicate 1.5 times the standard deviation. (**a**) Field-based method, (**b**) MSHA P-7 method

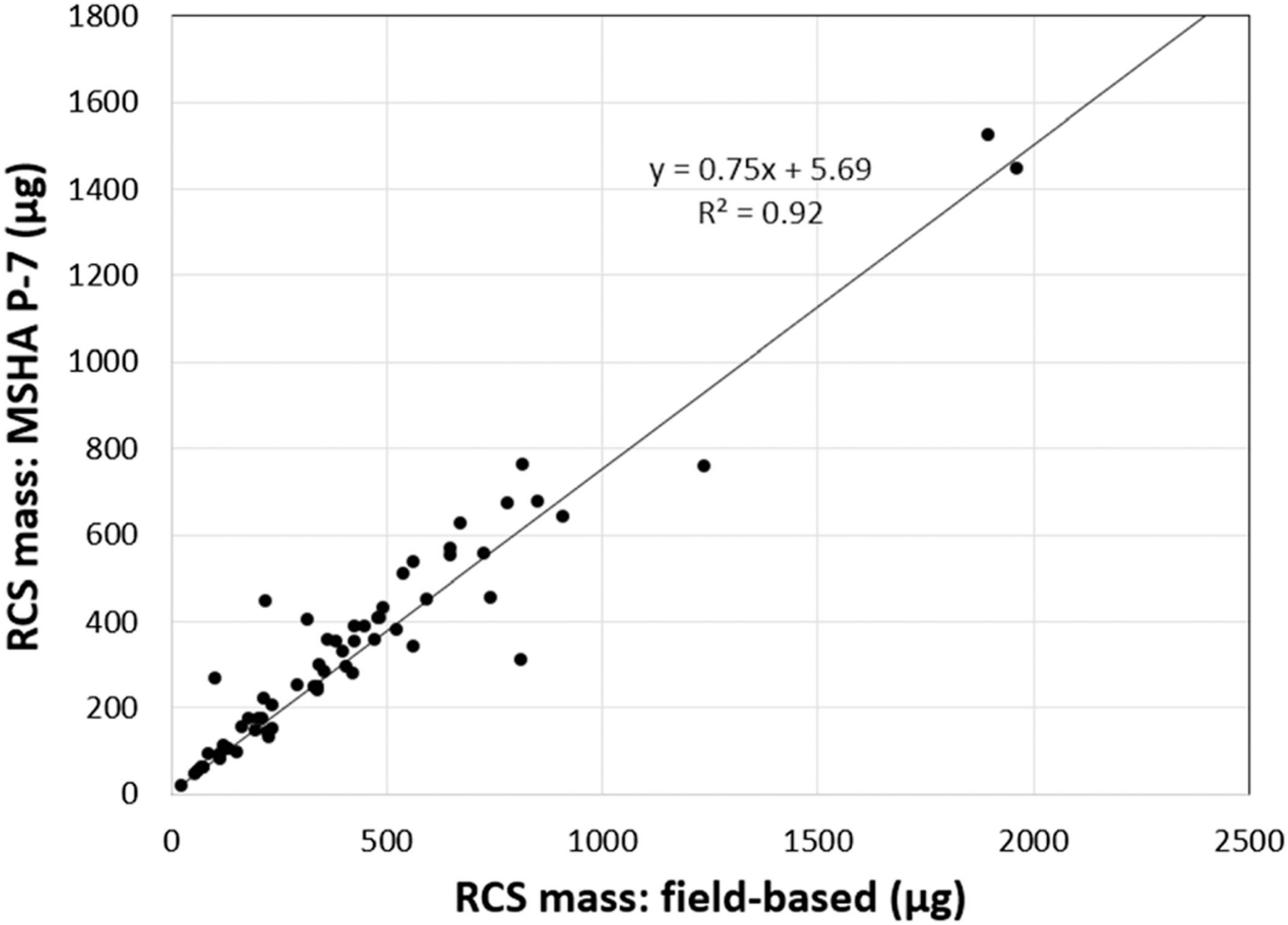

Fig. 3.

