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Personal respirable dust and respirable crystalline silica exposure in two shafts and a concentrator of a Zambian copper mine

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Abstract

Objectives: Since the 1920s, Zambia's mining sector has experienced growth, which has increased the number of mine workers employed in the industry. Consequently, the potential for occupational exposure and prevalence of occupational diseases have also increased. Unfortunately, Zambia does not currently have legislative guidelines for workplace air monitoring and compliance. This study's objectives were to evaluate copper miners' personal exposure to respirable dust and respirable crystalline silica (RCS) and to assess workplace compliance using the European Standard for workplace air monitoring and measurement (EN689:2018).

Methods: This cross-sectional study collected 100 personal respirable dust exposure samples at a Zambian copper mine in 2023. These samples were weighed using NIOSH method 0600 and analyzed for crystalline silica using Fourier transform infrared spectroscopy (KBr pellet) (NIOSH method 7602). Additionally, 253 respirable dust exposure measurements collected at the mine between 2017 and 2022 were included for comparison.

Results: The median respirable dust exposure for the 2023 exposure measurements was 0.200 mg/m^3 (95th percentile 2.871 mg/m^3) compared to 0.400 mg/m^3 (95th percentile 3.050 mg/m^3) for the historic data. The median RCS exposure was 0.012 mg/m^3 (95th percentile 0.163 mg/m^3). Using EN689:2018, it was found that from 15 work areas, only six work areas complied with the standard for respirable dust exposure and only seven work areas complied with the standard for RCS exposure.

Conclusions: At the mining site, several work areas had substantial exposure to respirable dust and RCS. Therefore, management needs to prioritize these areas when implementing control measures to reduce dust exposure. For the Zambia mining industry to manage exposure to respirable dust and RCS, it is necessary to implement standardized monitoring strategies. This study has demonstrated that EN689:2018 can be used successfully to determine compliance among Zambian mining work areas.

Key words: copper mine; dust exposure; EN689; occupational lung diseases; respirable crystalline silica.

What's Important About This Paper?

Currently, Zambia does not have legislative guidelines for workplace air monitoring and compliance assessment. This study applied the European Standard for workplace air monitoring and measurement (EN689:2018) to assess exposure to respirable dust and crystalline silica in a copper mine in Zambia. The study found EN689:2018 to be valuable framework and documented that some workers were exposed above the occupational exposure limits.

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Introduction

Mining involves the extraction of minerals and other valuable resources from the earth's crust and the activities involved in this process include mineral exploration, blasting, grinding, surface sanding, and lashing and transportation of ore. All these activities produce airborne dust and exposure can potentially lead to the development respiratory disorders such as a silicosis, which forms part of the pneumoconiosis group of lung diseases and is caused by exposure to respirable mineral dust particles (Joshi and Karkhanis 2004; Barber and Fishwick 2016; Otgonnasan et al. 2022). Larger fractions of dust (inhalable and thoracic) are more likely to cause bronchitis and chronic obstructive lung disorders than smaller fractions (respirable dust), which may contain compounds like silica that are likely to cause silicosis and pneumoconiosis (Brown et al. 2013). Unfortunately, very little information is available on exposure to respirable dust during activities in Zambian mines (Ngosa and Naidoo 2016; Mwaanga et al. 2019).

The evaluation of exposure concentrations is important because it aids in decision-making processes which are essential to protect the health and well-being of workers (Kromhout 2002; Swanepoel et al. 2009). Zambia does not currently have legislative guidelines for workplace air monitoring and compliance, which makes it difficult to evaluate exposure. For this study, respirable dust and respirable crystalline silica (RCS) exposure results were compared with the time-weighted average occupational exposure limits (TWA-OELs) for the South African mining industry which are 3 mg/m^3 for respirable dust and 0.1 mg/m^3 for RCS (Mine Health and Safety Council 2018). Zambia does not currently enforce any exposure limits and South Africa's TWA-OELs were chosen for comparison since it also forms part of the Sothern African Development Community and has similar socio-economic challenges.

A variety of studies have been conducted in the mining industry in relation to respirable dust and RCS exposure. Rumchev et al. (2022) and Sepadi et al. (2020) ascertained the association between exposure to respirable dust and RCS, and respiratory health effects among mine workers in Australia and South Africa, respectively. The studies found that even though the exposure levels for respirable dust and RCS were below the TWA-OELs, miners experienced high prevalence of phlegm and occupational respiratory diseases. In a Zambian copper mining investigation, it was found that the mean exposure concentrations to respirable dust ranged between 0.0 and 7.76 mg/m^3 for one mine and between 0.0 and 6.94 mg/m^3 for another mine, while the mean RCS exposure concentrations were between 0.0 and 1.302 mg/m^3, and 0.0 and 0.317 mg/m^3 for the mines, respectively (Hayumbu et al. 2008). In a South African gold mine, routine respirable dust measurements were found to range from 0.0 to 4.29 mg/m^3, with a mean silica percentage of 16%. Even though some areas revealed less exposure, significant correlations were found between prevalence of silicosis, intensity of exposure, and cumulative exposure (Churchyard et al. 2004). Despite measuring exposure, none of these studies reported compliance of exposure concentrations in the specific workplaces by using standardized methodologies.

