Alpha Foundation for the Improvement of Mine Safety and Health

Final Report

1.0 Project Details

Project Title	Evaluation of New Respirable Silica Monitoring Tools for the Aggregates Industry
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2.0 Executive Summary

Respirable crystalline silica (RCS) exposure remains an important occupational health concern in the aggregates industry, creating a need for monitoring approaches that can provide reliable and timely information beyond conventional laboratory-based exposure assessment. More timely RCS measurements could help aggregate operations better characterize baseline conditions, identify important exposure sources, evaluate the effectiveness of dust controls, and respond to changing workplace conditions. This project evaluated two emerging approaches with potential to address this need: the AIR XS, a portable direct-reading monitor designed to provide real-time estimates of RCS concentration, and direct-on-filter Fourier transform infrared (DOF FTIR) analysis, which enables rapid analysis of traditional respirable dust filter samples using a portable FTIR spectrometer.

The technical performance of both approaches was evaluated through a combination of controlled laboratory testing and field sampling at aggregate operations. The AIR XS evaluation included 23 laboratory tests using 12 dust source materials, followed by field testing across 11 aggregate operations. The monitor generally responded to temporal changes in airborne particulate concentrations, and side-by-side testing demonstrated similar temporal response between two AIR XS units. However, quantitative agreement between AIR XS-reported RCS concentrations and reference measurements varied substantially across both laboratory and field conditions. Both substantial overestimation and underestimation were observed, and the differences could not be explained solely by RCS content or respirable dust concentration. The results indicate that additional aerosol characteristics, including mineralogical and physical properties of the dust, may influence AIR XS response and that further development and validation are needed before quantitative RCS measurements can be reliably interpreted across diverse aggregate environments.

DOF FTIR was evaluated using respirable dust samples collected during the field campaigns, with reference RCS measurements obtained using NIOSH Method 7500. Across the combined field dataset, FTIR quartz peak area (QPA) showed a strong linear relationship with reference RCS mass after exclusion of two statistical outliers (R^2 = 0.9512), demonstrating the potential for rapid estimation of RCS mass using traditional filter samples. The evaluation also identified important practical considerations. Localized filter overloading can affect measurements because the FTIR analysis interrogates only the central portion of the filter, while site-specific mineralogy can produce spectral interference within the quartz integration region. These findings support the use of representative calibration samples, visual spectral quality evaluation, and periodic reference laboratory measurements when implementing DOF FTIR in aggregate operations.

The field evaluations also provided opportunities to demonstrate both monitoring approaches to participating industry personnel and obtain feedback regarding their potential use. Participating operations were provided with their sampling results, and an aggregated summary of the field findings was subsequently shared with project partners. Industry feedback indicated considerable interest in obtaining more timely RCS information, particularly for establishing baseline exposure conditions, tracking changes over time, evaluating engineering and administrative controls, and supporting worker training. Practical considerations affecting

potential adoption included equipment and operating costs, ease of use, data interpretation, training requirements, and confidence in measurement performance.

Project findings were translated into practical informational resources, including a demonstration video describing the DOF FTIR sampling and analysis workflow and a practical guide for developing and maintaining site-specific DOF FTIR calibrations. Findings were also disseminated through conference presentations and two journal manuscripts describing the AIR XS and DOF FTIR evaluations, both of which were submitted for peer review and publication.

The project demonstrated both the potential and current limitations of emerging approaches for obtaining more timely RCS exposure information in aggregate operations. The technical findings, industry feedback, and informational materials developed through this project provide a foundation for informed implementation and continued advancement of more timely RCS monitoring approaches in the aggregates industry.

3.0 Problem Statement and Objectives

Respirable dust (RD) poses an occupational health hazard to mine workers, and overexposure can lead to various forms of pneumoconiosis and other respiratory diseases [1]. When exposures include respirable crystalline silica (RCS), there is increased risk of severe health outcomes, including lung cancer and silicosis [2,3]. Silicosis is an incurable fibrotic disease that can continue to progress even after exposure has ceased [4]. Historically, substantial attention in the United States has been directed toward reducing RD and RCS exposures in coal mines, where federal regulations have long required routine workplace dust monitoring and health surveillance [5].

In April 2024, the Mine Safety and Health Administration (MSHA) published a new silica rule intended to provide more uniform protection from RCS exposure across the mining industry [6]. Among other requirements, the rule lowered the RCS permissible exposure limit to 50 µg/m³, established an action level of 25 µg/m³, and increased sampling requirements for metal/nonmetal mines [6]. Implementation of these requirements presents practical challenges for operations with limited experience or resources dedicated to RCS monitoring and control. Aggregate operations are particularly relevant in this context because they represent approximately 70% of U.S. mines but only about 26% of permanent mine employees [6], reflecting a sector composed of numerous, often relatively small operations. Reliable and frequent RCS information could help these operations establish baseline conditions, identify important RCS sources, evaluate dust controls, and respond more efficiently to changing workplace conditions.

Traditionally, RCS exposure assessment relies on collection of respirable dust samples followed by post-collection analysis in certified laboratories, with turnaround times that can range from days to weeks [6,7]. To provide more timely information, NIOSH has advanced direct-on-filter Fourier transform infrared (DOF FTIR) spectroscopy for rapid analysis of traditional filter samples [8]. The method measures α-quartz directly on the filter and, when implemented using a portable spectrometer, can potentially provide results at or near the end of a work shift. Although previous field demonstrations showed promise [9,10], application in metal/nonmetal operations, including aggregates, may require site-specific calibration to account for interfering minerals or the presence of non-quartz RCS forms [11].

Particle counters offer another option for obtaining real-time information on airborne respirable dust. Previous studies have suggested pairing these instruments with filter sampling to estimate RCS concentrations "by proxy," whereby time-series RD measurements are interpreted using the average RCS content determined from the filter sample [10,12]. However, this approach does not directly distinguish RCS particles from other components of the respirable dust. Lower-cost particle counters are also available, although these instruments are generally designed for ambient monitoring and remain largely untested in mine environments [13].

The AIR XS represents a different approach because it was introduced as the first commercially available monitor specifically marketed for real-time RCS monitoring [14]. The instrument combines conventional particle counting and sizing with an optical classification approach intended to distinguish silica from other particles based on characteristic optical features [15]. This capability could potentially provide mine operators with continuous information on changing RCS concentrations rather than relying solely on total respirable dust measurements or RCS estimates by proxy. However, at the outset of this project, no peer-reviewed literature reporting independent AIR XS performance data was available, and the lack of publicly available validation data had raised concerns regarding its performance. Thus, objective evaluation across a range of dust conditions was needed before the monitor's potential applications in aggregate operations could be established.

These technologies represented two distinct approaches for obtaining more timely RCS information at aggregate operations. This project focused specifically on the following two RCS monitoring tools (Figure 1):

> **Tool 1. DOF FTIR**: Rapid analysis of traditional respirable dust filter samples using a portable Fourier transform infrared spectrometer, with the potential to provide RCS results at or near the end of a sampling shift.
>
> **Tool 2. AIR XS**: A portable particle-counting instrument with advanced optical technology designed to provide real-time estimates of RCS concentration.

The overarching goal of this project was to determine if, where, and how these tools might be effectively used at aggregate operations. The project was organized around three specific objectives:

> **Objective 1**. Evaluate the technical performance of both tools.
>
> **Objective 2**. Demonstrate tools to a range of aggregate operations and solicit feedback.
>
> **Objective 3**. Develop informational materials which convey key findings.

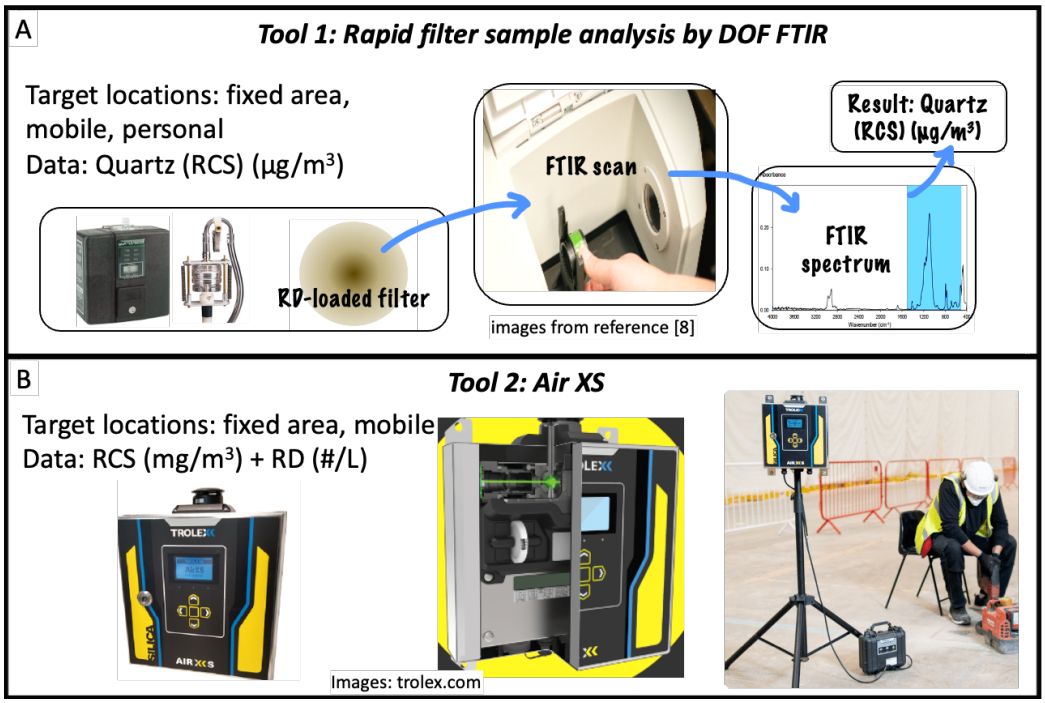


Figure 1. Two RCS monitoring tools being evaluated by this project.

4.0 Research Approach

The research approach was organized around the three project objectives. Under Objective 1, the technical performance of the two RCS monitoring tools was evaluated through controlled laboratory testing and field testing at aggregate operations. The AIR XS was first evaluated under controlled laboratory conditions and was subsequently deployed alongside DOF FTIR during field campaigns. The field visits also provided opportunities to demonstrate both tools and collect feedback from participating operations under Objective 2. Under Objective 3, project findings and lessons learned from the technical and field evaluations were used to develop practical informational materials for aggregate operators.

4.1 Objective 1: Evaluation of Technical Performance

The technical evaluation was conducted in two phases. First, controlled laboratory testing was performed to evaluate the AIR XS across a range of dust materials, RCS contents, and airborne dust concentrations. Second, field testing was conducted at aggregate operations to evaluate both the AIR XS and DOF FTIR under actual operating conditions. Reference aerosol monitors and established filter-based sampling and analytical methods were used as appropriate to evaluate the measurements produced by the two tools.

4.1.1 Laboratory Evaluation

A special testing chamber (Figure 2) was constructed to evaluate the AIR XS under controlled conditions. The chamber measured approximately 1.22 × 0.73 × 0.73 m, with a total volume of approximately 0.65 m³, and was constructed using extruded aluminum framing with clear polycarbonate wall panels and neoprene rubber seals. The end panels were designed for removal to provide access to the chamber. Two battery-powered fans were used to circulate airborne

particles, while test dust was introduced using compressed-air pulses through a jet mill. This configuration provided dispersion of fine particles throughout the chamber during testing.

The AIR XS was operated inside the chamber together with reference instrumentation. A TSI Optical Particle Sizer (OPS) 3330, which counts particles in the range of about 0.3-10 µm; and a TSI DustTrak™ DRX Aerosol Monitor 8530, which estimates the mass concentration of respirable dust (RD, i.e., measured as PM4) (Figure 3 top). These monitors were used as references for time series data logged by the AIR XS. Moreover, standard filter samplers (typically n=4) were used to evaluate the AIR XS TWA RCS concentration measurement. Each filter sampler consisted of a small air pump (operating at 1.7 L/min) and 10-mm nylon cyclone to collect respirable-sized particles directly onto a pre-weighed 37-mm filter housed inside a two-piece styrene cassette (Figure 3 bottom). Filters were post-weighed to determine total sample weight, and the TWA RD concentration was computed using the total sample volume. For the lab testing, the RCS content (mass %) of all dust feed materials was determined by a certified lab using the standard NIOSH Method 7500. Thus, the TWA RCS concentration during each test could be determined as a percentage of the TWA RD concentration.

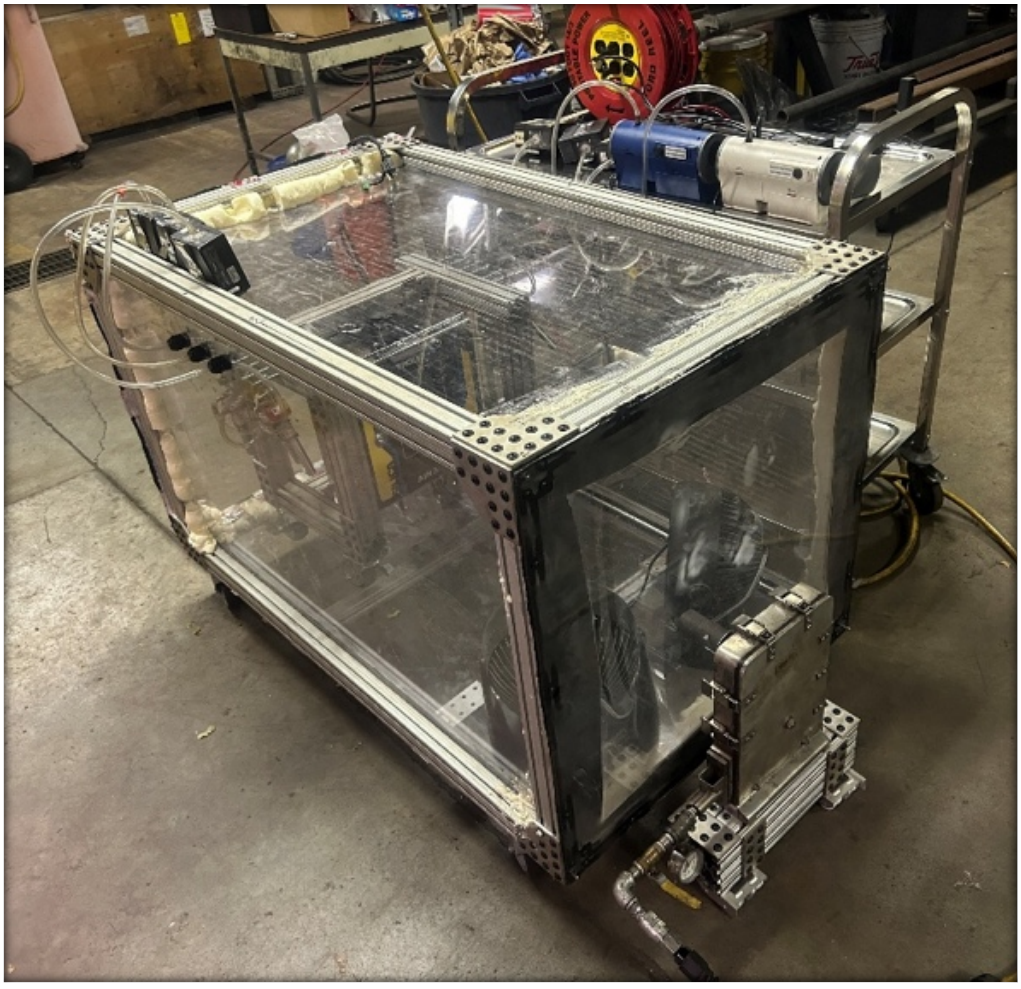


Figure 2. Chamber for lab testing of AIR XS.



