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ORIGINAL PAPER

Impact of air quality on the health of present-day workers in an Asbestos roof manufacturing industry, Sri Lanka

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Abstract The study's objective was to determine the air quality in an asbestos-related industry and its impact on current workers' respiratory health. Seventy-seven air and 65 dust samples were collected at 5-day intervals in an asbestos roofing sheets production factory in Sri Lanka having two production facilities. Sampling was performed in ten sites: Defective sheets-storage, Production-plant, Pulverizer, Cement-silo, and Loading-area. A detailed questionnaire and medical screening were conducted on 264 workers, including Lung Function Tests (LFT) and chest X-rays. Asbestos fibres were observed in deposited dust samples collected from seven sites. Free chrysotile fibres were absent in the breathing air samples. Scanning Electron Microscopy confirmed the presence of asbestos fibres, and the Energy Dispersive X-ray analysis revealed Mg, O, and Si in depositions. The average concentrations of trace metals were Cd-2.74, Pb-17.18, Ni-46.68, Cr-81.01, As-7.12, Co-6.77, and Cu-43.04 mg/kg. The average Zn, Al, Mg, and Fe concentrations were within 0.2–163 g/kg. The highest concentrations of $PM2.5_{2.5}$ and $PM10_{10}$, 258 and 387 μg/m^3, respectively, were observed in the Pulverizer site. Forty-four workers had respiratory symptoms, 64 presented LFT abnormalities, 5 indicated chest irregularities, 35.98% were smokers, and 37.5% of workers with abnormal LFT results were smokers. The correlation coefficients between LFT results and work duration with respiratory symptoms and work duration and chest X-ray results were 0.022 and 0.011, respectively. In conclusion, most pulmonary disorders observed cannot directly correlate to Asbestos exposure due to negligible fibres in breathing air, but fibres in the depositions and dust can influence the pulmonary health of the employees.

Keywords Asbestos fibres · Chrysotile · Dust · Lung function test · Occupational exposure

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Introduction

Air pollution is the prime environmental risk factor threatening human health, including premature deaths and climate (WHO, 2022). Industrial emissions are

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a major culprit in air pollution, releasing gases and particulate matter (PM) during their production processes. Asbestos includes a variety of mineral silicate fibres, classified into two groups known as the serpentine group and the amphibole group, and the common feature of these fibres is the structure of the minerals; at the same time, these groups are principally different in their mineralogical and chemical composition, in morphology and bio persistence (a function of the solubility of the fibre in the lung, and the natural ability of the lung to clear the fibre from the lung) (Giacobbe et al., 2021; Gualtieri et al., 2018). The chrysotile fibres are in the serpentine group. Globally, chrysotile is being used as a raw material for 90–95% of products (Frank, 2020), such as in domestic, commercial and industrial products, which include roofing, thermal and electrical insulation, cement pipe and sheets, flooring, gaskets, friction materials (e.g. brake pads and shoes), coating and compounds, plastics, textiles, paper, mastics, thread, fibre jointing, and millboard. Due to its remarkable durability and fire resistance, asbestos has been used in pottery and clothing for at least 4500 years (Iliopoulou et al., 2017).

However, in 1960, the potential hazards to human health from exposure to asbestos fibres were indicated by a publication reporting several cases of pleural mesothelioma in miners working in South African mines contaminated with asbestos (Niklinski et al., 2004). Most human exposures to asbestos are due to inhalation. The breathing of this fibrous asbestos is the culprit for aggressive malignant mesothelioma (Avramescu et al., 2023), lung, laryngeal, and ovarian cancer, and the non-cancerous diseases involve progressive asbestosis, pleuritis, atelectasis and conditions like pleural plaques(Bolan et al., 2023; Mirabelli et al., 2008; Pira et al., 2018). The International Agency for Research on Cancer (IARC) of the World Health Organization (WHO) confirmed that "There is sufficient evidence in humans for the carcinogenicity of all forms of asbestos" (IARC, 2012). WHO indicates the need to count respirable fibres with a length of ≥ 5 μm, ≤ 3 μm in diameter and an aspect ratio of $\geq 3:1$ as they pose potential risks to human health (WHO, 1998). Until the end of the 1970s, the use of asbestos was not regulated. According to the standards listed by the occupational safety and health administration fact sheet, Permissible Exposure Limit (PEL) for asbestos is 0.1 fibre/cm^3 of air as an eight-hour time-weighted average (TWA), with an excursion limit (EL) of 1.0 asbestos fibre/cm^3 over 30 min (OSHA).