Although copper ore mining was established in the 1920s in Zambia, there has been no legislation to guide mining companies on respirable dust and RCS exposure assessment (Zambian Parliament 2010). Therefore, this study aimed to assess respirable dust and RCS exposure among copper miners and aimed to determine compliance among work areas using the European Standard for workplace air monitoring and measurement (EN689:2018) at the mining site (European Committee for Standardization 2019). If successful, this strategy can be suggested to the Zambian government to guide exposure assessment in the mining industry.

Methods

Study design

The study was conducted at a Zambian copper mine, which included 2 underground mining shafts and a surface concentrator plant. Surface and underground operations are separated at the mining site. Drilling, blasting, tramming, tipping, and primary crushing of the copper ore are carried out underground, while secondary and tertiary crushing (milling) and copper extraction processes like flotation and smelting are carried out on the surface. Employees from 15 different departments in the 2 mining shafts and the concentrator plant participated in this cross-sectional survey in 2023 and sampling was done during the day for an entire 8-h shift. The departments included are summarized in Fig. 1. These specific work areas were selected to be included in the study following an analysis of the personal respirable dust exposure data collected at the mine between 2017 and 2022. One hundred (66 underground and 34 surface) miners' full-shift personal respirable dust exposure was measured and analyzed for crystalline silica content. This included 42 samples from mining shaft A, 24 from mining shaft B, and 34 from the concentrator. The study received ethics approval from Copperbelt University's research ethics committee (3 February 2022), and the workers gave informed consent prior to participation.

Sampling and analysis

Respirable dust samples were collected for a full-work shift (8 h) within the breathing zone of the workers.

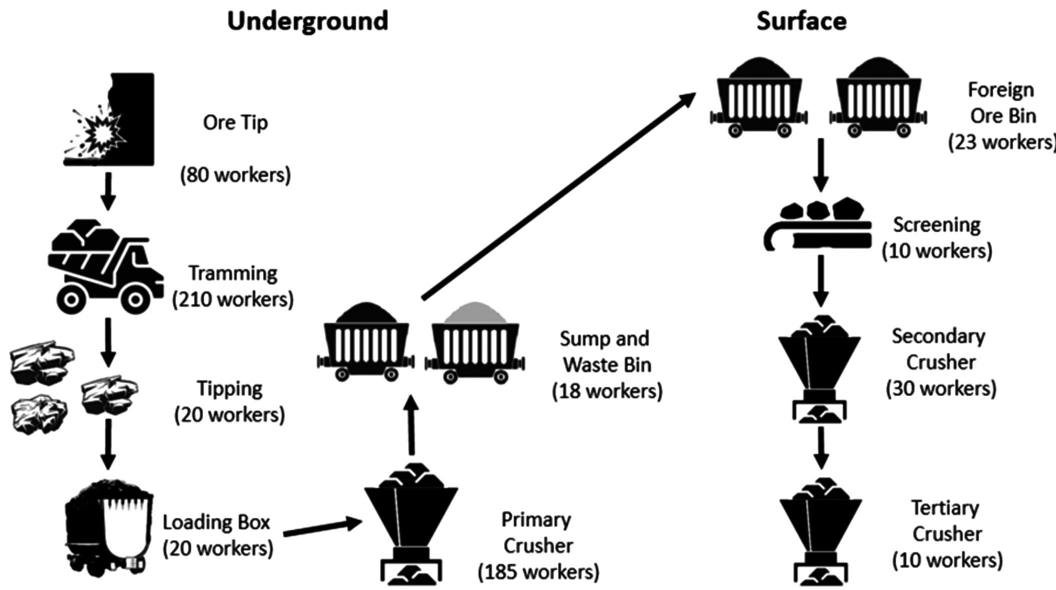

Fig. 1. Schematic of underground and surface operations at the copper mine. The number of workers employed at each section are shown in brackets.

All the measurements were performed during the day shift and the mean sampling time for the study was 553 min. The collection followed the National Institute of Occupational Safety and Health (NIOSH) method 0600. The sampling train consisted of a 37 mm polyvinyl chloride (PVC) membrane filter (0.5 µm pore size) fitted inside a two-stage cassette with a 10 mm conductive cyclone (Dorr–Oliver Style) (Environmental Express, Ocala, FL, USA) and connected to a GillAir Plus personal sampling pump (Sensidyne, St. Petersburg, FL, USA) which operated at a flow rate of 1.7 L/min. Before and after sampling, the airflow rate was calibrated using a Gilibrator-2 air flow calibrator (Sensidyne, St. Petersburg, FL, USA). For gravimetric analysis, the average weight for each sample was calculated from 3 repeats using an XS3DU micro-balance (Mettler Toledo, Greifensee, Switzerland). Following gravimetrical analysis, the personal respirable dust samples were analyzed for crystalline silica quartz content with Fourier transform infrared spectroscopy (FTIR) (KBr pellet) (NIOSH method 7602) by using the Tensor 27 FTIR (Bruker Corporation, Billerica, MA, USA). Quartz was measured at a wavelength of 694 s m^{-1} and the limit of detection for the method was 0.012 mg/m^3 for RCS. All analyses were performed in an ISO-accredited laboratory (BBE Laboratory, Pretoria, South Africa).