Figure 3. Top: Optical Particle Sizer 3330 (left), DustTrak™ DRX Aerosol Monitor 8530 (middle), AIR XS (right). Bottom: Filter sampler cyclone and filter cassette assembly (left), air pump (right).

In total, we conducted 23 tests using dust generated from 12 different source materials: (1) Min-U-Sil 5, (2) Min-U-Sil 10, and (3) Min-U-Sil 40 are high-purity quartz materials that vary by particle size distribution; these are often used as reference materials for analytical method development. (4) Arizona Road Dust 0-5 µm [ISO 12103-1] and (5) Arizona Road Dust 0-10 µm are also standard reference materials with moderate quartz content; (6) High-purity kaolin powder, (7) limestone powder, and (8) sieved limestone powder represent materials with high crystalline mineral content but low RCS content; (9) pulverized raw coal, and (10-12) materials taken from the dust collection system on roof bolter machines in three separate coal mines were also used. The coal is mostly non-crystalline, providing an important reference for how the AIR XS responds to particles with little to no birefringence (since the AIR XS is designed to identify RCS based on principles of optical refraction). The bolter dust materials contain a variety of crystalline minerals, including RCS. In 19 tests, dust was sourced from only a single material; and in the other four tests, one of the Min-U-Sil products was combined with either the kaolin or raw coal.

Table 1 summarizes the particle size distributions (PSDs) of the 12 dust materials. Notably, for four tests (i.e., Tests 4, 11, 13 and 16) we included a second AIR XS–which we rented from a nationwide provider of industrial hygiene equipment–to enable comparison between two different units. Figure 4 shows the lab chamber setup for these 'dual AIR XS' tests.

Table 1: Particle size distributions for dust materials used for lab testing of AIR XS. Data are shown as the volume percentage of particles finer than each size class.

Size (um)	1 Min-U-Sil5	2 Min-U-Sil10	3 Min-U-Sil40	4 Arizona Road Dust 0-5 µm	5 Arizona Road Dust 0-10 µm	6 Kaolin powder	7 Limestone powder	8 Sieved Limestone	9 Coal (Mine13)	10 Bolter Dust (Mine24)	11 Bolter Dust (Mine 18)	12 Bolter Dust (Mine 13)
150	100	100	99.3	100	100	100	96.1	100	97	96.3	100	94.3
100	100	100	98.6	100	100	99.6	90.7	99.8	96.1	92.9	99.5	92.1
75	100	100	97.6	100	100	97.6	81.1	99.1	95.1	88.1	98.8	90.7
50	100	100	95.1	100	100	92	71.4	97.1	92.1	74.7	97.3	86.7
40	100	100	91.8	100	100	86.6	64.5	96.2	88.3	67.4	96.1	84.4
20	100	100	69	100	100	77.4	48.9	90.6	62.5	37.3	88.1	69.5
10	100	92.5	43.4	100	96.5	62.2	35.5	84.3	35.8	25.8	74.3	48.7
5	97.2	71	15.2	92.5	65.2	41.8	22.3	76.4	15.6	17.5	56.1	28.2
4	92.3	63.5	21.3	85.2	53.3	36	19.5	73.5	11.7	15.1	45.5	23.4
1.1	19.6	18.6	1.6	7.8	2.7	6.8	2.4	34.9	2.2	4.5	16.1	2.5
0.5	1.5	1.3	0	0.2	0	1.3	0	7.9	0.2	0.6	3.6	0.2
0.1	0	0	0	0	0	0	0	0	0	0	0	0

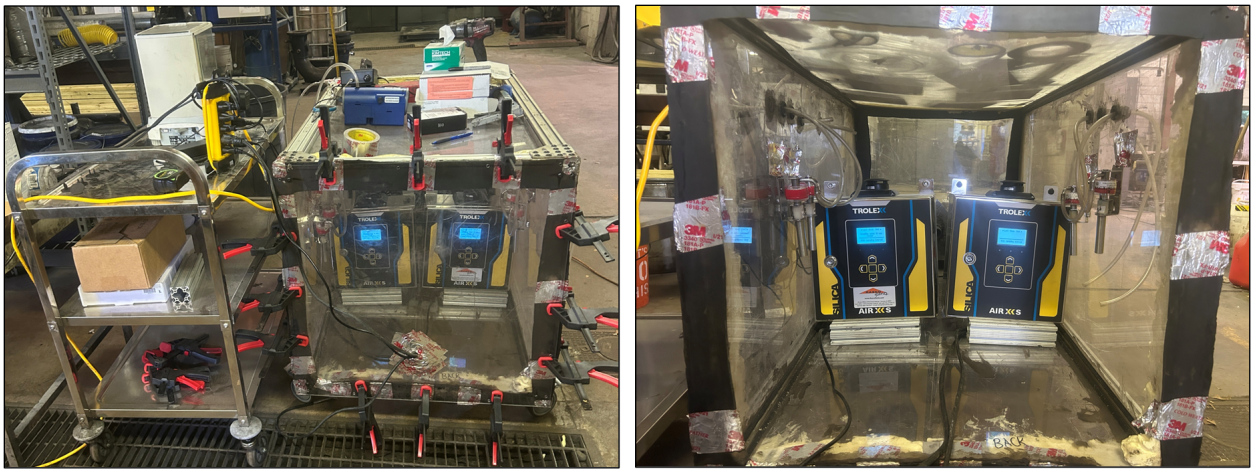


Figure 4. Test setup for dual AIR XS testing (external and internal view of chamber system.)

4.1.2 Field Evaluation

Field evaluations were completed at 11 aggregate operations to evaluate both the AIR XS real-time RCS monitor and the direct-on-filter Fourier transform infrared (DOF FTIR) method for rapid analysis of traditional respirable dust filter samples under representative workplace conditions.

The general field sampling strategy is illustrated in Figure 5. At each operation, respirable dust samples were collected at three locations selected in consultation with site personnel to represent a range of work activities and exposure conditions. Traditional filter samples were analyzed using both the DOF FTIR method and the reference laboratory method while real-time monitoring was conducted at one of these locations using the AIR XS together with two co-located reference aerosol monitors (i.e., the same TSI DustTrak 8530 and OPS 3330 instruments). Representative field sampling configurations are shown in Figure 6.

Location		Equipment		
		filter samplers	Trolex Air XS	Reference monitors
1	Fixed area	4x 		
2	Area, mobile	4x 		
3	Area, mobile	4x 		

Figure 5. Summary of sampling setup for field testing.



Figure 6. Filter samplers and the real-time monitors set up in different field testing locations. At the site shown in photo (1), we were able to collect data with our AIR XS and the unit we rented for limited lab testing.

Field sampling was designed to support evaluation of both the AIR XS monitor and the DOF FTIR method. At each sampling location, respirable dust samples for DOF FTIR analysis were collected in triplicate using pre-weighed 37-mm PVC filters (5-µm nominal pore size) housed in three-piece styrene cassettes with 10-mm nylon cyclones operated at 1.7 L/min. An additional respirable dust sample was collected on a polycarbonate filter for subsequent SEM analysis. Following sampling, PVC filters were gravimetrically analyzed to determine RD mass and corresponding TWA RD concentrations in our Virginia Tech lab. Each filter was then scanned with a Bruker Alpha II

portable FTIR spectrometer. The resulting spectrum was subjected to a blank PVC filter subtraction, and then the integrated area under the characteristic α-quartz doublet peak (QPA) was measured. A representative subset of samples was also submitted for reference laboratory analysis using NIOSH Method 7500 (X-ray diffraction) to evaluate the relationship between QPA and RCS mass.

To evaluate AIR XS performance under field conditions, the monitor's rolling 15-minute average RCS concentrations were compared with the corresponding rolling 15-minute average respirable dust concentrations measured by the co-located aerosol monitors to assess temporal response. In addition, AIR XS-reported TWA RCS concentrations were compared with the corresponding reference measurements obtained from paired filter samples analyzed using NIOSH Method 7500 to evaluate agreement with established laboratory methods.

4.2 Objective 2: Field Demonstrations and Industry Feedback

Activities under Objective 2 were conducted in parallel with the field evaluations described in Section 4.1.2. The approach was designed to provide participating aggregate operations with direct exposure to both RCS monitoring tools while also creating opportunities to obtain feedback regarding their potential usefulness and practical implementation.

Prior to each site visit, a brief meeting was held with participating personnel to provide an overview of the AIR XS and DOF FTIR approaches and explain the planned field activities. During each visit, project personnel demonstrated operation and setup of the AIR XS as well as the collection of traditional respirable dust filter samples and their subsequent analysis using the portable FTIR. The demonstrations also provided opportunities for site personnel to ask questions and discuss how the monitoring approaches might fit within their existing dust monitoring and control practices.

Following each site visit, a brief summary of the sampling results was prepared and provided to the corresponding industry partner. After completion of the field campaign, an aggregated summary of the field sampling results was also shared with participating partners. These communications were intended to provide context for the monitoring approaches and support subsequent discussions regarding their potential applications at aggregate operations.

In addition to feedback obtained through the field demonstrations and discussions, a structured survey was developed to collect input from industry partners regarding current RCS monitoring practices, monitoring needs, and considerations that could influence adoption of emerging monitoring technologies. The survey included questions addressing familiarity with emerging RCS monitoring approaches, current monitoring needs and objectives, potential applications for more timely RCS measurements, and practical factors that could affect implementation. Open-ended questions were also included to allow respondents to provide additional comments and identify considerations not captured by the structured questions.

The survey was distributed to participating industry partners following the field demonstration activities. The complete survey questionnaire is provided in Appendix A. Survey responses were subsequently compiled and analyzed to identify common themes related to monitoring priorities, perceived usefulness, and adoption considerations. The resulting findings are presented in Section 5.2, with summary charts provided in Appendix B.

4.3 Objective 3: Development of Informational Materials

Activities under Objective 3 focused on translating the technical findings and practical lessons from the project into informational materials that could support aggregate operators interested in more timely RCS monitoring. The materials were developed based on experience gained during the laboratory and field evaluations, discussions with participating industry personnel, and analytical considerations identified during evaluation of the two monitoring approaches.

Particular emphasis was placed on DOF FTIR because implementation of this approach requires several analytical and quality-assurance steps beyond routine collection of respirable dust filter samples. A demonstration video was developed to provide a practical overview of the DOF FTIR workflow, including filter handling and scanning, blank-filter subtraction, determination of QPA, and development of a calibration relationship between the FTIR response and reference RCS measurements. The material was developed with field operators and safety personnel as the primary audience and was intended to complement the demonstrations conducted during the field campaigns.

A practical implementation guide was also developed to describe a recommended approach for establishing and maintaining a site-specific DOF FTIR calibration. The guidance was informed by the field evaluation and was structured around the collection of representative respirable dust samples, paired DOF FTIR and reference laboratory analyses, review of FTIR spectra for potential interference, development and application of the calibration relationship, and periodic quality-assurance measurements. The purpose of this approach was to account for site-specific factors, including variations in dust mineralogy and spectral response, that could influence the relationship between QPA and RCS mass.

5.0 Research Findings

5.1 Objective 1: Evaluation of Technical Performance

5.1.1 Laboratory Evaluation

Table 2 summarizes the agreement between AIR XS-reported TWA RCS concentrations and the corresponding reference measurements obtained from gravimetric respirable dust samples analyzed using NIOSH Method 7500. Only four of the twenty-three laboratory experiments produced AIR XS measurements within the manufacturer's stated ±25% accuracy specification, whereas substantially larger deviations were observed for the remaining tests. The relative percent difference (RPD) for each experiment is summarized in Table 2 and presented graphically in Figure 7 as a function of (a) respirable crystalline silica content of the test material and (b) reference TWA respirable dust concentration.

Table 2: Summary of lab chamber tests with AIR XS.

Test	Dust Material	RCS Content (%)	Filter TWA RD Conc. (mg/m³)	Filter TWA RCS Conc. (µg/m³)	AIR XS TWA RCS Conc. (µg/m3)		Implied RCS Content (%)		AIR XS RPD (%)	
					Unit 1	Unit 2	Unit 1	Unit 2	Unit 1	Unit 2
1	Min-U-Sil5	75	3.01	2257	130		4		-94	
2	Min-U-Sil5	75	0.83	620	31		4		-95	
3	Min-U-Sil10	86	1.58	1357	100		6		-93	
4	Min-U-Sil10	86	2.36	2023	236	241	10	10	-88	-88
5	Min-U-Sil40	68	8.04	5475	240		3		-96	
6	Min-U-Sil40	68	0.61	414	85		14		-79	
7	Kaolin	0.7	16.81	118	730		4		520	
8	ARD 0-5 µm	8.3	0.32	27	52		16		93	
9	ARD 0-10 µm	8.8	0.25	22	19		8		-14	
10	ARD 0-10 µm	8.8	1.87	164	180		10		10	
11	ARD 0-10 µm	8.8	2.56	225	380	295	15	11	69	31
12	Pulverized Coal	0.4	0.6	2	52		9		2079	
13	Pulverized Coal	0.4	5.76	23	169	120	3	2	631	419
14	Limestone	1.3	0.45	6	73		16		1154	
15	Sieved Limestone	1.3	1.15	15	143		12		852	
16	Sieved Limestone	1.3	2.14	28	273	384	13	18	882	1282
17	Bolter_Dust_Mine24	23	0.56	126	77		14		-39	
18	Bolter_Dust_Mine18	13	0.98	123	138		14		12	
19	Bolter_Dust_Mine13	18	1.05	191	149		14		-22	
20	Kaolin+Min-U-Sil 5	18	0.71	129	80		11		-38	
21	Coal+Min-U-Sil 10	19	0.77	145	96		12		-34	
22	Coal+Min-U-Sil 10	40	0.93	373	136		15		-63	
23	Coal+Min-U-Sil 10	68	0.85	579	122		14		-79	

As shown in Figure 7a, AIR XS generally overestimated RCS concentrations for several materials containing relatively low silica contents, including coal-, kaolin-, and limestone-based dusts, while underestimation was more common for several materials with higher silica contents, such as Min-U-Sil reference materials. However, substantial variability was also observed among materials with similar RCS contents, indicating that silica content alone does not adequately explain monitor response.