Comparison of MSHA P-7 method results versus field-based method predictions by linear regression, Case Study Part 1

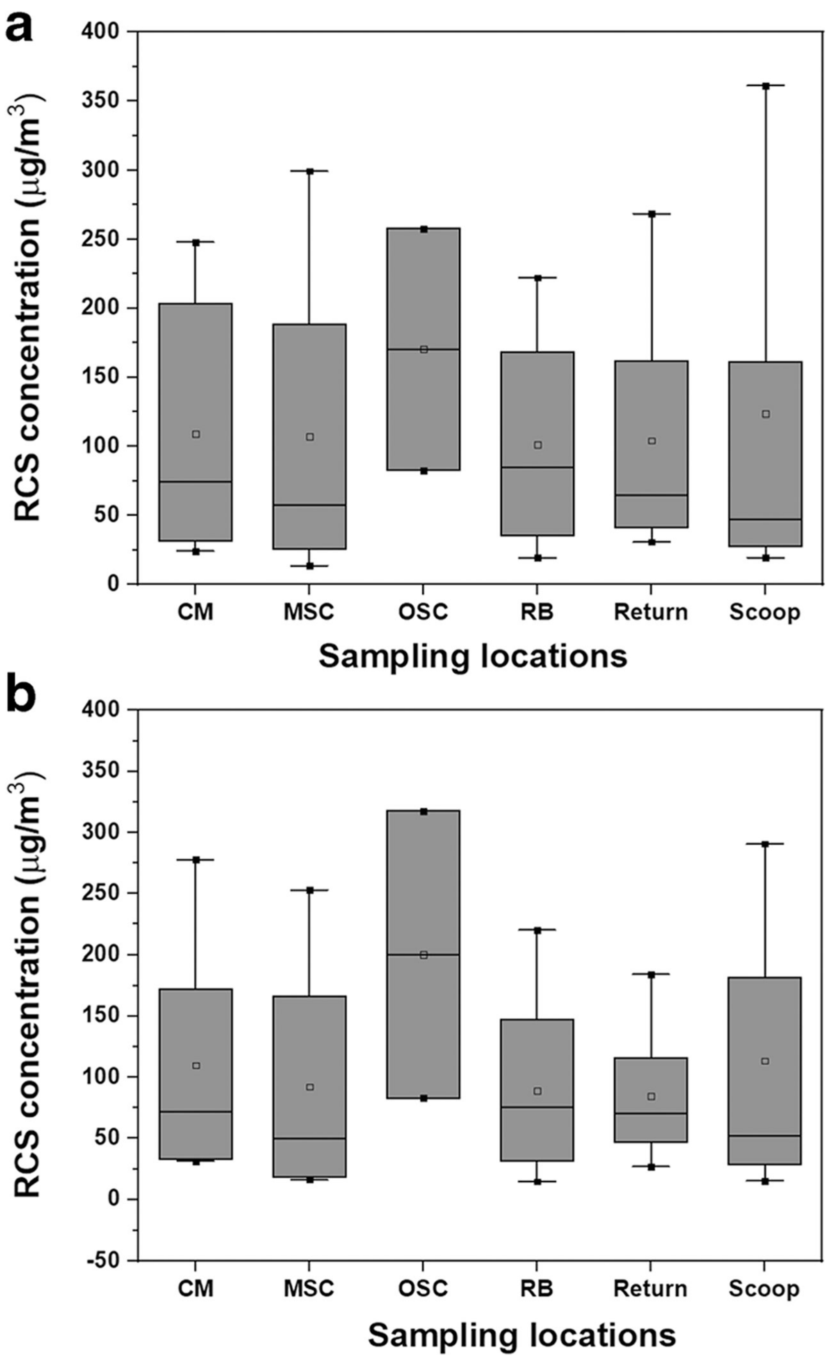

Fig. 4.