Statistical analysis

A summary of descriptive statistics with the number of samples (n), minimum (Min), percentiles (P25, P50, P75, and P95) maximum (Max), arithmetic mean (AM), standard deviation (SD), geometric mean (GM) at 95% confidence interval and geometric standard deviation (GSD) for the work areas and the job titles were generated using GraphPad Prism® version 5.03 (GraphPad Software). Fifty-two samples (52%) were below the limit of detection for the RCS sampling method (0.012 mg/m^3). When deciding on the method to estimate non-detected RCS values, certain statistically sophisticated methods such as β-substitution and ND-Expo (as suggested by EN689) were considered (European Committee for Standardization 2019). However, since the aim of this manuscript is to recommend a method to evaluate respirable dust and RCS exposure in the Zambian mining industry, it was decided to use a simple method that could easily be implemented by the industry. It was subsequently decided to substitute all non-detected RCS exposure concentrations with 0.012 mg/m^3 (the lowest possible concentration for RCS exposure that could accurately be measured). Even though this method overestimates exposure concentrations below the detection limit, it can easily be implemented in the statistical analysis required by EN689. Note that when assessing compliance according to EN689, work areas where all exposure concentrations were below the limit of detection (0.012 mg/m^3) were evaluated to have low exposure according to EN689 (<10% of the OEL for RCS).

Mann–Whitney tests were used to evaluate statistical differences in exposure measured between historical

(2017–2022) and 2023 data (P value of ≤0.05 was considered statistically significant). The historical data used was collected from 6 mining shaft work areas and three work areas from the concentrator. From 2017 to 2022 the sampling strategy used when collecting personal respirable dust exposure measurements was not systematic and the number and work areas sampled varied substantially over the years. The details of the historical dataset are presented in another manuscript that is currently under review.

To determine if work areas complied with OELs, the online software application *BWstats*, (https://www.bsoh.be/?q=nl/bwstat) was used. *BWstat* was built based on EN689 and calculates 70% of the upper confidence limit of the 95th percentile as is required by the standard. Legal noncompliance is classified when any exposure measurements in a work area exceeds the OEL and statistical noncompliance indicates that even though the individual exposure results comply with the limit, the variation in the results show substantial risk and there will probably be overexposure if more exposure measurements are collected. Statistical noncompliance according to EN689 means that it is not 70% certain that less than 5% of the employees in that location have exposure above the TWA-OEL (British Occupational Hygiene Society 2011).

Results

Respirable dust and RCS exposure in the work areas

The study collected 100 personal respirable dust samples from 15 departments in the 2 underground mining shafts and the surface concentrator plant. These samples were analyzed both gravimetrically and for crystalline silica. The AM and GM (GSD) for RCS in the collected samples from the entire mine were 0.029 mg/m^3 and 0.019 mg/m^3 (2.114), respectively, and 5% of the samples exceeded the RCS TWA-OEL of 0.1 mg/m^3. Table 1 summarizes the respirable dust concentrations obtained at the mine between 2017 and 2022 as well as the results from this study, while Table 2 summarizes the RCS concentrations obtained from this study. According to the results, the respirable dust exposure of 4 workers, 1 from the loading box, 2 from the tramming section for mining shaft A, and 1 from the foreign ore bin at the concentrator exceeded the TWA-OEL of 3 mg/m^3. For RCS, the personal exposure of 5 workers exceeded the TWA-OEL of 0.1 mg/m^3. This included 1 from the primary crusher, 1 from the loading box, and 2 from the tramming work area of the mining shaft A and 1 from the foreign ore bin at the concentrator. The highest exposure concentrations for respirable dust at the mining shafts A and B and concentrator were 5.425 mg/m^3, 2.625 mg/m^3, and 4.479 mg/m^3, respectively, while those for RCS were 0.178 mg/m^3 for mining shaft A, 0.077 mg/m^3 mining shaft B, and 0.365 mg/m^3 for the concentrator.

When exposure results were stratified into job titles, exposure measurements that exceeded the TWA-OEL for respirable dust were, 1 loader driver (5.425 mg/m^3), 1 skip man (3.418 mg/m^3), and a locomotive driver (4.455 mg/m^3) in mining shaft A and a locomotive driver (4.479 mg/m^3) at the foreign or bin of the concentrator. RCS exposure also exceeded the TWA-OEL for the same samples as respirable dust (mining shaft A: loader driver (0.159 mg/m^3), 1 skip man (0.178 mg/m^3) and a locomotive driver (0.176 mg/m^3); foreign or bin of the concentrator locomotive driver (0.365 mg/m^3), as well as for 1 workman at the primary crusher in mining shaft A (0.167 mg/m^3). The details of the exposures measured for different job titles are detailed in Supplementary Table S1 and Supplementary Table S2.

Comparison of respirable dust exposure measurements between historical (2017–2022) and 2023 data

The mine collected personal respirable dust exposure measurements between 2017 and 2022, and this historical respirable dust exposure data were compared with the 2023 respirable dust exposure measurements for different work areas (Table 1). Using the 95th percentile, for historical data, 7 work areas exceeded the TWA-OEL of 3 mg/m^3 (shaft A: ore tip, loading box, and tramming, contractor: foreign ore bin, conveyer, secondary crusher, and tertiary crusher) and 3 work areas of the 2023 exposure measurements exceeded the TWA-OEL at 95th percentile (Shaft A: Loading box and tramming, Concentrator: foreign ore bin). Mann–Whitney tests were conducted to determine statistical differences between the work areas' historical and 2023 respirable dust exposure measurements. The exposure measured in 3 areas, namely the screening, tipping area, and secondary crusher, were significantly lower in 2023 compared to the historical data as summarized in Figure 2.