Similarly, Figure 7b shows no consistent relationship between AIR XS RPD and reference TWA RD concentration. Materials tested over similar respirable dust concentration ranges often produced markedly different responses, while some materials exhibited relatively consistent bias across a broad range of dust concentrations. Collectively, these observations indicate that AIR XS performance was influenced by additional aerosol characteristics beyond respirable crystalline silica content or respirable dust concentration alone.

Figure 8 compares AIR XS-implied RCS content with the corresponding reference RCS content for all laboratory experiments. Overall, AIR XS-implied RCS content ranged from approximately 2% to 18% despite the substantially broader range of reference RCS contents represented by the test materials. These results further demonstrate that AIR XS response could not be explained solely by the actual RCS content of the dust, suggesting that additional aerosol characteristics influenced monitor response.

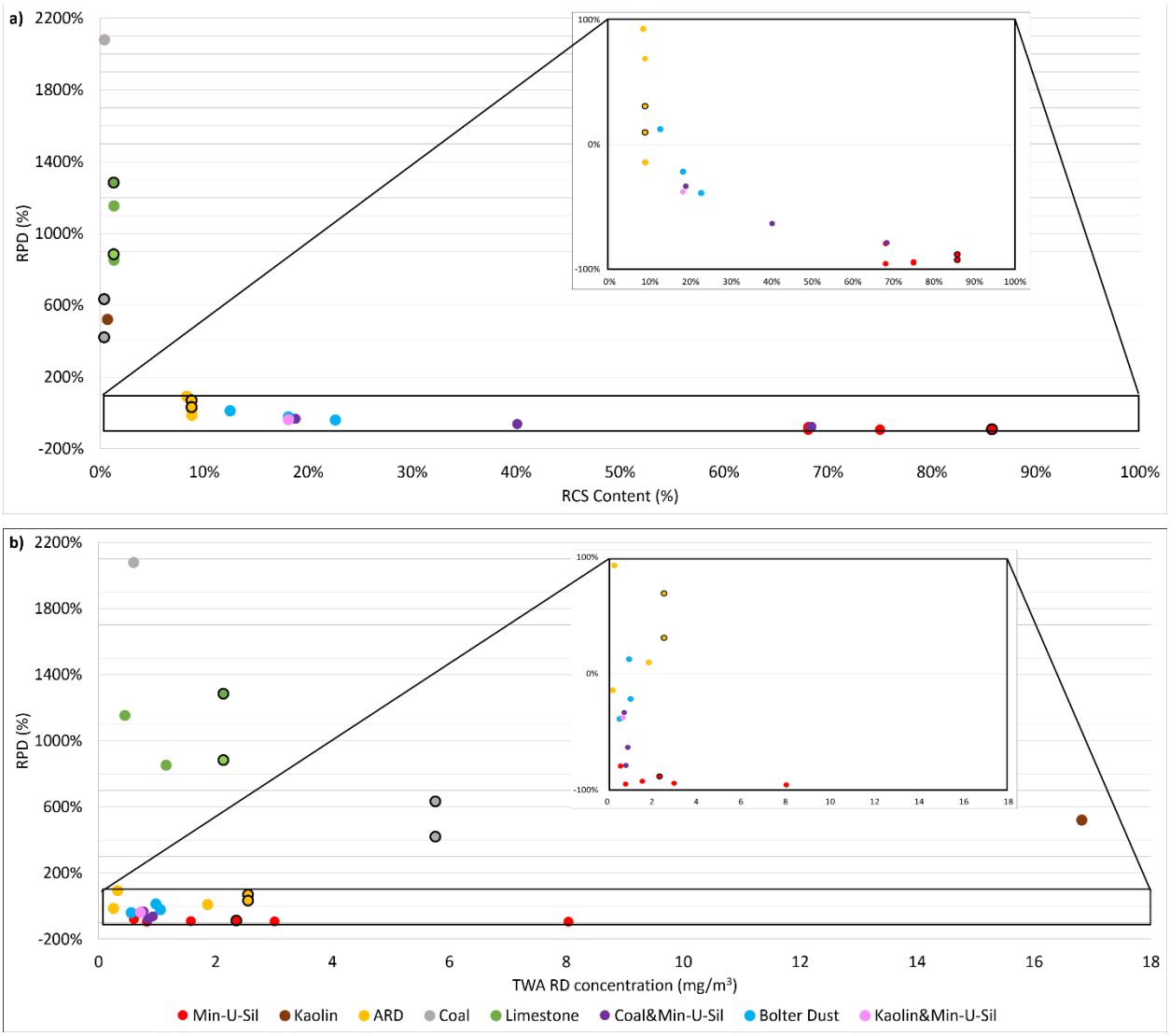


Figure 7. Relative percent difference (RPD) between AIR XS-reported and reference TWA RCS concentrations for the laboratory evaluation. Results are plotted as a function of (a) test material RCS content and (b) reference TWA RD concentration. Black-outlined symbols indicate experiments conducted with two AIR XS monitoring units.

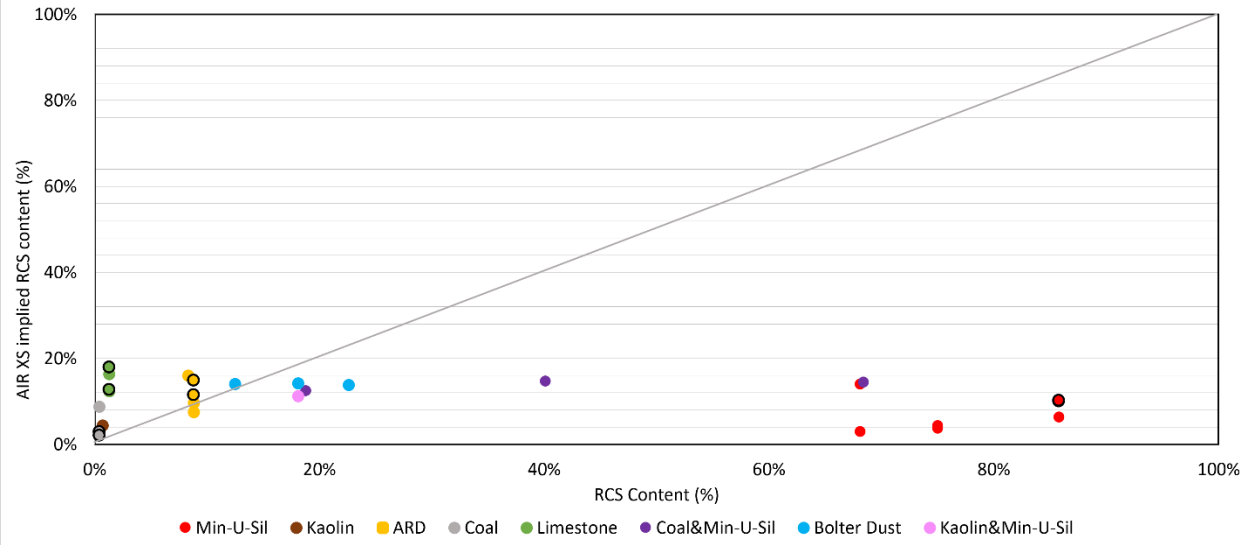


Figure 8. Comparison of AIR XS-implied RCS content and reference RCS content for the laboratory evaluation. Black-outlined markers indicate experiments performed using two AIR XS monitoring units.

Representative laboratory time-series measurements are presented in Figure 9. Although small differences between the two AIR XS units were observed during individual experiments, both monitors consistently captured the temporal changes in airborne particulate concentrations and closely followed the trends measured by the co-located DustTrak instruments. These results demonstrate good repeatability in monitor response to changing aerosol conditions. However, as demonstrated by the laboratory evaluation presented in Figures 7 and 8, consistent temporal response did not necessarily correspond to accurate TWA RCS measurements across the full range of dust materials evaluated.

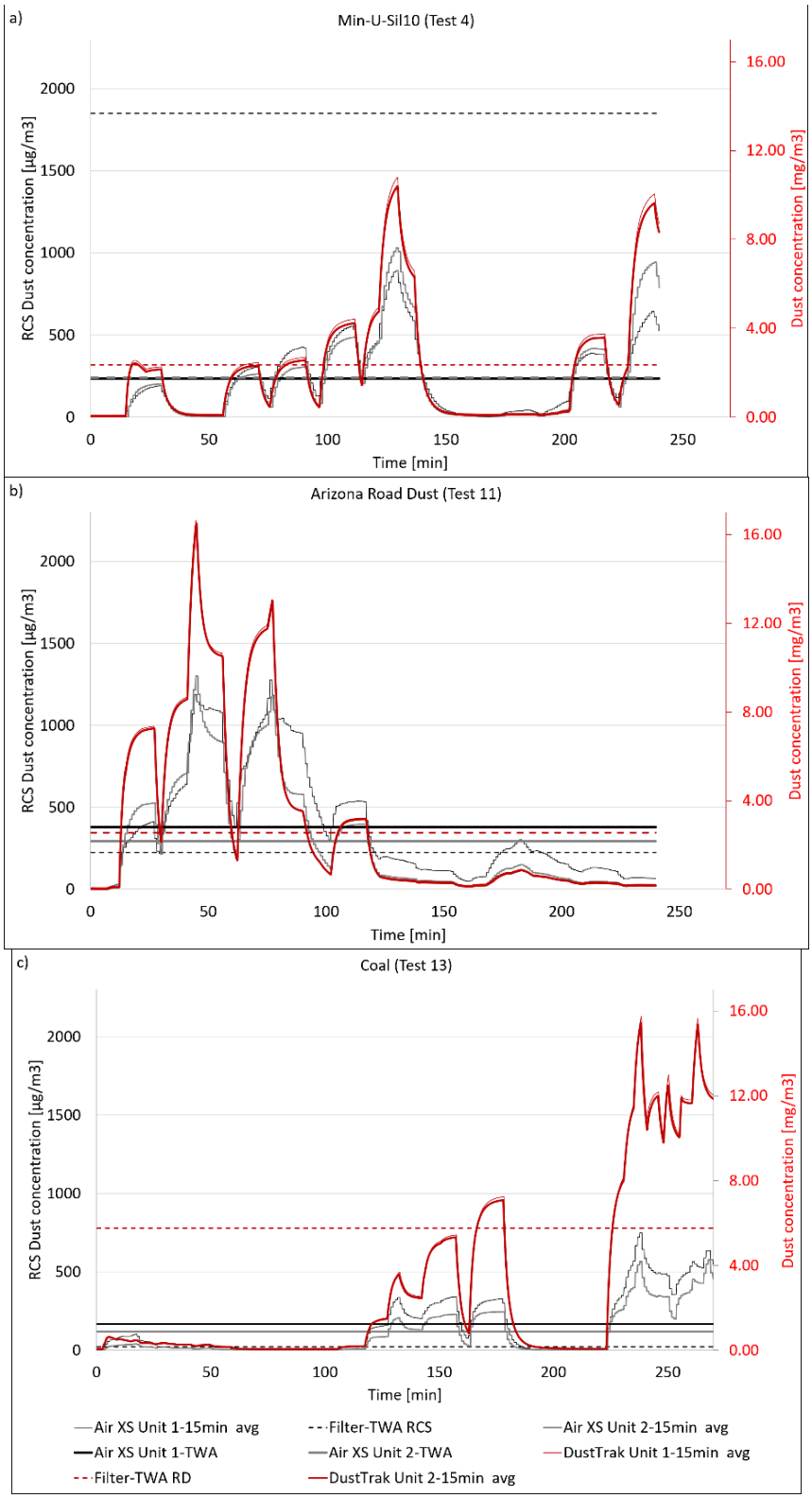


Figure 9. Representative time-series comparison of AIR XS-reported rolling 15-minute average RCS concentrations, reference TWA RCS concentrations, and DustTrak RD measurements for three laboratory experiments: (a) Min-U-Sil10 (Test 4), (b) Arizona Road Dust (Test 11), and (c) Pulverized Coal (Test 13). Two AIR XS monitoring units and two co-located DustTrak instruments were operated during each experiment.

5.1.2 Field Evaluation

Table 3 summarizes the field evaluation results obtained at the 11 aggregate operations included in this study, including two sampling campaigns conducted at Site 2. For each site, Table 3 presents the reference RCS concentration determined from paired filter samples, the corresponding AIR XS-reported TWA RCS concentration, the AIR XS-implied RCS content, and the resulting RPD between AIR XS and the reference measurements. (Notably, during the Site 4 and Site 11 tests, the Air XS stopped working prematurely. For these tests, the DustTrak data were used to estimate the reference RD and RCS TWA concentrations corresponding to the shorter Air XS sampling period; in essence, the ratio of the DustTrak TWA during the AIR XS sampling period to the full-test DustTrak TWA was applied to the full-test filter-based reference concentrations for RD and RCS.)