Respirable crystalline silica (RCS) concentration by mine occupation, Case Study Part 2, as measured by the field-based method and MSHA P-7 method. Each box represents the range of 25%–75% of the data. The line is the median, the empty symbol the mean, and the black symbols the minimum and maximum. The whiskers indicate 1.5 times the standard deviation. (**a**) Field-based method, (**b**) MSHA P-7 method

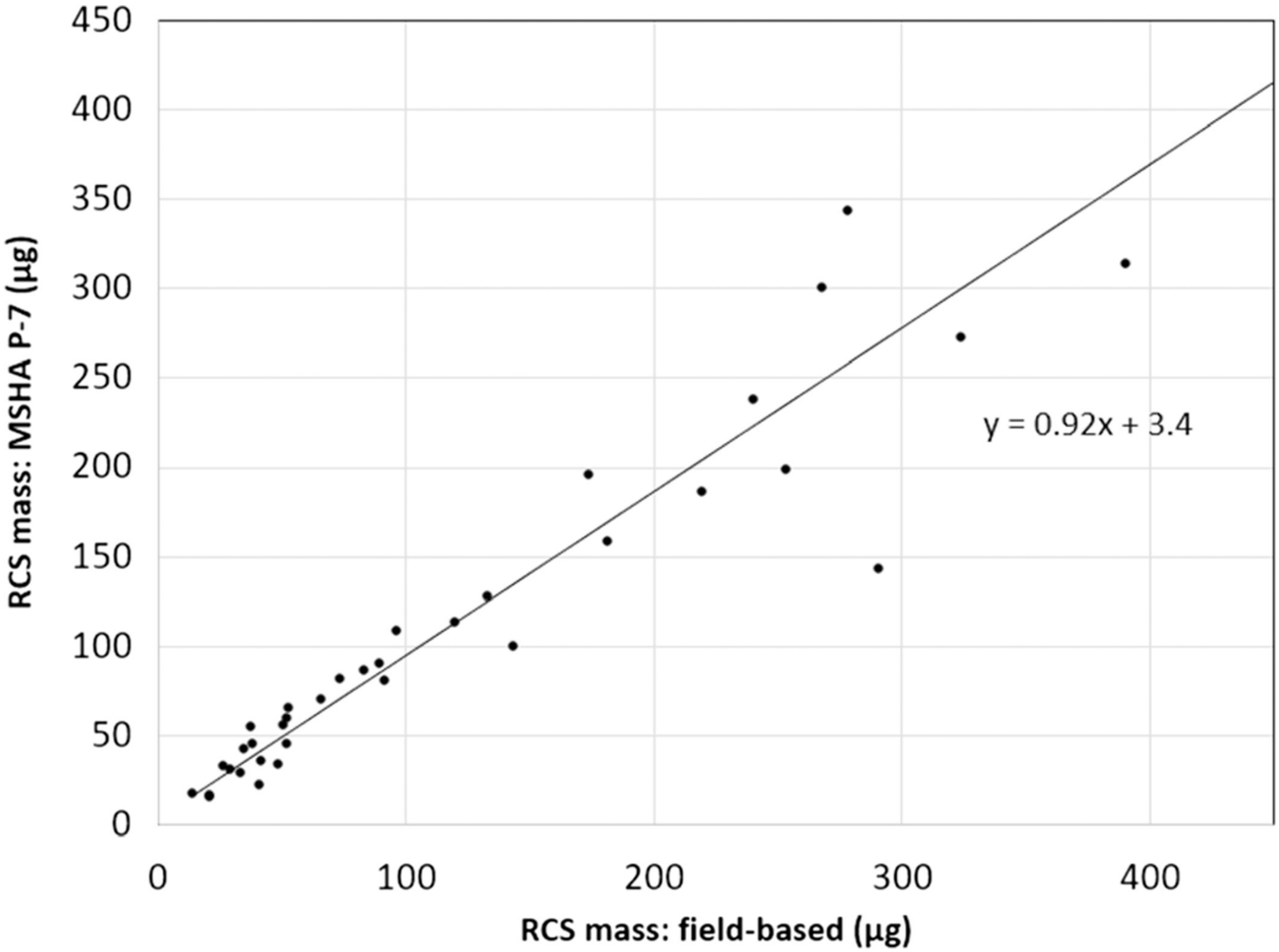

Fig. 5.
Comparison of field-based method versus MSHA P-7 method results by linear regression, Case Study Part 2