Respirable crystalline exposure measurements within work areas

A total of 100 personal exposure measurements from 15 work areas in the mine were analyzed for quartz content. The 95th percentile for shaft A tramming, primary crusher, and loading box and concentrator foreign ore bin exceeded the TWA-OEL of 0.1 mg/m^3, while the primary crusher and tramming work areas at mining Shaft A and foreign ore bin at the concentrator also recorded individual measurements higher than the OEL as summarized in Figure 3. The percent (%) silica for shaft A was highest at the loading box work area (8.0%), shaft B sump and waste bin (7.0%) and concentrator foreign ore bin (8.0%).

Table 1. Summary of personal respirable dust concentrations (TWA mg/m³) from the historical (2017–2022) data and the 2023 study.

Work area	n	Min	P25	P50	P75	P95	Max	AM	SD	GM	GSD	n > OEL
TWA historic respirable dust data (mg/m³)												
Entire mine	253	0.022	0.210	0.405	0.825	3.050	18.00	0.922	1.831	3.214	0.490	14
Shaft A	95	0.031	0.203	0.395	0.831	1.992	18.00	0.881	1.944	2.975	0.553	5
Ore tip	19	0.055	0.293	0.665	1.640	3.390	3.392	0.934	0.885	3.395	0.974	1
Primary crusher	5	0.124	0.125	0.140	1.405	2.290	2.291	0.645	0.093	3.003	1.491	–
Loading box	9	0.134	0.293	0.315	0.456	3.030	3.033	0.621	0.912	2.334	0.752	1
Tramming	22	0.602	0.180	0.490	0.940	3.082	3.222	0.731	0.887	2.890	0.705	1
Tipping	40	0.031	0.225	0.350	0.665	2.930	18.00	1.033	2.833	3.043	0.601	2
Shaft B	104	0.021	0.191	0.320	0.642	1.472	8.054	0.625	0.955	2.973	0.423	2
Ore tip	45	0.021	0.165	0.435	0.847	2.528	3.092	0.664	0.708	3.052	0.555	1
Loading box	5	0.204	0.210	0.310	0.350	0.380	0.384	0.283	0.754	1.311	0.556	1
Tramming	2	0.745	0.745	0.750	0.754	0.763	0.761	0.700	1.341	3.536	0.463	1
Sump and waste bin	39	0.036	0.176	0.270	0.643	2.535	8.054	0.701	1.343	3.532	0.462	1
Pump and filter chamber	13	0.064	0.135	0.291	0.365	0.670	0.672	0.294	0.182	1.972	0.371	–
Concentrator	54	0.052	0.294	0.625	1.594	4.344	14.00	1.573	2.603	3.672	0.962	7
Foreign ore bin	9	0.883	0.282	0.712	3.026	4.433	4.431	4.353	1.674	4.241	2.354	2
Conveyer screening	7	0.271	0.301	0.983	6.490	10.91	10.95	3.321	4.374	4.666	6.734	2
Secondary crusher	9	0.224	0.612	1.077	3.964	13.99	14.00	3.262	4.677	3.645	4.542	2
Tertiary crusher	19	0.092	0.324	0.781	1.162	5.075	5.072	1.154	1.181	2.897	1.231	1
Dams	4	0.174	0.238	0.465	0.677	0.731	0.733	0.463	0.233	0.400	1.866	–
Flotation	6	0.052	0.087	0.225	0.317	0.494	0.492	0.411	1.151	0.192	1.990	–
TWA 2023 respirable dust data (mg/m³)												
Entire mine	100	0.001	0.096	0.200	0.487	2.871	5.425	0.555	0.962	0.203	4.846	4
Shaft A	42	0.001	0.186	0.407	0.896	3.391	5.425	0.850	1.199	0.329	5.729	3
Ore tip	4	0.125	0.196	0.558	0.901	0.910	0.219	0.538	0.424	0.387	2.737	–
Primary crusher	9	0.127	0.219	0.699	0.791	2.694	2.694	0.811	0.812	0.537	2.672	–
Loading box	4	0.090	0.264	0.608	1.527	3.417	3.418	1.183	1.528	0.554	4.566	1
Tramming	17	0.004	0.163	0.328	0.892	4.795	5.425	1.045	1.630	0.275	7.585	2
Tipping	8	0.008	0.262	0.439	0.622	0.996	0.069	0.022	0.023	0.020	1.985	–
Shaft B	24	0.007	0.068	0.096	0.171	0.887	2.625	0.271	0.543	0.109	3.698	–
Loading box	3	0.097	0.102	0.118	0.128	0.131	0.131	0.115	0.017	0.114	1.165	–
Primary Crusher	6	0.018	0.052	0.312	0.956	2.624	2.625	0.713	1.002	0.231	6.524	–
Tramming	3	0.089	0.056	0.076	0.245	0.451	0.291	0.168	0.108	0.147	1.843	–
Tipping	6	0.010	0.069	0.073	0.089	0.132	0.146	0.078	0.044	0.061	2.529	–
Sump and waste Bin	6	0.007	0.106	0.208	0.274	0.124	0.451	0.444	0.152	0.079	4.215	–
Concentrator	34	0.002	0.097	0.184	0.460	0.972	4.479	0.392	0.768	0.172	3.925	1
Foreign ore bin	8	0.099	0.103	0.133	0.207	2.605	4.479	0.794	1.627	0.266	3.682	1
Conveyer screening	6	0.002	0.123	0.112	0.394	0.252	0.475	0.276	0.153	0.242	1.756	–
Secondary crusher screening	3	0.026	0.180	0.050	0.075	0.098	1.111	0.074	0.047	0.062	2.197	–
Secondary crusher	11	0.002	0.080	0.124	0.316	0.862	0.816	0.209	0.241	0.096	5.254	–
Tertiary crusher	6	0.049	0.161	0.473	0.557	0.943	1.070	0.448	0.378	0.271	3.597	–

Concentrations: TWA of respirable dust in mg/m³, n, number of measurements, Min, minimum, P25, P50, P75, and P95 are percentiles, Max, maximum, AM, arithmetic mean, SD, standard deviation, GM, geometric mean, GSD, geometric standard deviation, n > OEL, number of measurements above the occupational exposure limit of 3 mg/m³.