Table 3. Summary of field test data

Site	RCS Content (%)	Filter TWA RD Conc. (mg/m3)*	Filter TWA RCS Conc. (µg/m³)	AIR XS TWA RCS Conc. (µg/m3)		Implied RCS Content (%)		AIR XS RPD (%)	
				Unit 1	Unit 2	Unit 1	Unit 2	Unit 1	Unit 2
1	3	9.63	199	281		3		41	
2	<3	0.25	<8	154		63		1823	
	2	2.50	41	691		28		1577	
3	78	0.33	257	133		40		-48	
4	20	1.12 (1.36)	222 (269)	502		37		90	
5	21	0.36	75	36		10		-52	
6	16	1.78	282	295	383	17	22%	5	36
7	5	1.46	71	431		29		508	
8	38	0.10	40	12		12		-69	
9	6	2.08	131	1121		54		753	
10	4	0.39	15	130		34		740	
11	31	0.24 (0.56)	75 (176)	141		25		-20	

*Values shown in parentheses for tests at Site 4 and Site 11 were estimated for the time period during which the Air XS was operating.

The agreement between AIR XS-reported TWA RCS concentrations and the corresponding reference measurements varied substantially across the field evaluation. As shown in Figure 10, RPD values are presented as a function of (a) the reference RCS content and (b) the reference TWA RD concentration. Similar to the laboratory evaluation, AIR XS generally overestimated TWA RCS concentrations at sites with relatively low reference RCS contents while underestimation was more common at several sites with higher RCS contents. However, considerable variability was observed among sites with comparable RCS contents, and no consistent relationship was evident between RPD and either reference RCS content (Figure 10a) or reference TWA RD concentration (Figure 10b). These observations indicate that field performance, like laboratory performance, could not be explained solely by RCS content or airborne dust concentration.

Figure 11 compares AIR XS-implied RCS content with the corresponding reference RCS content for all field evaluations. Consistent with the laboratory results, the AIR XS-implied RCS content did not scale proportionally with the reference RCS content across the range of aggregate operations evaluated. While several sites with relatively low reference RCS contents produced substantially higher implied RCS contents, other sites with moderate or high reference RCS contents exhibited comparatively low implied values. These observations further support the conclusion that AIR XS response was influenced by additional aerosol characteristics beyond RCS content alone, likely reflecting differences in the mineralogical and physical properties of airborne dust encountered under field conditions.

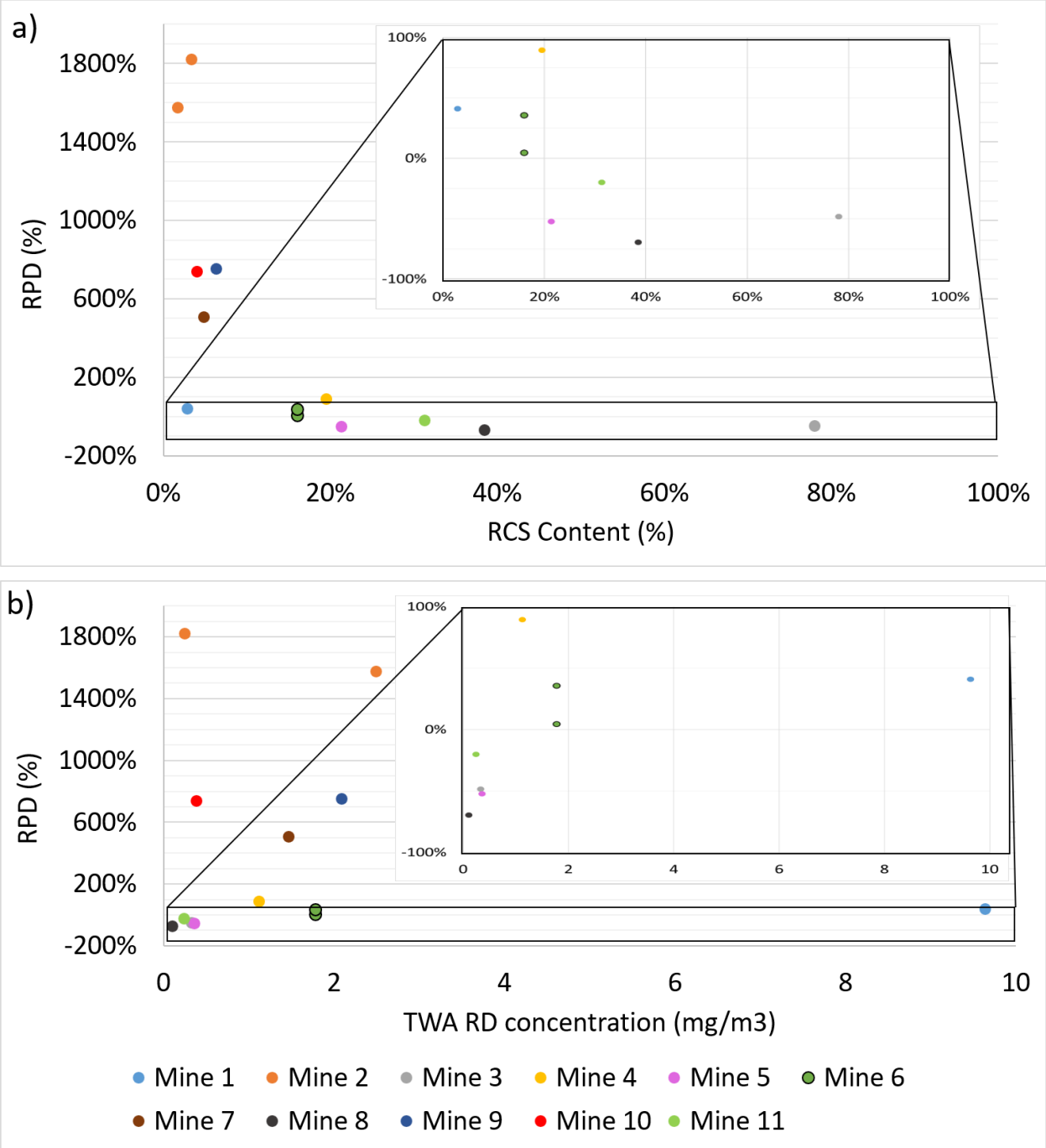


Figure 10. Relative percent difference (RPD) between TWA RCS concentration derived from the AIR XS versus reference measurements for the field tests. RPD values are shown as a function of (a) RCS content of the site dust and (b) TWA RD concentration during sampling. Data points with black outlines indicate tests conducted with two monitoring units.

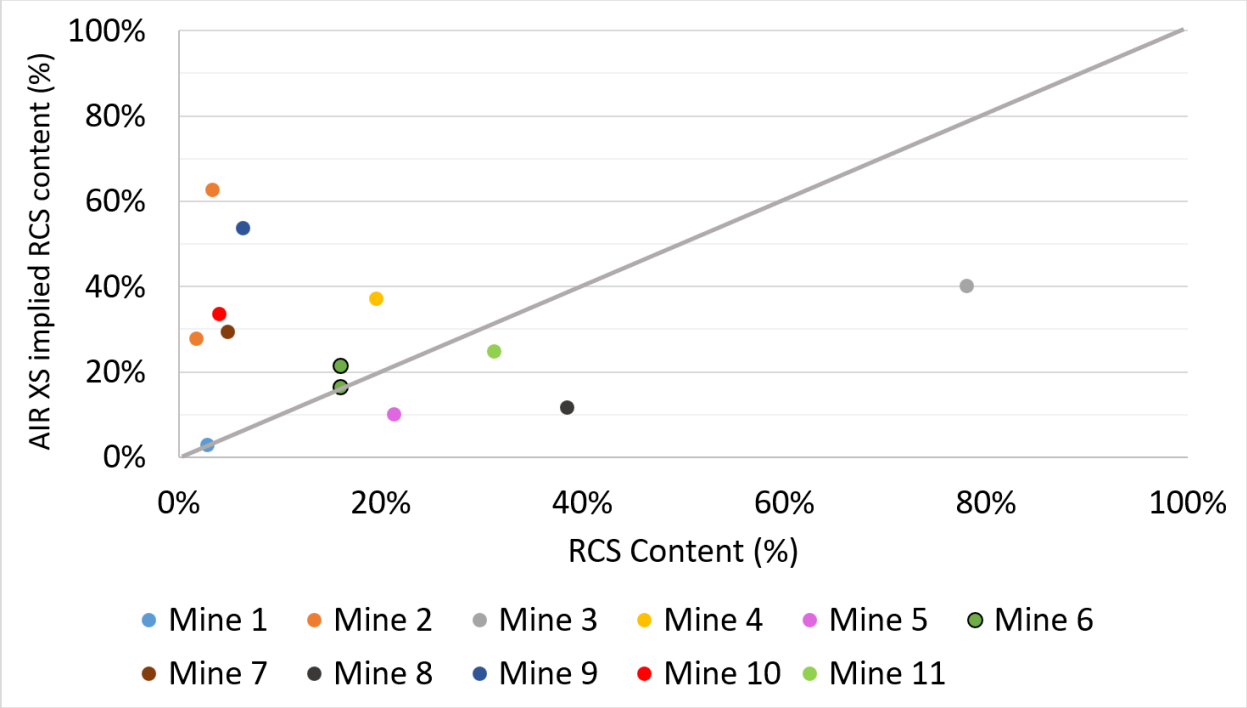


Figure 11. AIR XS-implied RCS content versus reference RCS content for the field tests. Data points with black outlines indicate tests where both AIR XS units were used.

A side-by-side comparison of two AIR XS monitoring units was completed during the evaluation at Site 6. Representative time-series data are presented in Figure 12, where measurements from both AIR XS units are compared with the co-located DustTrak aerosol monitor. Both AIR XS units exhibited similar temporal response characteristics and closely followed changes in airborne particulate concentrations measured by the DustTrak throughout the sampling period. Agreement with the reference TWA RCS concentration was also substantially better than that observed at many other field locations, with RPD values of 5% and 36% for the two AIR XS units. Although these results demonstrate good repeatability under the conditions encountered at Site 6, they should be interpreted within the context of the broader field evaluation, which showed substantial variability in monitor performance across different aggregate operations.

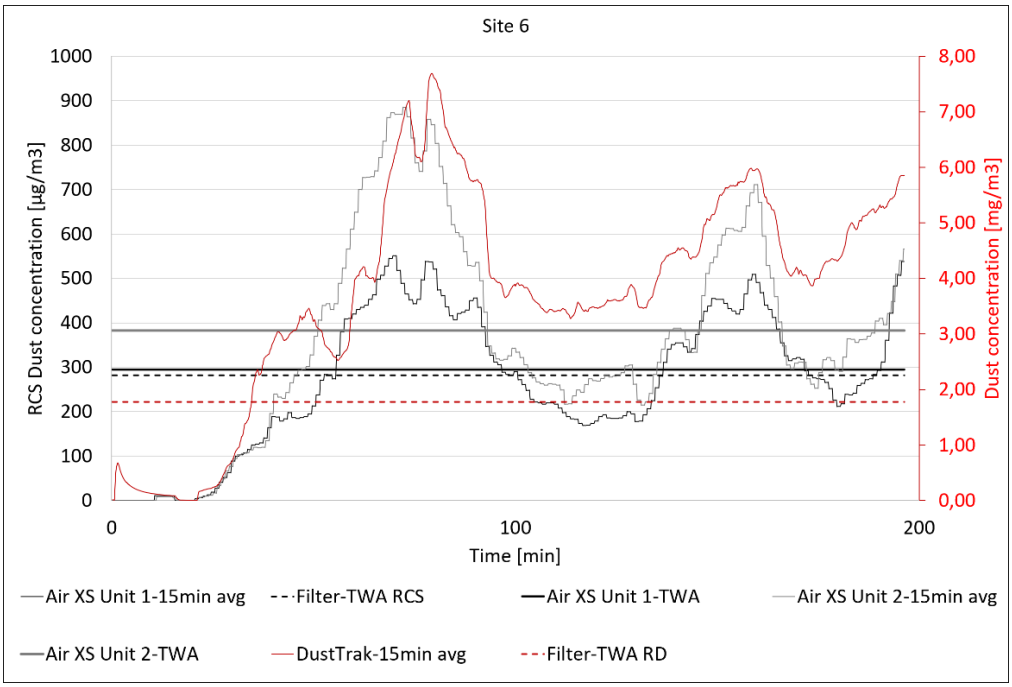


Figure 12. 15-minute rolling average RCS concentration reported by the AIR XS and PM4 concentration reported by the DustTrak for Site 6.

Table 4 summarizes the results obtained from DOF FTIR analysis together with the corresponding reference RCS masses determined by NIOSH Method 7500. DOF FTIR performance depends on the relationship between the integrated QPA and reference RCS mass. Throughout this study, quartz was identified as the predominant crystalline silica polymorph at all sampling locations, while cristobalite and tridymite were negligible, supporting the applicability of α-quartz-based FTIR analysis for these aggregate operations.

The relationship between QPA and reference RCS mass is presented in Figure 13. The dataset includes 36 paired samples collected from 11 aggregate operations, representing a broad range of RCS masses and geologic conditions. As expected, QPA was generally well correlated with measured RCS mass. One sample (from Site 10, Location 3) exhibited a clearly discordant QPA-RCS result and was excluded from the regression fit but retained in Figure 4 as an open data point. The regression was fit to the remaining 35 data points, and residuals were subsequently screened using the 1.5×IQR criterion. Two additional observations (from Site 9, Location 2 and Site 11, Location 3) were flagged by this screening but were retained in the regression because examination of replicate and supporting analytical data did not provide sufficient justification for their exclusion.

After exclusion of the Site 10–Location 3 sample, the linear regression model (n = 35) exhibited an $R^2 \approx 0.96$ and a relatively small y-intercept (0.01 QPA units; Figure 13). The fitted relationship was QPA = 0.0050(RCS mass) + 0.01, corresponding to an approximate conversion of QPA/0.0050 for estimation of RCS mass. This is remarkably similar to the model already used by the NIOSH FAST software for sampling under the same conditions used in this study (NIOSH, 2021). Greater variability in QPA response was observed at lower RCS masses, while samples with the highest RCS masses exerted substantial influence on the fitted regression.

Table 4. Summary of NIOSH Method 7500 and DOF FTIR analysis results.