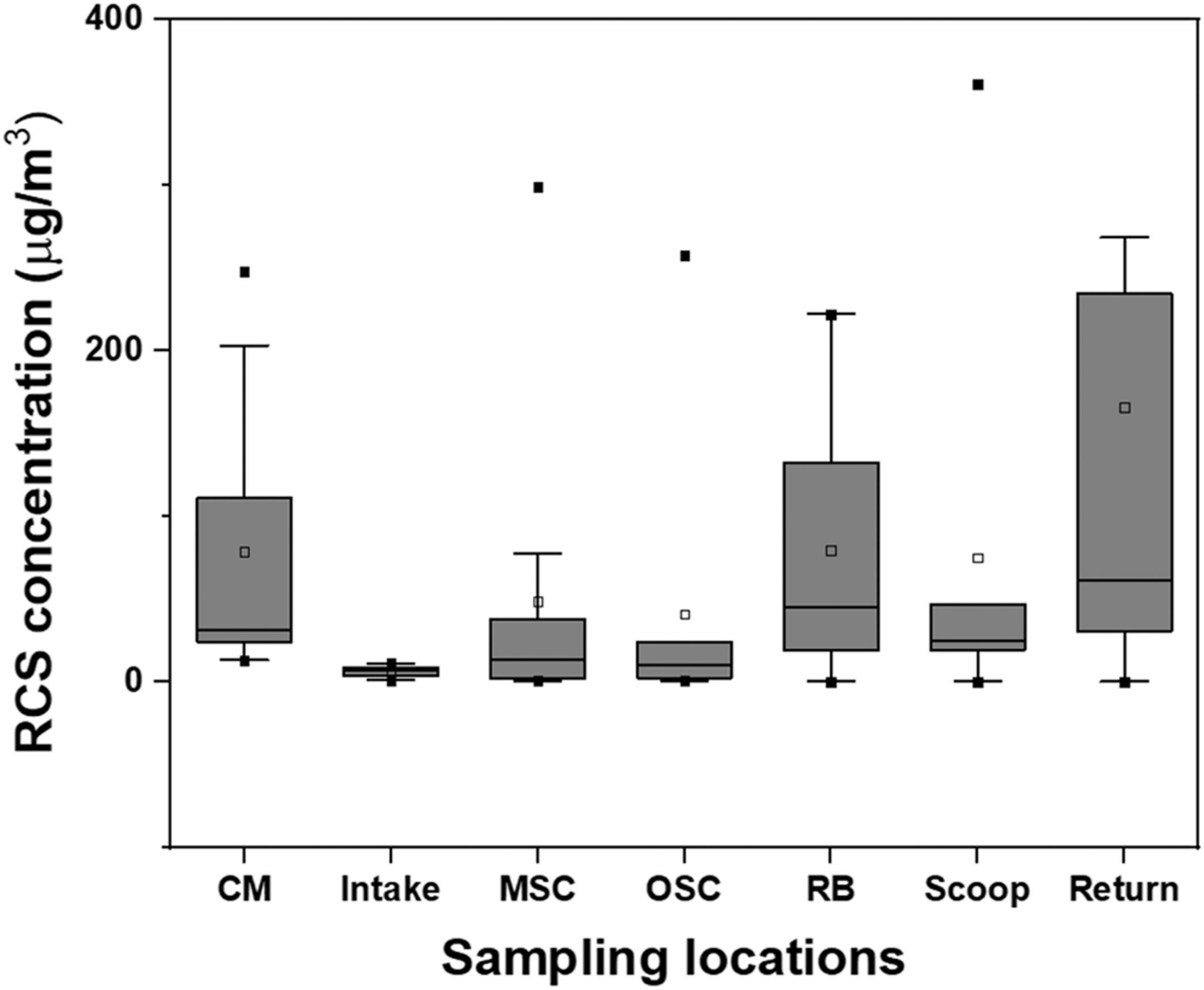

Fig. 6.