Table 2. Summary of personal RCS concentrations (TWA mg/m³) of 2023 study per work area.

Respirable crystalline silica OEL = 0.1 mg/m³													
Work area	*n*	Min	P25	P50	P75	P95	Max	AM	SD	GM	GSD	*n* > OEL	% Silica
Entire mine	100	0.012	0.012	0.012	0.026	0.163	0.365	0.029	0.047	0.019	2.114	5	5.3
Shaft A	42	0.012	0.012	0.019	0.038	0.175	0.178	0.038	0.047	0.024	2.334	4	4.9
Ore tip	4	0.012	0.014	0.028	0.042	0.043	0.043	0.028	0.015	0.024	1.839	–	6.0
Primary crusher	9	0.012	0.012	0.013	0.029	0.167	0.167	0.034	0.050	0.021	2.381	1	4.0
Loading box	4	0.012	0.012	0.051	0.512	0.178	0.178	0.073	0.074	0.047	3.142	1	8.0
Tramming	17	0.012	0.012	0.019	0.040	0.176	0.176	0.039	0.052	0.024	2.488	2	4.0
Tipping	8	0.012	0.012	0.019	0.031	0.070	0.070	0.026	0.019	0.020	1.930	–	5.0
Shaft B	24	0.012	0.012	0.012	0.012	0.067	0.077	0.017	0.015	0.015	1.632	–	4.9
Loading box	3	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.00	0.012	1.009	–	BDL
Primary crusher	6	0.012	0.012	0.017	0.047	0.077	0.077	0.029	0.026	0.022	2.164	–	4.0
Tramming	6	0.012	0.012	0.012	0.018	0.037	0.012	0.012	0.000	0.012	1.001	–	BDL
Tipping	6	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.000	0.012	1.005	–	BDL
Sump and waste Bin	3	0.012	0.012	0.012	0.012	0.021	0.037	0.016	0.000	0.014	1.584	–	7.0
Concentrator	34	0.012	0.012	0.012	0.020	0.153	0.365	0.028	0.061	0.017	2.011	1	6.0
Foreign ore bin	8	0.012	0.012	0.012	0.021	0.365	0.365	0.064	0.133	0.021	3.570	1	8.0
Conveyer screening	6	0.012	0.012	0.012	0.023	0.024	0.024	0.016	0.006	0.015	1.400	–	5.0
Secondary crusher screening	3	0.012	0.012	0.012	0.012	0.013	0.013	0.012	0.001	0.012	1.047	–	BDL
Secondary crusher	11	0.012	0.012	0.012	0.018	0.083	0.034	0.015	0.007	0.014	1.410	–	7.0
Tertiary crusher	6	0.012	0.012	0.012	0.026	0.039	0.039	0.020	0.010	0.018	1.555	–	4.0

Concentrations: TWA of RCS exposure in mg/m³, *n*, number of measurements, Min, minimum, P25, P50, P75, and P95 are percentiles, Max, maximum, AM, arithmetic mean, SD, standard deviation, GM, geometric mean, GSD, geometric standard deviation, *n* > OEL, number of measurements above the occupational exposure limit of 0.1 mg/m³, BDL, below detection limit; % silica, the average percentage silica in samples where silica was detected.

Testing compliance of work areas using the EN689:2018

The Zambian legislation does not require a specific sampling program to determine compliance of exposure to hazardous substances in a workplace, which is why this study used EN689:2018, an internationally recognized standard, to test compliance. All work areas were tested for compliance concerning personal respirable dust and RCS exposure using the EN689:2018 standard. A minimum number of 3 measurements were collected as representative samples for each work area and a preliminary test was conducted before determining compliance. The results showed that although some work areas did not record exposure measurements exceeding the TWA-OEL (legal compliance) for respirable dust and RCS, they still recorded statistical noncompliance. Legal and statistical noncompliance for respirable dust was recorded in 3 and 6 work areas, respectively. For RCS, legal and statistical noncompliance were recorded in 4 work areas each. The detail of this assessment is shown in Supplementary Table S3 and Supplementary Table S4.

Discussion

Respirable dust and RCS exposure in work areas

The type of minerals found in a mine determines the degree of exposure to respirable dust and RCS (Otgonnasan et al. 2022). Previous studies have assessed the exposure of mine workers to respirable dust and RCS in coal mining in the United States of America (Doney et al. 2020), copper mining in Mongolia (Otgonnasan et al. 2022), iron mining in Sweden (Andersson et al. 2008), talc mining in the United States of America (Rossner et al. 2020), platinum and gold mining in South Africa (Churchyard et al. 2004; Sepadi et al. 2020) to name a few. However, only one investigation has been published from the Zambian copper mining industry with regard to personal exposure to respirable dust and RCS (Hayumbu et al. 2008). Subsequently, this study aimed to evaluate personal respirable dust and RCS exposure concentrations at the 2 mining shafts and the concentrator plant at a Zambian copper mine.