Site ID	Sampling Locations	NIOSH Method 7500			DOF-FTIR
		RCS mass* (µg)	RCS Concentration* (µg/m³)	Estimated RCS Content* (%)	Mean QPA (STDEV)
1	L1: Haul Truck	<5	<3	<4%	0.041 (0.018)
	L2: Screens	88	199	2%	0.502 (0.082)
	L3: Crushers	10	12	5%	0.083 (0.008)
2-Day1	L1: Haul Truck	<5	<6	<9%	0.032 (0.017)
	L2: Lime Plant	<5	<8	<3%	0.049 (0.024)
	L3: Screen Tower	11	72	2%	0.065 (0.020)
2-Day2	L4: Screen Tower				0.049
		7	32	1%	0.03
		13	30	1%	0.074
		26	41	2%	0.14
	L5: Outside Screen Tower				0.025 (0.010)
3	L1: Jaw Crusher	59	66	71%	0.265 (0.026)
	L2: Cone Crusher	213	257	78%	1.124 (0.050)
	L3: Haul Truck	<5	<6	<23%	0.012 (0.013)
4	L1: Tertiary Plant	14	34	7%	0.179 (0.010)
	L2: Primary Plant	69	222	20%	0.343 (0.015)
	L3: Pit				0.026 (0.016)
5	L1: Feed Hopper				0.017 (0.014)
	L2: Crusher Discharge	44	75	21%	0.286 (0.016)
	L3: Loader Cab				0.036 (0.003)
6	L1: Jaw Crusher	76	169	14%	0.321 (0.039)
	L2: Dust Belt	94	282	16%	0.508 (0.030)
	L3: Cone Crusher				0.055 (0.018)
7	L1: Vibratory Screen	17	58	4%	0.025 (0.018)
	L2: Cone Crusher #1	23	71	5%	0.014 (0.007)
	L3: Cone Crusher #2	21	71	4%	0.007 (0.009)
8	L1: Screen House	9	56	39%	0.051 (0.012)
	L2: Mill	15	40	38%	0.092 (0.025)
	L3: Loadout Booth	192	579	77%	0.957 (0.171)
9	L1: QC Lab				0.006 (0.003)
	L2: Surge Tunnel	57	131	6%	0.202 (0.013)
	L3: Crusher Deck	56	129	23%	0.240 (0.117)
10	L1: Jaw Crusher	12	22	16%	0.070 (0.028)
	L2: Surge Tunnel	7	15	4%	0.119 (0.015)
	L3: Cone Crusher	28	65	3%	0.941 (0.105)
11	L1: Dryer Control Room	19	52	38%	0.106 (0.003)
	L2: Bulk Bagger Area	20	75	31%	0.131 (0.019)
	L3: Dryer Tower	152	461	35%	0.995 (0.178)

Representative FTIR spectra from sampled operations are shown in Figure 14. Although the characteristic α-quartz doublet was evident across all sites, variability in spectral structure surrounding the quartz response region was observed. Differences included variation in baseline shape, adjacent absorbance features, and overall spectral complexity. These differences were most pronounced for Site 7, with less pronounced differences evident for Sites 4 and 10.

Notably, QPA values at all three Site 7 sampling locations fell below the generalized QPA-RCS relationship, suggesting that the deviation at this operation was systematic rather than attributable to a single anomalous sample or specific sampling location. On the other hand, the two data points from Site 9 points that fell below the generalized trend were both from the same sampling location, whereas points two points from another location at this Site were consistent with the generalized trend. These observations suggest a location specific anomaly at Site 9.

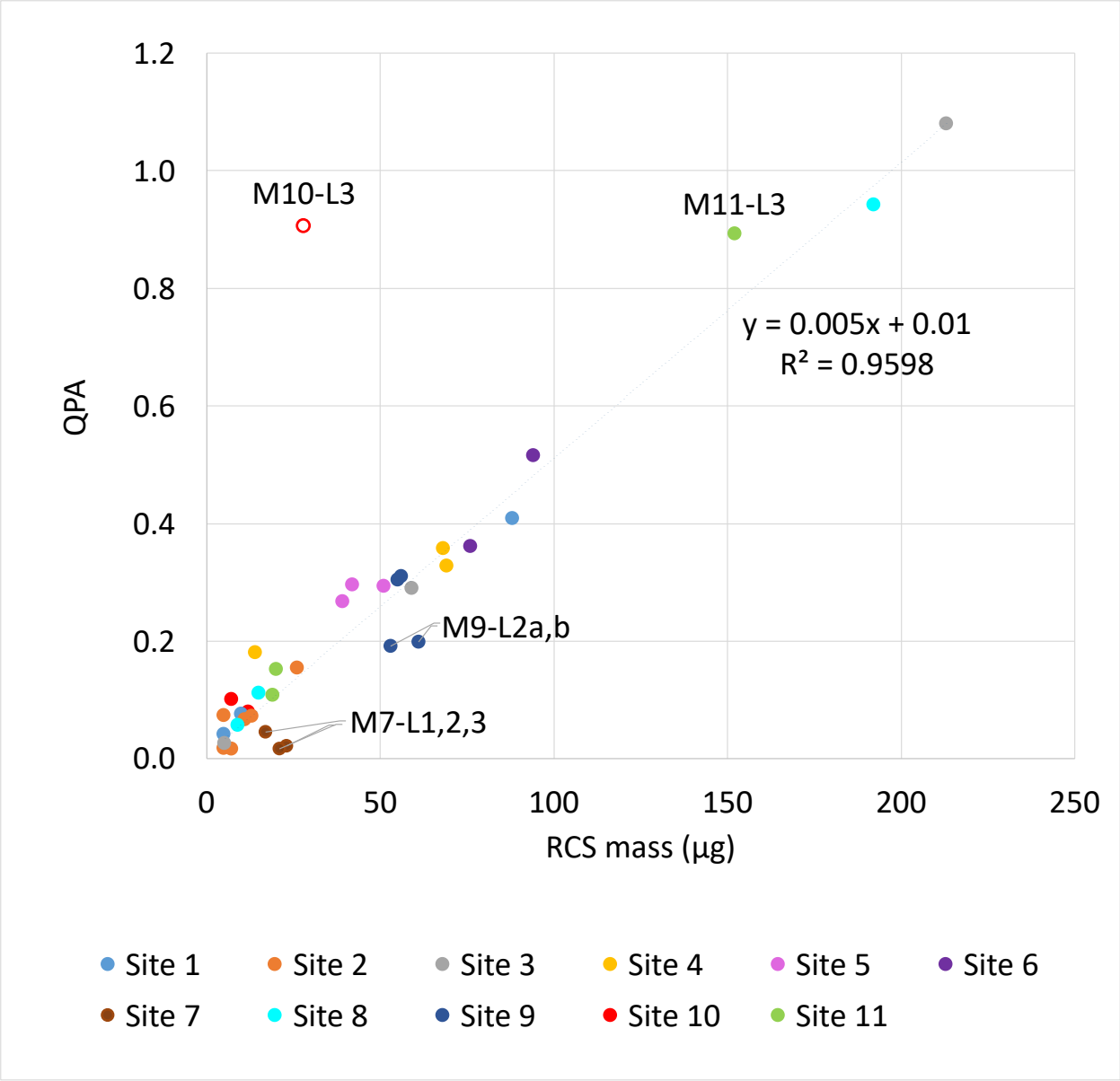


Figure 13. Relationship between DOF-FTIR QPA and reference RCS mass determined by NIOSH Method 7500.

As mentioned, a single sample from each site was also analyzed by SEM to gain insights regarding mineral composition of the respirable dust. In addition to quartz, a range of other silicate minerals was inferred across the sampled operations, including feldspars (e.g. orthoclase, albite) and other aluminosilicates. Substantial carbonate mineral content was also observed at the two limestone operations, as expected. Overall, silicate minerals (including quartz) and carbonates accounted for the great majority of mineral volume characterized by TIMA, although their relative proportions varied considerably among sites. These results are discussed in more detail in the manuscript associated with this particular study.

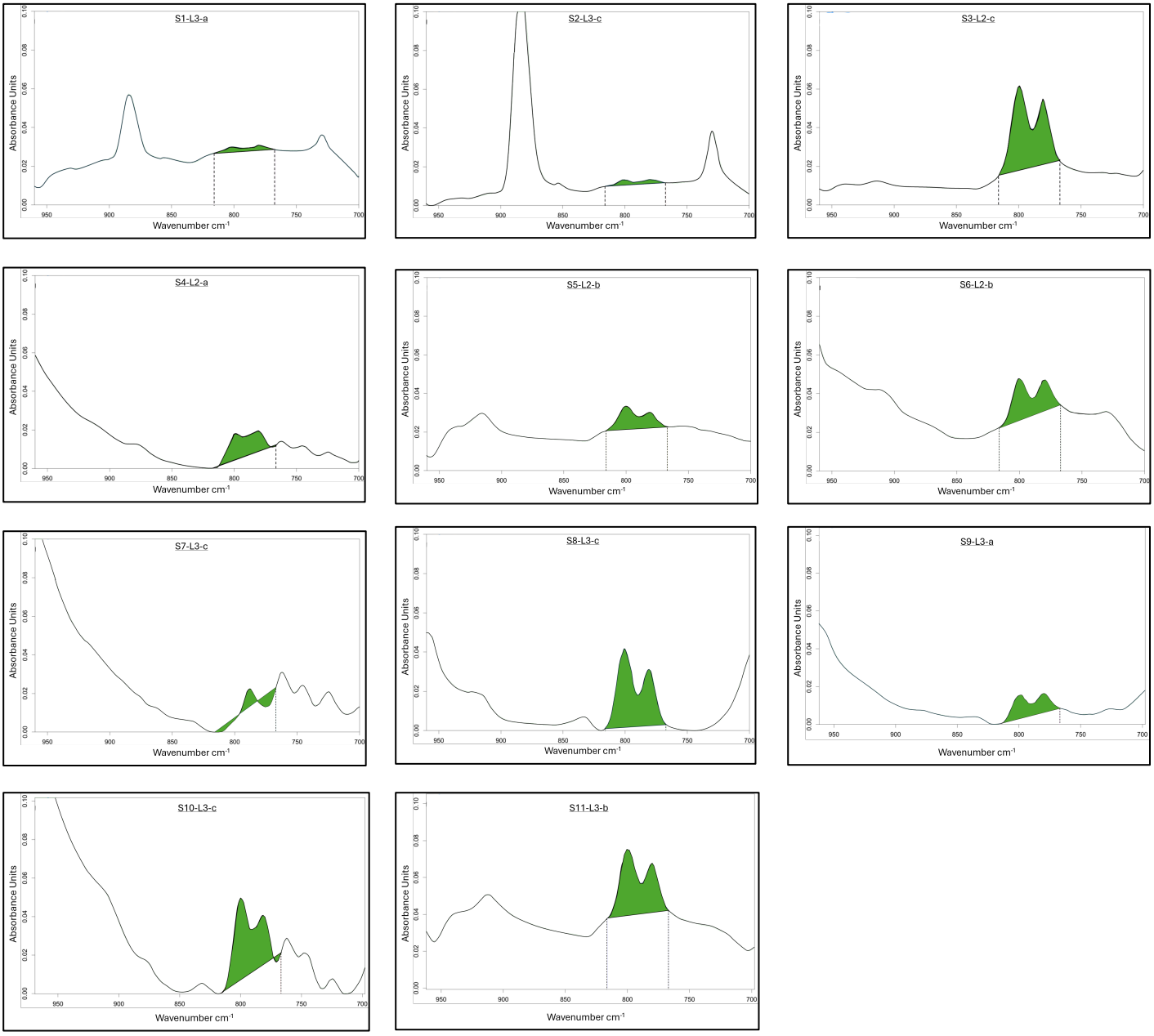


Figure 14. Representative FTIR spectra for samples collected in each aggregate production site. The shaded region represents the integrated quartz peak area (QPA) between 816-767 cm^{-1}.

5.2 Objective 2: Field Demonstrations and Industry Feedback

The survey consisted of four primary categories of questions:

1. Familiarity with Emerging Monitoring Tools
2. Current monitoring needs and objectives
3. Perceived usefulness of different monitoring tool capabilities
4. Factors affecting adoption of monitoring technologies

In addition, respondents were asked to provide open-ended feedback regarding respirable silica monitoring tools.

Familiarity with Emerging Monitoring Tools

Respondents were asked to evaluate their familiarity with the monitoring approach examined in this research project before and after participating in the field sampling activities.

In general, respondents reported limited familiarity with this type of monitoring tool prior to the project. After seeing the equipment during field testing and reviewing the project information, respondents indicated increased understanding of its potential applications. These responses suggest that direct exposure to emerging monitoring technologies through field demonstrations can significantly improve industry awareness and understanding of their potential uses.

Current Silica Monitoring Needs

Across the responding sites, several consistent monitoring priorities emerged. Nearly all respondents indicated that silica monitoring is needed not only for regulatory compliance but also for operational decision-making and exposure management.

The most commonly identified needs included:

- Establishing baseline silica concentrations across work areas
- Tracking changes in silica concentrations over time, particularly as geology or mining conditions change
- Evaluating engineering controls, such as dust suppression systems
- Assessing administrative controls and operational practices
- Supporting worker training and awareness programs

In several responses, participants also noted interest in improved monitoring capabilities that would allow more rapid feedback on exposure conditions, enabling quicker evaluation of control strategies.

Perceived Usefulness of Monitoring Technologies

The responses indicate strong interest in monitoring approaches that provide faster exposure information while maintaining acceptable reliability. Traditional compliance sampling methods, such as wearable filter samplers analyzed by certified laboratories, remain important because they are currently required for regulatory compliance. However, these methods are limited by the time delay associated with laboratory analysis.

Participants indicated that tools capable of providing near real-time or end-of-shift results could significantly improve the ability to evaluate exposure conditions and adjust operational controls.

In particular, respondents expressed interest in:

- Portable monitoring tools that could be used to evaluate specific work areas
- Wearable monitors that allow direct assessment of worker exposures
- Monitoring approaches that provide end-of-shift silica measurements

Factors Influencing Technology Adoption

Respondents also evaluated several factors that influence whether new monitoring tools would be adopted at aggregates sites.

The most important factors identified were:

- Ease of use
- Ease of data interpretation
- Ability to support regulatory compliance
- Cost of equipment and operation

Among these factors, the ability to generate clear and actionable data was repeatedly emphasized. Industry stakeholders indicated that monitoring tools must provide information that can be easily interpreted by site personnel and translated into operational decisions.

Cost considerations were also identified as important. While participants acknowledged the potential benefits of advanced monitoring technologies, equipment costs and ongoing operational expenses remain practical constraints for many sites.

Additional Feedback from Industry Participants

Open-ended responses provided additional insights into industry perspectives on silica monitoring. Several respondents emphasized the importance of continued research and development of improved monitoring tools for aggregates operations. In particular, participants expressed interest in monitoring technologies that could provide faster feedback while maintaining sufficient accuracy for operational decision-making.