Full Case Study Part 2 data set, analyzed by field-based method, to show variability among samples collected in different locations. Each box represents the range 25%–75% of the data. The line is the median, the empty symbol the mean, and the black symbols the minimum and maximum. The whiskers are 1.5 times the standard deviation

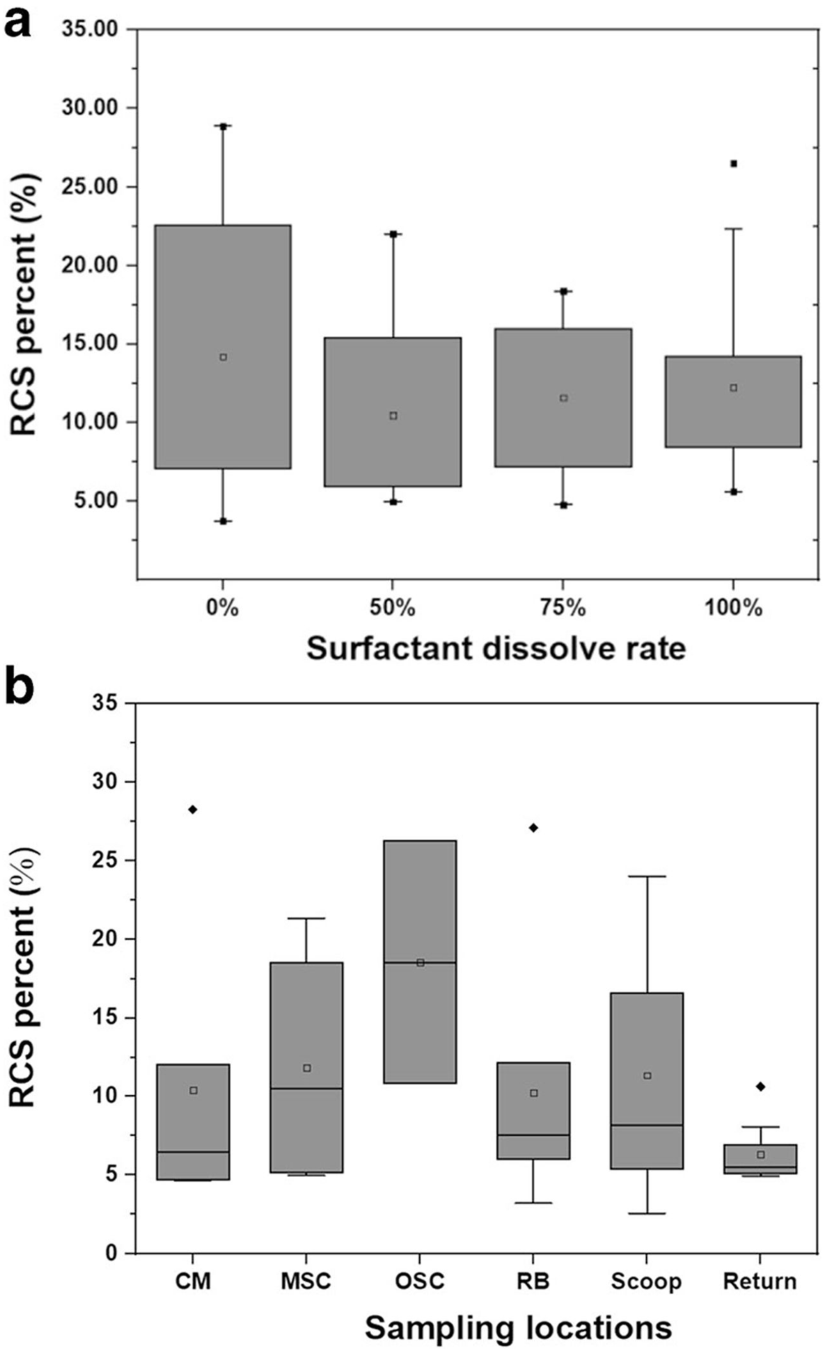

Fig. 7.

Crystalline silica fraction of total respirable dust is variable across conditions. Each box represents the range 25%–75% of the data. The line is the median, the empty symbol the mean, and the black symbols the minimum and maximum. The whiskers are 1.5 times the standard deviation. (**a**) Case Study Part 1, percent RCS by surfactant condition, (**b**) Case Study Part 2, percent RCS by occupation