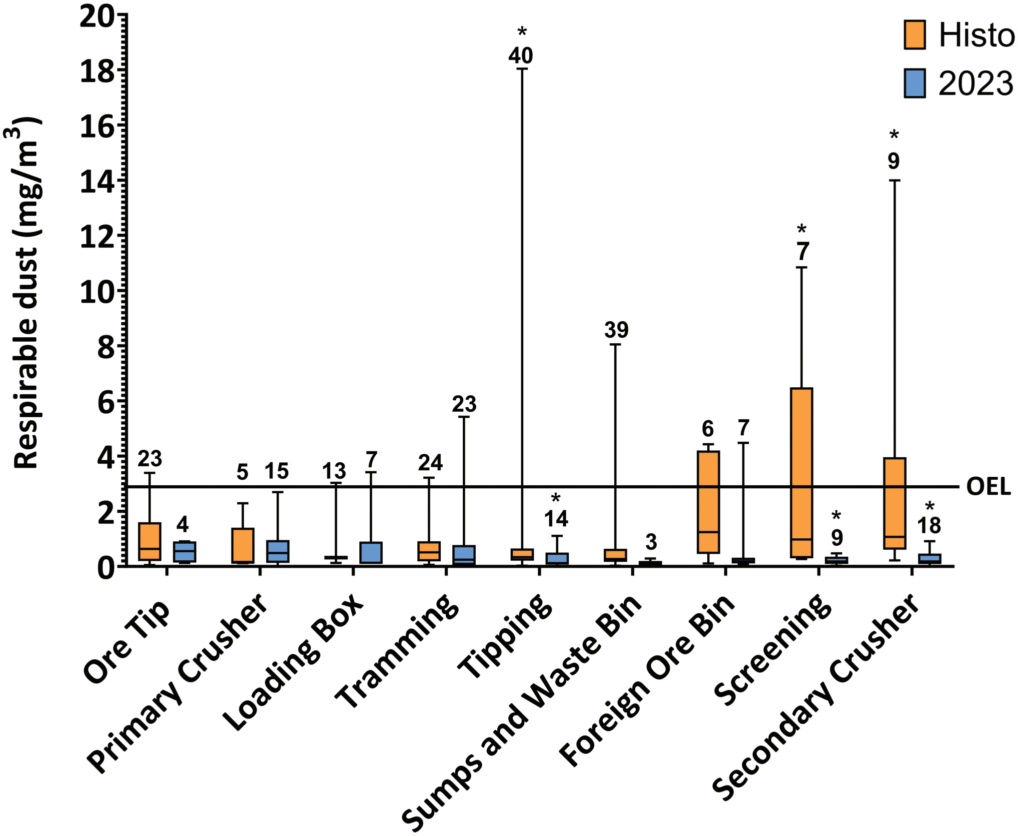

Fig. 2. Personal respirable dust exposure in work areas at the mining shafts and concentrator plant as measured during this study (2023) and historical (2017–2022). OEL refers to the South African time-weighted average—occupational exposure limit of 3 mg/m^3. The box extends to the 25th and 75th percentiles and the line in the middle of the box indicates the median. The whiskers illustrate the minimum and maximum concentrations, the numbers are the number of samples collected for each area, and the asterisk indicates significant statistical differences between historical and 2023 data ($P < 0.05$).

Based on the 95th percentile of the historical analyses for respirable dust, at least 5% of measurements at work areas such as the ore tip, tramming, and loading box of shaft A, and the foreign ore bin, conveyer screening, secondary crusher, and tertiary crusher at the concentrator plant exceeded the respirable dust TWA-OEL. For the 2023 exposure measurements, only the loading box and tramming areas at Shaft A's 95th percentiles exceeded the respirable dust TWA-OEL of 3 mg/m^3. The respirable dust concentrations for individual measurements exceeded the TWA-OEL at the loading box and tramming areas at Shaft A as well as the foreign ore bin area at the concentrator plant. These exceedances can be attributed to the work activities conducted in the work areas. For example, the loading box involves loading crushed copper ore into the box using front-end loaders in preparation for the primary crusher and this exposed the workers to airborne dust. Consequently, one respirable dust exposure measurement recorded in this work area (3.418 mg/m^3) exceeded the TWA-OEL. Tramming at mining shaft A involves transportation of the blasted copper ore from the ore tip to the tipping work area and the highest exposure measurement recorded in this area was 5.425 mg/m^3. The measurements exceeding the TWA-OEL in the tramming area can be attributed to the cabins of the loaders and locomotives not having adequate air conditioning and fresh air circulation for the drivers to close the windows. Drivers operated the loaders and locomotives with open windows, which exposed them to respirable dust. The foreign ore bin area at the concentrator also recorded an individual measurement (4.479 mg/m^3) above the TWA-OEL, which can also be attributed to the cabins of the locomotives being used by the drivers not protecting them from dust exposure during the transportation of copper ore from the mining shafts to the foreign ore bin at the concentrator. The results discussed above are consistent with the results of Hayumbu et al. (2008), who found high exposure respirable dust concentrations at 2 mining