Some participants also indicated willingness to continue collaborating in research efforts, highlighting the value of partnerships between industry and academic researchers in advancing exposure monitoring technologies.

5.3 Objective 3: Development of Informational Materials

In addition to peer-reviewed journal publications (see Section 6), two materials were developed related to the DOF FTIR method: a demonstration video and a practical guide for site-specific calibration.

5.3.1 DOF FTIR Demonstration Video

To support implementation of the project's findings, a demonstration video was developed describing the DOF FTIR method, including filter scanning, blank-filter subtraction, QPA determination, and the development of site-specific calibration factors. The video provides practical guidance for implementing the DOF FTIR method in occupational settings and has been shared with participating industry partners. It is also publicly available on YouTube at https://youtu.be/66B3xCOyEdk.

5.3.2 Practical Guide for Site-Specific DOF FTIR Calibration

A practical implementation guide was developed to summarize the recommended workflow for establishing and maintaining a site-specific DOF FTIR calibration (Figure 15). The guide was developed directly from the findings of this project and incorporates lessons learned during both the laboratory and field evaluations, including recommendations for representative sampling, calibration development, spectral quality assessment, and quality assurance.

Unlike traditional laboratory procedures, the guide was designed as a concise field reference for industrial hygienists, mine operators, and safety professionals responsible for RCS monitoring. The workflow emphasizes practical decision-making during implementation while incorporating the technical recommendations established through the DOF FTIR field evaluation described in Section 5.1.2.

The recommended workflow consists of seven sequential steps, each addressing a critical component of calibration development and implementation.

Step 1. Collection of Representative Samples

Development of a reliable calibration model begins with collection of representative respirable dust samples spanning the range of dust compositions and exposure conditions expected at the operation. Based on the findings of this project, a minimum of approximately ten representative samples is recommended. Samples should be collected over multiple days and from different production areas to ensure that the calibration reflects the variability in dust mineralogy encountered during routine operations. Including filters covering both low and high dust loadings further improves the robustness of the calibration.

Step 2. DOF FTIR Analysis

Each respirable dust filter should be analyzed using the DOF FTIR method following the analytical procedure developed during this project. This includes acquisition of the infrared spectrum, blank-filter subtraction, determination of the integrated quartz peak area (QPA), and evaluation of the spectrum within the quartz integration region. The QPA serves as the quantitative FTIR response used during calibration development.

Step 3. Reference Laboratory Analysis

The same filters should subsequently be submitted to an accredited laboratory for analysis using an accepted reference method, such as NIOSH Method 7500. These laboratory measurements provide the reference RCS mass required to establish the calibration relationship between FTIR response and respirable crystalline silica mass.

Step 4. Spectral Quality Evaluation

Prior to calibration development, each FTIR spectrum should be visually reviewed to verify acceptable spectral quality. As illustrated in Figure 15, spectra exhibiting a well-defined quartz doublet, stable baseline, and minimal spectral interference are generally appropriate for calibration development. Spectra affected by distorted quartz peaks, excessive filter loading, or mineralogical interference should be evaluated carefully before inclusion in the calibration dataset.

Step 5. Calibration Development

Following spectral quality evaluation, calibration is developed by relating measured QPA values to the corresponding laboratory-determined RCS masses using linear regression. Regression statistics should be evaluated to confirm that the calibration adequately represents the site-specific dust characteristics before being applied to routine field measurements.

The reference RCS mass obtained from the laboratory analysis is plotted on the x-axis, while the corresponding FTIR QPA values are plotted on the y-axis. A linear trendline is then fitted to the dataset.

A best-fit linear regression is then used to describe the relationship:

$$QPA = m * RCS\ mass + b$$

where m represents the calibration slope (i.e., the sensitivity of the FTIR response to changes in silica mass) and b represents the intercept, which accounts for baseline offsets or small systematic differences between the FTIR response and the reference laboratory measurements.

The strength of the calibration is evaluated using the coefficient of determination (R^2). A strong linear relationship indicates that FTIR measurements reliably track changes in silica mass for the dust composition at that site. If the data exhibit large scatter or poor correlation, this may indicate spectral interference, inconsistent sampling conditions, or insufficiently representative calibration samples.

Step 6. Application of the Calibration

Once the calibration relationship has been established, the regression equation can be rearranged to estimate respirable crystalline silica mass directly from the measured QPA of newly collected field samples:

$$Estimated\ RCS\ mass = \frac{QPA - b}{m}$$

where QPA is obtained from the FTIR spectrum of the filter, and m and b are the site-specific calibration coefficients determined during Step 5.

The estimated RCS mass can then be combined with the total sampled air volume to calculate the corresponding respirable crystalline silica concentration. Because the calibration coefficients are derived from representative dust collected at the same operation, the resulting estimates inherently account for site-specific mineralogical characteristics that influence the FTIR response.

Step 7. Quality Assurance

Periodic quality assurance is recommended to verify that the calibration remains representative of current site conditions. Approximately one out of every ten samples should periodically be submitted for reference laboratory analysis to confirm continued calibration performance. Recalibration should be considered whenever substantial changes in dust mineralogy, operating conditions, or spectral characteristics are observed.

MOTIVATION

Direct-on-filter (DOF) FTIR provides a rapid method for estimating respirable crystalline silica (RCS) mass and airborne concentration from respirable dust samples. While not accepted for regulatory compliance, DOF FTIR can be a valuable engineering tool for baseline monitoring, silica dust source identification, and evaluation of engineering controls. This guide outlines a practical approach for developing and applying site-specific calibrations for improved field measurements.

WANT TO LEARN MORE?

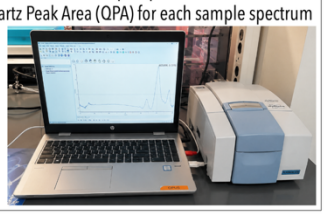
Check out this short video on dust sampling and DOF FTIR analysis for respirable crystalline silica

Step 1 - Collect Representative Samples

- Collect a minimum of 10 representative respirable dust samples
- Cover the expected concentration range
- Include different work locations and job tasks
- Use full-shift or breathing-zone sampling whenever possible

STEP 2 - Analyze Filters by FTIR

- Analyze each PVC filter using DOF FTIR
- Analyze a blank PVC filter (from the same lot, if possible)
- Perform a blank subtraction for each sample spectrum
- Then determine the Quartz Peak Area (QPA) for each sample spectrum by integrating the area under the curve in the quartz doublet range (816–767 cm^{-1})
- *Always be sure to use consistent acquisition parameters*



STEP 3 - Obtain Reference Measurements

- Submit the same filters to an accredited laboratory
- Analyze using an accepted reference method (e.g., NIOSH 7500 / XRD)
- Record reference respirable crystalline silica (RCS) mass
- Include samples covering the expected concentration range

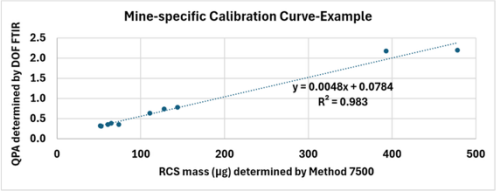
STEP 4 - Evaluate Spectra Before Calibration

- Review every spectrum before developing the calibration model.
- (See the other side for example spectra evaluations.)
- Only spectra with acceptable spectral quality should be included in the calibration dataset.

STEP 5 - Develop Calibration Curve

- Plot Quartz Peak Area (QPA) versus reference RCS mass
- Fit a linear regression model
- Evaluate calibration performance (R^2 and residuals)
- If performance is acceptable, the regression equation can be used to establish a site-specific calibration factor, e.g.,

$$RCS\ mass = \frac{QPA}{slope}$$



STEP 6 - Apply Site-Specific Calibration for RCS Monitoring

- Collect filter samples, measure QPA using same FTIR instrument and conditions
- Apply Site-Specific calibration factor to estimate RCS mass (µg)

STEP 7 - Quality Assurance

- Periodically verify calibration performance, e.g.,
  - Analyze some minimum % of samples using the reference method
  - Investigate unexpected results
- Update the calibration when site conditions or mineralogy change

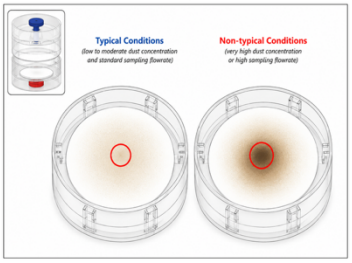
Reference

Chubb, L. G., & Cauda, E. G. (2022). Direct-on-filter analysis for respirable crystalline silica using a portable FTIR instrument. NIOSH Mining Program Information Circular, IC 9533. Pittsburgh (PA): National Institute for Occupational Safety and Health (NIOSH). https://purl.fdlp.gov/GPO/gpo173580

NOTES OF CAUTION

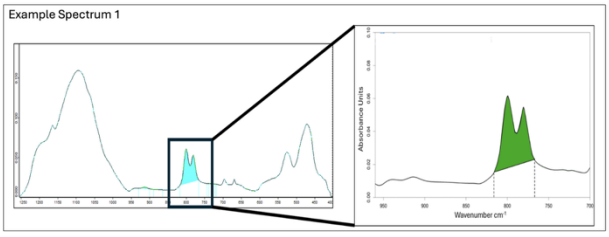
Collecting Suitable Samples for DOF FTIR Calibration and Analysis

- Since QPA values derived from a central scan area (filter center), and then correlated to RCS mass values representing an entire filter, dust deposition patterns must be consistent between filters
- Thus, filter samples should be collected under standard flowrate conditions and typical dust concentrations
- Further, filter samples must be handled carefully to avoid dust disturbance or contamination



CHARACTERISTICS OF HIGH-QUALITY SPECTRA

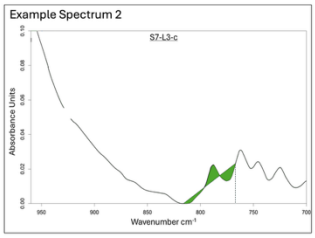
- FTIR instrument well maintained, and passes internal calibration checks
- Spectra exhibit stable baselines and low noise
- No interfering peaks near the characteristic quartz doublet range (816–767 cm^{-1})
- Example spectrum 1 is considered high quality

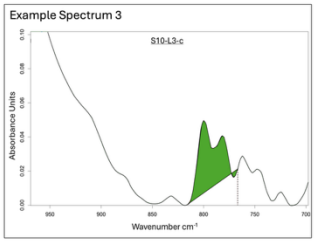


COMMON INDICATORS OF POOR-QUALITY SPECTRA

POORLY RESOLVED OR DISTORTED QUARTZ DOUBLET

- This often indicates mineral interference with the quartz measurement
- Example Spectra 2 and 3 both exhibit clear peaks to the right of the characteristic quartz double range; these adjacent peaks have substantial effect on the QPA baseline slope, effectively reducing the QPA value
- For Example Spectrum 2, the effect on QPA value may be relatively small; however, for Example Spectrum 3, the QPA value becomes negative due to areas which fall above the curve.





MINERAL INTERFERENCE WITHOUT OBVIOUS DISTORTION

- Mineral interference without obvious distortion is also possible, such as in the case of kaolinite
- Kaolinite has a primary peak near 930-900 cm^{-1}, and a secondary peak occurring within the quartz doublet range as shown in Example Spectrum 4; thus, presence of kaolinite may positively bias quartz estimates.
- For samples where kaolinite is the only suspected interferent, a correction factor might be applied

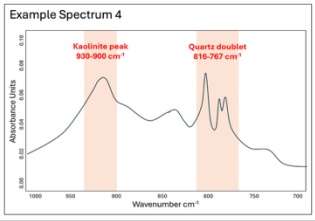


Figure 15. Practical workflow for development and implementation of a site-specific DOF FTIR calibration for respirable crystalline silica monitoring.

6.0 Publication and Dissemination Efforts

Project findings have been disseminated through journal manuscripts, professional presentations, informational materials, and direct communication with participating industry partners. These activities were intended to communicate both the technical findings of the project and their practical implications for RCS monitoring in aggregate operations.

Two journal manuscripts were prepared based on the technical evaluations conducted under Objective 1. The first manuscript reports the laboratory and field evaluation of the AIR XS, including its quantitative performance relative to reference RCS measurements and its ability to track temporal changes in airborne particulate concentrations. The second manuscript reports the field evaluation of DOF FTIR using samples collected across participating aggregate operations, with emphasis on the relationship between QPA and reference RCS mass, calibration considerations, and factors such as filter loading, spectral interference, and mineralogical variability. Both manuscripts have been submitted for peer-reviewed publication.

1. Uluer, ME, Sarver, E. (in revision) Field Study of Direct-on-Filter FTIR to Estimate Respirable Crystalline Silica in Aggregate Operations. Submitted journal: Journal of Occupational and Environmental Hygiene.
2. Uluer, ME, Sarver, E. (in review) Laboratory and Field Testing of a Real-Time Respirable Crystalline Silica Monitor. Submitted journal: Journal of Occupational and Environmental Hygiene.

Project findings related to DOF FTIR were also disseminated through professional conferences. A presentation entitled "*Evaluating Direct-on-Filter FTIR Analysis for Respirable Silica Monitoring at Aggregates Operations*" was delivered at the 2026 Society for Mining, Metallurgy & Exploration (SME) Annual Conference & Expo. This presentation provided an opportunity to communicate the project findings to a broader mining and occupational health audience and discuss the potential application of portable FTIR analysis for obtaining more timely RCS information from traditional respirable dust filter samples.

A project poster entitled "*Practical Guide to Site-Specific Calibration for Direct-On-Filter FTIR Analysis of Respirable Crystalline Silica*" was subsequently prepared and presented at the 2026 Society of Mining Professors (SOMP) Annual Meeting.

The DOF FTIR demonstration video developed under Objective 3 (Section 5.3) was also made publicly available online and shared with participating industry partners, further extending dissemination of the project findings and practical guidance.

Dissemination to participating industry partners occurred throughout the field component of the project. Site-specific sampling summaries were provided following individual field visits, and an aggregated summary of the field results was subsequently shared with participating partners. Field demonstrations, follow-up communications, survey activities, and the informational materials developed through the project provided multiple opportunities for industry personnel to engage directly with the findings and consider potential applications of the evaluated monitoring approaches.