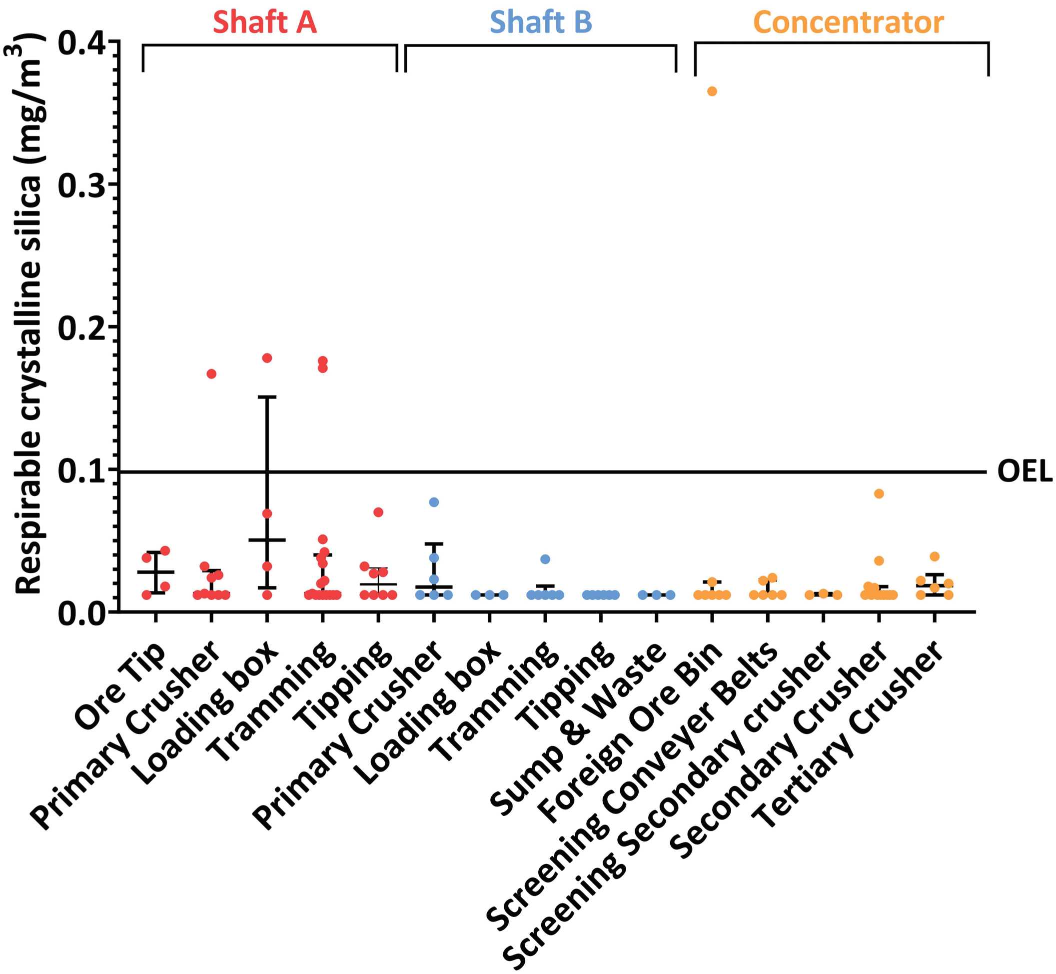

Fig. 3. Personal RCS exposure in work areas at the 2 mining shafts and the concentrator. OEL refers to the South African time-weighted average—occupational exposure limit of 0.1 mg/m³. The dots indicate concentrations from individual measurements while the horizontal lines indicate the median and the whiskers the interquartile range.

sites in Zambia. However, Hayumbu et al. (2008) did not highlight in which areas the overexposure occurred. Figure 2 shows that there was a decrease in exposure to respirable dust measured during 2023 compared to the historical data. This can possibly be attributed to improved general airborne dust management strategies implemented by the mine. However, since the sampling strategy used by the mine between 2017 and 2022 did not follow a standardized structure, the significance of this reduction must be interpreted with care.

The results of RCS exposure measurements at Shaft A tramming, loading box, and primary crusher revealed a 95th percentile exceeding the TWA-OEL of 0.1 mg/m³. The foreign ore bin at the concentrator recorded the highest concentration of 0.365 mg/m³. The high RCS concentration in these work areas can be attributed to high respirable dust exposure among workers in the work areas. A total of 4 out of the 5 workers with high RCS exposure measurements also experienced high respirable dust exposure, except for one measurement from the primary crusher mining shaft A, which is the first point of crushing copper ore and dust is generated. Workers are exposed to respirable dust that contains a certain percentage (%) of silica. If the percentage is high then the risk for RCS exposure is higher because you can be exposed to lower concentrations of respirable dust and still be exposed to RCS. The percentage silica in the ore was highest at the loading box of shaft A (8%), sump and waste bin for shaft B (7%), and foreign ore bin at the concentrator (8%), and these areas need to be prioritized in terms of monitoring dust exposure at the mining site. It should, however, be noted that 8% of silica in the respirable dust collected at the mining site is low compared to other commodities such as gold mines in South Africa where a silica percentage of greater than 50% has been reported (Brouwer and Rees 2020).