7.0 Conclusions and Impact Assessment

This project evaluated two emerging approaches for obtaining more timely information on RCS exposures at aggregate operations: the AIR XS for direct real-time monitoring and DOF FTIR for rapid analysis of traditional respirable dust filter samples. Through controlled laboratory testing, field evaluations across 11 aggregate operations, and direct engagement with industry partners, the project provided independent information regarding the technical performance, practical capabilities, and limitations of both approaches. The work also extended beyond instrument evaluation by considering how these technologies could be implemented and interpreted in operational settings.

The laboratory and field evaluations demonstrated that the AIR XS can respond to temporal changes in airborne particle concentrations. In both controlled testing and selected field measurements, AIR XS measurements generally followed changes observed by co-located aerosol monitors, indicating potential utility for identifying changes in airborne dust conditions. However, its quantitative estimates of RCS concentration showed substantial variability relative to reference measurements. Laboratory testing revealed a general tendency toward overestimation at relatively low RCS contents and underestimation at higher RCS contents, while field performance was even more variable across operations. The results therefore indicate that, although the AIR XS may provide useful time-resolved information on changing aerosol conditions, its quantitative RCS measurements should be interpreted cautiously based on the performance observed in this study.

DOF FTIR demonstrated much better potential for practical application as a rapid analytical approach for traditional respirable dust filter samples. Across the field dataset, QPA exhibited a strong correlation with RCS mass determined by the reference laboratory method, illustrating how portable FTIR measurements can provide useful estimates of RCS mass substantially sooner than conventional off-site analysis. Although the combined field dataset supported development of a generalized relationship between QPA and RCS mass, the results also showed the value of site-specific validation—and possibly calibration. A calibration developed from representative samples collected at an individual operation can better account for local geology, mineralogical composition, and associated spectral behavior. Periodic comparison with an accepted reference laboratory method can then provide quality assurance and indicate when changes in site conditions warrant updating the calibration. Under this framework, DOF FTIR is best viewed as a complementary approach that can provide more timely information from traditional filter samples while maintaining a connection to established reference analytical methods.

The project also demonstrated that technical performance alone does not determine whether an emerging monitoring technology will be useful in aggregate operations. Field demonstrations and industry engagement highlighted the importance of practical considerations such as ease of use, training requirements, cost, confidence in measurement accuracy, and the ability to translate measurements into actionable information. The survey and discussions with participating operations further indicated potential value for more timely RCS information in establishing baseline conditions, identifying important dust sources or changing conditions, evaluating controls, and supporting proactive exposure-management decisions.

To support translation of the research findings into practice, the project produced informational resources addressing implementation of DOF FTIR, including guidance for site-specific calibration and quality assurance. These resources, together with the field demonstrations and dissemination activities described in Sections 5.3 and 6.0, provide aggregate operators with practical information for understanding not only the potential benefits of more timely RCS measurements, but also the limitations and analytical considerations that must be addressed before those measurements are used for decision-making.

8.0 Recommendations for Future Work

The findings of this project identify several areas where additional research would strengthen understanding of both monitoring approaches and support their appropriate application in aggregate operations. Future work should focus not only on expanding the available performance data, but also on identifying the specific conditions that influence measurement reliability and developing practical procedures for routine implementation.

For the AIR XS, additional independent evaluation is warranted across a broader range of dust compositions, RCS contents, particle size distributions, and field environments. Particular attention should be directed toward understanding the tendency observed in this study for the monitor to overestimate RCS at relatively low RCS contents and underestimate at higher RCS contents. Further investigation of particle characteristics that may influence the optical response, including mineralogy and birefringence, could help explain the variability observed among dust materials. Ultimately, further development and validation of the underlying measurement and classification approach may be necessary before AIR XS measurements can be used confidently for quantitative RCS assessment.

For DOF FTIR, future studies should expand the field dataset to include a larger number of aggregate operations, geologic settings, and representative samples from individual sites. Such data would allow more rigorous evaluation of when a generalized calibration relationship is sufficient and when a site-specific calibration provides a meaningful improvement. Previous field research and NIOSH guidance similarly support the value of site-specific calibration where mineralogical interference may influence the FTIR response. Additional work should also investigate the spectral effects of specific interfering minerals identified in aggregate dust and determine whether these effects can be recognized or corrected systematically.

Finally, additional research should evaluate routine operational implementation of DOF FTIR at aggregate operations. Longer-term studies could assess the stability of site-specific calibration relationships, appropriate frequencies for reference laboratory quality-assurance measurements, operator training requirements, and procedures for recognizing when recalibration is necessary. Evaluating the approach under routine monitoring conditions would help determine how DOF FTIR can most effectively complement established laboratory methods while providing operators with more timely information for identifying changing exposure conditions and evaluating dust controls.

Together, these efforts would build on the findings of the current project by moving from initial performance evaluation toward a clearer understanding of the conditions under which emerging RCS monitoring approaches can provide reliable and actionable information in aggregate operations.

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Appendix A. Industry Survey Questionnaire

Information collected on this form will be used for gauging (1) industry needs and interests for respirable silica monitoring tools, and (2) perceptions about the "adoptability" of the two specific tools we tested at your site.

Section 1. Site and Contact Information

1. Company Name
2. Site Name (where sampling was conducted)
3. Name of person completing form
4. Email address of person completing form
5. This submission represents
   - only your own responses or
   - coordinated responses between yourself and others who participated in the site visit (or reviewed the results memo)

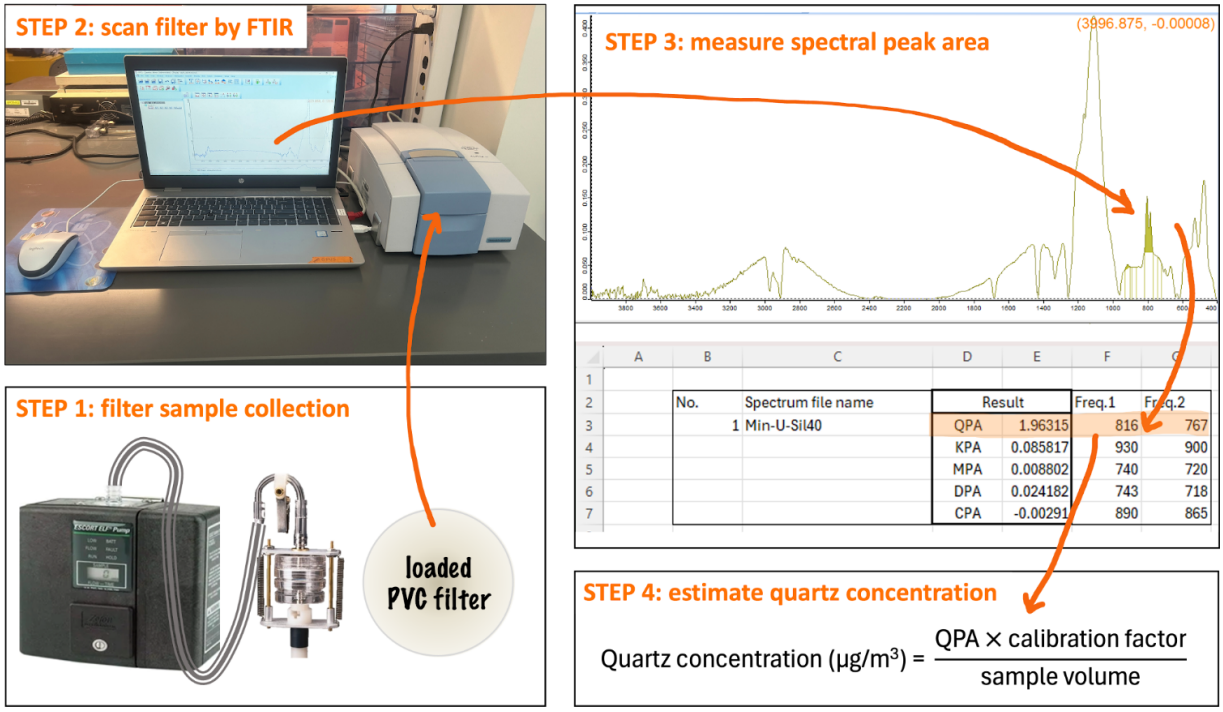
Section 2. Needs and Interests for Respirable Silica Monitoring Tools

1. Aside from regulatory compliance, what are the current needs/interests for silica monitoring at this site? (Choose one of the selections; No need/interest, Some need/interest, High need/interest)
   - Evaluation of baseline silica concentrations
   - Evaluation of trends in silica concentrations over time (e.g., with changes in geology or mining conditions)
   - Evaluation of current/new engineering controls
   - Evaluation of current/new administrative controls
   - Generation of data to support worker training and education
2. Beyond the general categories listed in the question above, please describe any other specific silica monitoring needs/interests at this site?
3. Considering the needs/interests at your site, how useful could the following capabilities be? (Note: wearable = personal monitoring, portable = fixed area or mobile location monitoring) (Choose one of the selections; Not useful, Somewhat useful, Very useful)
   - Wearable filter sampler with later respirable dust and silica measurement in a certified lab (currently used for compliance sampling)
   - Portable filter sampler with later respirable dust and silica measurement in a certified lab (same as option used for personal sampling)
   - Wearable, real-time respirable dust monitor (commercially available options)
   - Portable, real-time respirable dust monitor with later silica analysis in a certified lab (commercially available options)
   - Wearable filter sampler with end-of-shift respirable dust and silica measurement (being tested on this project))
   - Portable filter sampler with end-of-shift respirable dust and silica measurement (being tested on this project))
   - Wearable, real-time respirable silica monitor (no options currently available)
   - Portable, real-time respirable silica monitor (being tested on this project)

4. The question above covers factors related to wearability and data timeliness. How important are the following other factors in terms of adopting respirable dust or silica monitoring tools? (Choose one of the selections; Not important, Somewhat important, Very important)
    - Capital costs (equipment)
    - Operating costs (consumables, maintenance)
    - Ease of use
    - Ease of data interpretation
    - Can be used for demonstrating regulatory compliance
    - Can be used for engineering studies, other internal assessments

Section 3. Perceptions of Respirable Silica Monitoring Tools Evaluated on this Project

(The next few questions relate to Tool 1: Direct-on-filter silica analysis by portable FTIR (DOF FTIR) (Note: this is sometimes called the "end-of-shift" or "rapid" silica method)
A summary of the method is depicted in the image below, and we have also created a short video tutorial, which you can find here: https://youtu.be/66B3xCOyEdk)



1. How familiar were/are you with this tool (Choose one of the selections; Not familiar, Somewhat familiar, Very familiar)
    - ...before this research project?
    - ...after seeing it on site and/or reviewing the information we provided pre and post sampling
2. Based on what you now know about this tool, could it be useful for any of the following tasks at this site? (Choose one of the selections; Not useful, Unsure, Very useful)
    - Evaluation of baseline silica concentrations
    - Evaluation of trends in silica concentrations over time (e.g., with changes in geology or mining conditions)

- Evaluation of current/new engineering controls
- Evaluation of current/new administrative controls
- Generation of data to support worker training and education

3. Do you have outstanding questions or concerns about this tool?

The next few questions relate to Tool 2: Trolex AIR XS Monitor (referred to here as a real-time crystalline silica monitor). The instrument is depicted in the image below, along with an example of the type of data it can produce. More information about the instrument is available at: https://trolex.com/product/air-xs/

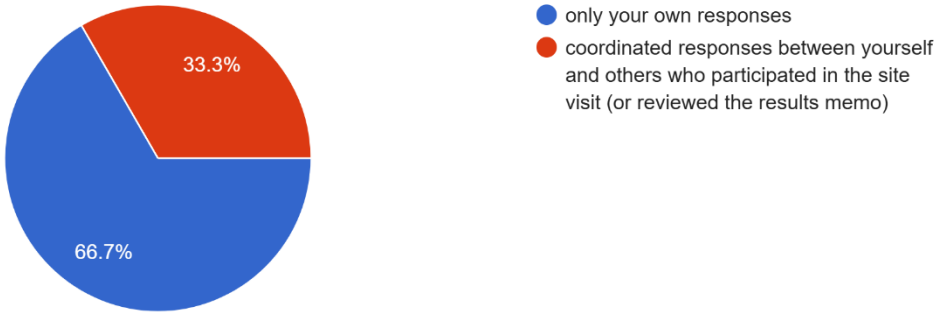
4. How familiar were/are you with this tool (Choose one of the selections; Not familiar, Somewhat familiar, Very familiar)
    - ...before this research project?
    - ...after seeing it on site and/or reviewing the information we provided pre and post sampling
5. Based on what you now know about this tool, could it be useful for any of the following tasks at this site? (Choose one of the selections; Not useful, Unsure, Very useful)
    - Evaluation of baseline silica concentrations
    - Evaluation of trends in silica concentrations over time (e.g., with changes in geology or mining conditions)
    - Evaluation of current/new engineering controls
    - Evaluation of current/new administrative controls
    - Generation of data to support worker training and education
6. Do you have outstanding questions or concerns about this tool?

Please feel free to provide any other feedback you have about respirable silica monitoring tools for aggregates sites.

Appendix B. Industry Survey Summary Responses

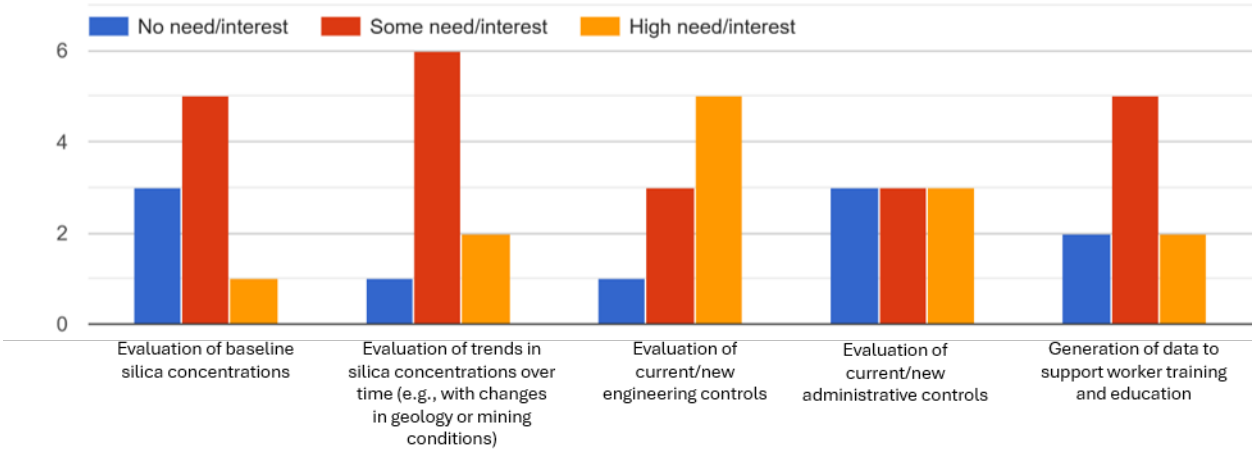
Section 1. Site and Contact Information

Section 1. Question 5. *This submission represents*



Section 2. Needs and Interests for Respirable Silica Monitoring Tools

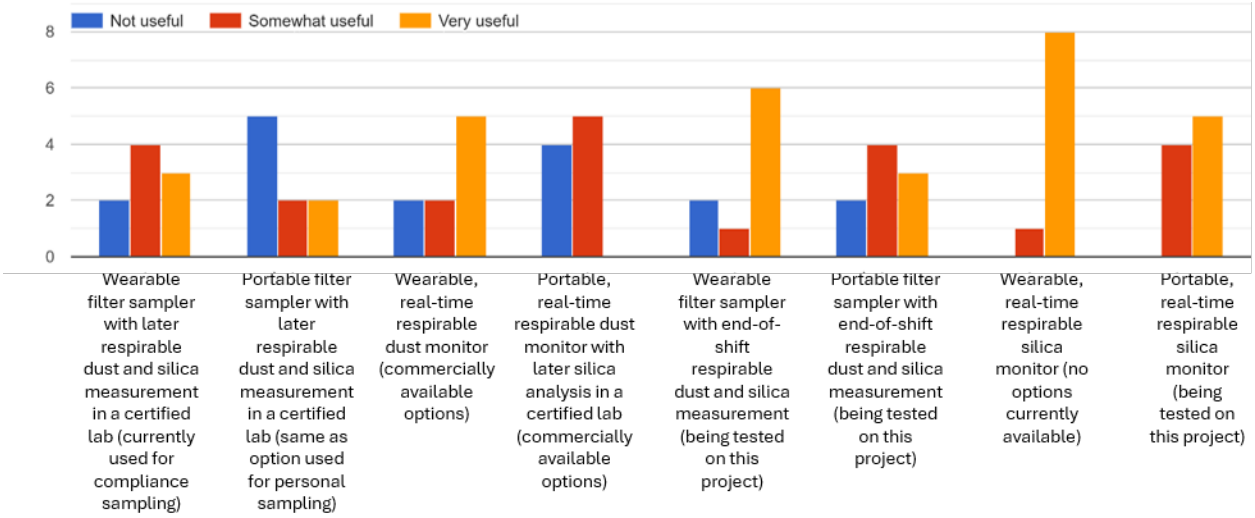
Section 2. Question 1. *Aside from regulatory compliance, what are the current needs/interests for silica monitoring at this site?*



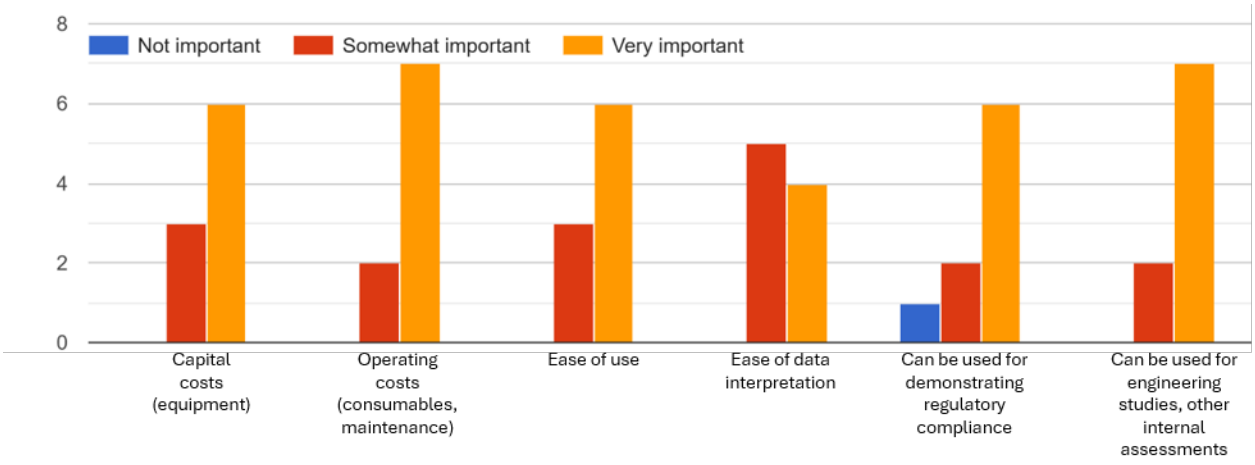
Section 2. Question 2. *Beyond the general categories listed in the question above, please describe any other specific silica monitoring needs/interests at this site?*

Respondents emphasized the need for more timely RCS monitoring information to support evaluation and control of site-specific dust exposures. Feedback highlighted challenges associated with maintaining effective dust controls under certain operating and environmental conditions, as well as strong interest in faster silica analysis and continued development of real-time RCS monitoring technologies.

Section 2. Question 3. *Considering the needs/interests at your site, how useful could the following capabilities be? (Note: wearable = personal monitoring, portable = fixed area or mobile location monitoring)*



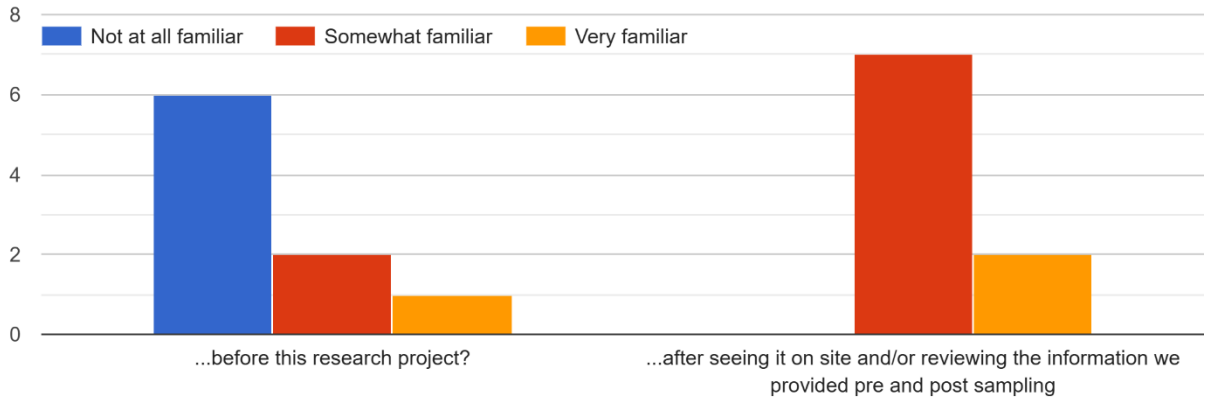
Section 2. Question 4. *The question above covers factors related to wearability and data timeliness. How important are the following other factors in terms of adopting respirable dust or silica monitoring tools?*



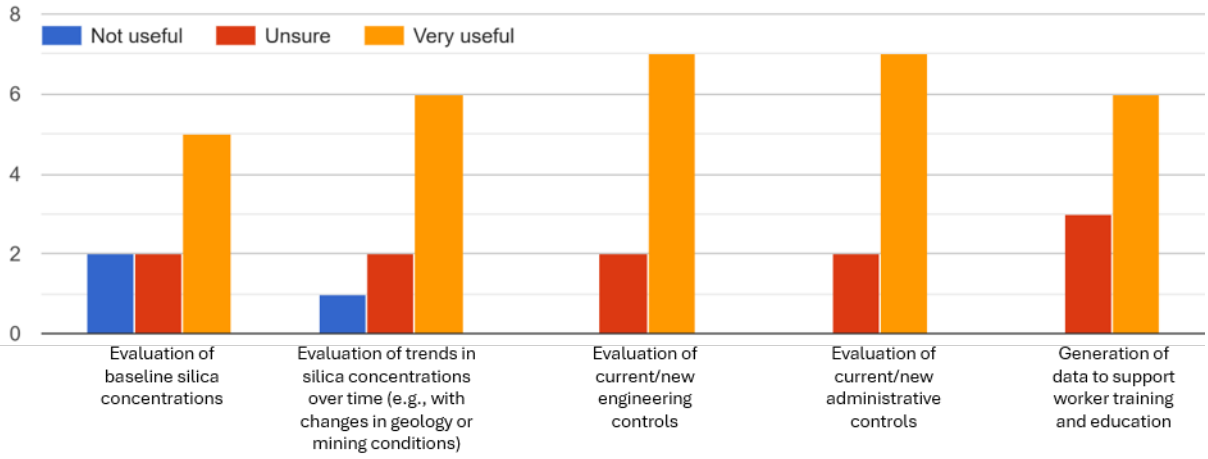
Section 3. Perceptions of Respirable Silica Monitoring Tools Evaluated on this Project

Tool 1: Direct-on-filter silica analysis by portable FTIR (DOF FTIR) (Note: this is sometimes called the "end-of-shift" or "rapid" silica method)

Section 3. Question 1. *How familiar were/are you with this tool...*



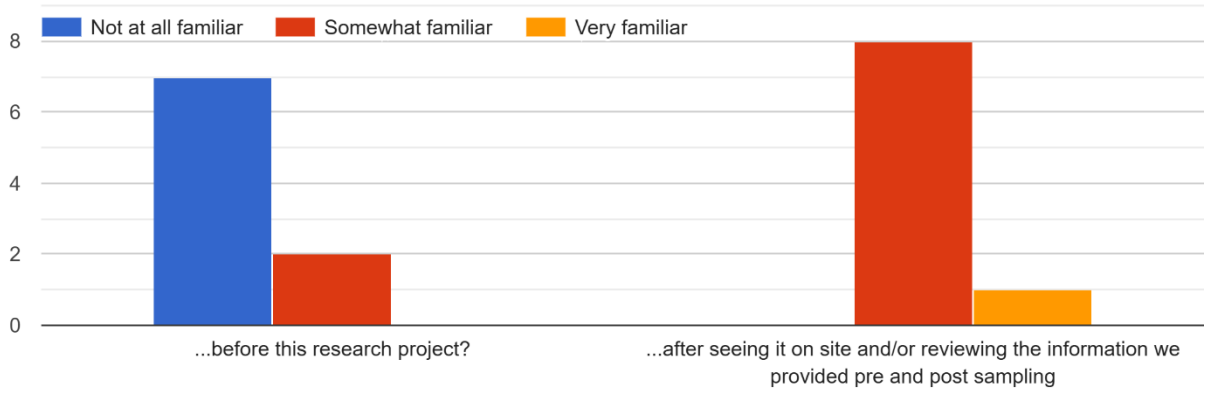
Section 3. Question 2. *Based on what you now know about this tool, could it be useful for any of the following tasks at this site?*



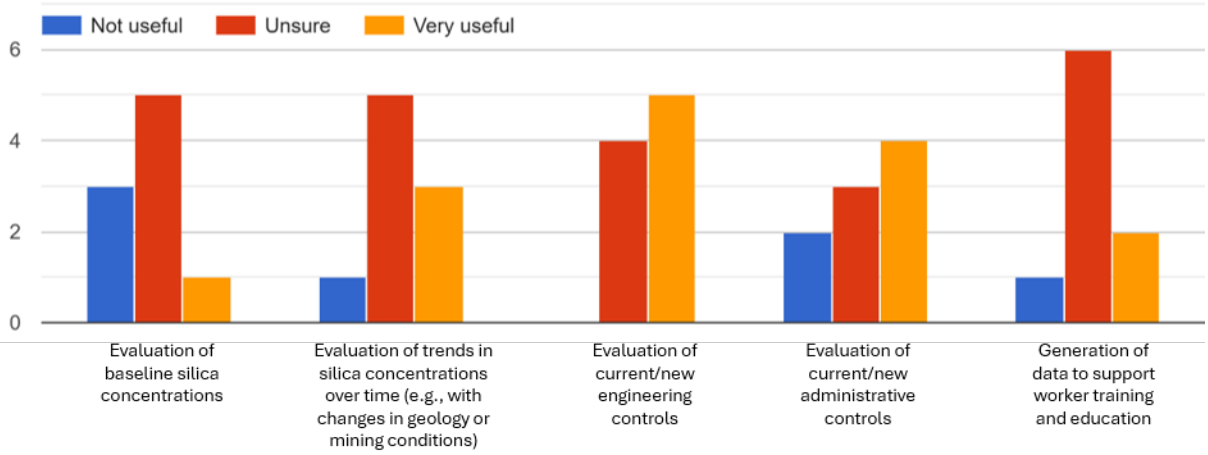
Section 3. Question 3. *Do you have outstanding questions or concerns about this tool?*

Respondents expressed concerns regarding the practical implementation of the tool by personnel with limited industrial hygiene or laboratory experience. Feedback emphasized the need for clear, simple operating instructions and appropriate training to support consistent use by field safety and health personnel. Respondents also requested additional information regarding the accuracy and precision of the method relative to certified laboratory analyses.

Tool 2: Trolex Air XS Monitor (referred to here as a real-time crystalline silica monitor).
Section 3. Question 4. *How familiar were/are you with this tool...*



Section 3. Question 5. *Based on what you now know about this tool, could it be useful for any of the following tasks at this site?*



Section 3. Question 6. *Do you have outstanding questions or concerns about this tool?*

One respondent identified access to power for equipment setup as a practical concern.

Section 3. Additional Feedback. *Please feel free to provide any other feedback you have about respirable silica monitoring tools for aggregates sites.*

Respondents expressed continued interest in technologies that could provide more timely RCS measurements, while emphasizing the importance of measurement reliability and cost-effectiveness. Feedback reflected concerns regarding variability in AIR XS measurements, particularly near exposure levels of practical significance. DOF FTIR was viewed as a potentially valuable approach for more timely analysis of filter samples, although its practical value was noted to depend in part on whether implementation could reduce reliance on external laboratory analysis sufficiently to justify the associated equipment costs. Respondents also expressed interest in continued research toward portable or wearable real-time RCS monitoring technologies.