Determination of compliance in the work areas using the EN689:2018

EN689:2018, which describes a procedure to assess workplace exposure by monitoring exposure to hazardous agents through inhalation, was followed to ascertain which work areas complied with exposure limits since the Zambian legislation does not give guidance on how compliance monitoring should be conducted. It was incorporated into this study as a way to determine work area compliance with regulatory exposure standards in order to protect mine workers against excessive respirable dust and RCS exposure. The use of a nonsystematic sampling procedure, as was done by the mine between 2017 and 2022, resulted in the collection of exposure measurements that could not lead to any scientifically sound conclusions. The use of a more specialized sampling plan, such as the EN689:2018, will be economically advantageous to the Zambian mining industry because the samples collected (and the associated expenses) will lead to usable and scientifically justifiable conclusions. Additionally, EN689:2018 allows for compliance decisions to be made while using a relatively few number of samples.

Following the 2023 sampling campaign, preliminary testing was performed on the results obtained from work areas with less than 6 exposure measurements, and complete statistical analysis was performed for work areas that had ≥6 exposure measurements. The statistical analysis shows that of the 15 work areas, only 6 work areas complied with the standard for respirable dust exposure and only 7 work areas complied with the standard for RCS exposure. This means that the TWA-OELs were exceeded and the study is 70% not certain that less than 5% of the workers in the non-compliant work areas will be exposed below the TWA-OEL. Therefore, if more exposure measurements were to be collected, there is a significant chance that there would be overexposure for >5% of those measurements. Based on the work areas that revealed legal and statistical noncompliance, there is a need for the mine to investigate exposure to respirable dust and RCS and to revise existing control measures or implement additional measures (engineering controls, administrative controls, and PPE). Thereafter, exposure should be measured again in these areas to determine if the controls implemented were effective. The following control measures are recommended to help reduce workers' exposure to respirable dust and RCS:

(1) The mine should prioritize improving the efficiency of the cabin air conditioning in vehicles such as front-end loaders and locomotives because workers were forced to drive with open windows to help regulate the temperature in the cabins. This resulted in exposure exceeding the TWA-OEL.

(2) Administrative controls such as improved training, organizational procedures, and supervision can help to educate workers on methods to help reduce exposure to respirable dust and RCS.

(3) The mine should ensure that workers continue wearing respiratory protective equipment with the correct assigned protection factor (APF) and that the workers undergo periodic respirator fit testing. Considering that the highest exposure measured in 2023 was 5.425 mg/m^3, the mining company should continue using the FFP2 respirators (APF of 10 and 94% filtration efficiency) during operations.

(4) Although not the focus of the study, management at the mining site may consider using direct reading instruments to measure respirable dust exposures in work areas such as tramming, tipping, primary crusher, and foreign ore bin. This will help to identify peak exposures and to improve the effectiveness of control measures.

(5) Due to the lack of a defined sampling protocol in the mining sector of Zambia, each mining house conducts sampling in accordance with their own standard and capacity. Therefore, if a standardized monitoring program such as EN689:2018 were to regulate sampling programs, it would be possible to obtain representative samples from work areas and statistically determine compliance of the work areas in various mines. It would also be possible for the country to keep a database for exposure measurements for miners because sampling will be uniformly done by the mining houses. Additionally, if the sampling is consistently carried out by mining houses, it would be feasible for the nation to maintain a database for exposure assessments of miners and link exposure with the development of diseases such as silicosis for specific occupations or regions. Based on the findings of the study, the investigators strongly advise adopting EN689:2018 for workplace air monitoring because it will track how many samples are collected in a work area and help keep track of which areas comply with the standards. This has been shown by the analysis of the respirable exposure data collected by the mine, which found that the sampling strategy employed by the mine between 2017 and 2022 was not adequate. It is important to highlight that a standardized technique was not followed

when conducting respirable dust exposure sampling at the mining site. However, the available data can still be used by the mine to perform the basic characterization of risk which is the starting point of EN689:2018. The data can also be used as a starting point for improvement of the sampling program at the mine. If EN689:2018 is not deemed to be the most suitable program, then an alternative monitoring program should be implemented based on the current results, historical results, and a cost–benefit analysis. The Zambian Government should also strongly consider publishing TWA-OELs that the proposed guidance can regulate.

The limitations of the study were as follows: (i) Due to budget constraints, the number of exposure measurements was limited to 100 and the mine should collect additional measurements to obtain a complete exposure profile of all areas at the mine; (ii) The method used to estimate results below the limit of detection was not the most statistically sophisticated method as proposed by EN689:2018. The simplest method that would not underestimate exposure was chosen because the persons implementing the dust monitoring program might not be familiar with the statistical methods, which also have their advantages and disadvantages.

Conclusion

The present study evaluated respirable dust and RCS exposure among copper miners and determined compliance among work areas using the European Standard for workplace air monitoring and measurement (EN689:2018) at the mining site. The study results revealed that workers in some work areas were over-exposed to respirable dust (4% of samples) and RCS (5% of samples). Crystalline silica can lead to respiratory health effects therefore, the mining site needs to prioritize the implementation of control measures in cabins with elevated exposure concentrations. These include improving air conditioning and fresh air supply in the cabins, administrative measures as well and wearing of RPE in order to reduce RCS exposure which can lead to nonreversible but preventable respiratory diseases. Additionally, there is a need for Zambia to (i) implement a standardized sampling strategy such as the EN689:2018, (ii) to develop a unified database for occupational exposure measurements among workers in the extractive industry, and (iii) to declare legislatively enforceable TWA-OELs. This will help in protecting workers from occupational exposure and associated respiratory diseases.

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Author contributions

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Conflict of interest

The authors declare that all the sources used in this paper have been duly acknowledged, and there are no conflicts of interest.

Data availability

Data are available on reasonable request from the corresponding author.

Supplementary data

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

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