Compared to the general public, people working in the Industry or occupational exposure is the most prominent cause of asbestos-related diseases. The workers involved in the asbestos industries are constantly exposed to this mineral-containing polluted air and are thus at a greater risk of developing health issues with time. Studies confirm that malignant mesothelioma has a latent period ranging from 15 to 50 years (Hiriart et al., 2019). As of the WHO fact sheet, about 125 million people in the world are exposed to asbestos at their place of work, and about half of the deaths from work-related cancer are likely to be instigated by asbestos (WHO, 2018). Furthermore, co-exposure to tobacco smoke and asbestos fibres escalates the risk for lung cancer, and heavy smokers are at a greater risk (WHO, 2018).

Many countries have prohibited the use of all forms of asbestos to limit exposure and control, prevent and ultimately eliminate asbestos-related diseases. Further mining and use of amphibole asbestos have been legally prohibited in most countries. However, white asbestos or chrysotile asbestos ($3MgO·2SiO_2·2\ H_2O$), made by mixing asbestos fibre with cement, continues to be used mainly as roofing sheets worldwide due to its durability and price. The first Asbestos factory in Sri Lanka was started in 1955. While many countries have prohibited the use of asbestos in any form, Sri Lanka has not yet done so, despite ongoing policy-level talks about evaluating the risk and developing solutions (EARF, 2021). However, the regulatory framework in Sri Lanka is in line with the global context because amphibole asbestos has been banned in Sri Lanka since 1997. Like the other countries, chrysotile is still used in Sri Lanka and Sri Lanka has been producing chrysotile roof sheeting for many decades. To regulate and manage the use of asbestos, several international efforts and organizations have been developed. The Environmental Protection Agency (EPA) of the United States, through the air toxics or hazardous air pollutants (HAP) provisions of the Clean Air Act (CAA), had formed national emission standards for hazardous air pollutants (NESHAP). Asbestos was branded as a HAP by the EPA on 31st March 1971 and publicized by the NESHAP on 6th of April 1973 (EPA, 2023). The regulatory environment in Sri Lanka is influenced by the worldwide asbestos regulatory setting, which includes international conventions and guidance from agencies such as the EPA (EARF, 2021). Sri Lanka has established rules and regulations in place to control the use of asbestos. One important organization controlling the use of asbestos in building materials is the National Building Research Organization (NBRO). Under Part II (particular sources) of the National Environmental Act of Sri Lanka, "waste arising from repairing/renovation processes and demolition/construction debris containing asbestos" is classified as a scheduled waste that needs a license to be disposed of (EARF, 2021).

In Sri Lanka, no adequate studies have been conducted to assess the airborne chrysotile fibre counts, and hence, there is no data available on its impacts on health. Further, few epidemiological studies have been conducted on the industrial sector. The current research is the first study, including collecting primary data and a medical examination of currently employed workers of an asbestos cement factory to determine their health status in connection with potential occupational exposure to suspended particles in the workplace air. Furthermore, the effect of the asbestos on the inhabitants living close to the factory was studied by selecting 10 houses within a 1 km radius of the two plants.

Methods

Ethics

Ethical clearance (THK/ERC/03/2019) for the study was obtained from the General (Teaching) Hospital, Kandy, Sri Lanka and the Postgraduate Institute of Science (PGIS), University of Peradeniya, Sri Lanka.

Study area selection

Four factories produce asbestos cement roofing sheets in Sri Lanka, and one of the largest asbestos roofing sheets producing factories in Sri Lanka with two production facilities was selected for the study. Deposition samples were collected from each production facility (1st production facility (PF)—Defective Sheets Storage (F_1D1), Production Plant (F_1D2), Pulverizer (F_1D3), Cement silo (F_1D4), Loading Area (F_1D5), 2nd PF—Defective Sheets Storage (F_2D1), Production Plant 1 (F_2D2) and 4 (F_2D3), Pulverizer (F_2D4), Loading Area (F_2D5) and analysed using SEM to understand the airborne asbestos fibres availability in breathing air. Air samples were collected from each production facility (1st production facility (PF)—Defective Sheets Storage (F_1A1), Production Plant (F_1A2), Pulverizer (F_1A3), Cement silo (F_1A4), Loading Area (F_1A5), Admin complex (F_1A6) 2nd PF—Defective Sheets Storage (F_2A1), Production Plant 1 (F_2A2) and 4 (F_2A3), Pulverizer (F_2A4), Loading Area(F_2A5)). The National Institute of Fundamental Studies, Kandy, Sri Lanka was selected as the control site.

Sample collection

Air and dust sampling were conducted in the year 2019 from May to December, before the COVID-19 pandemic to monitor the air quality at the selected factories. Sampling was performed at both production facilities, Premises 1 and 2. In total, 142 samples, which included 65 dust and 77 air samples, were collected at workplaces and in the sanitary protection zone of the factory for morphological and chemical testing using Envirotech APM550 Fine Particulate Air Sampler and passive industrial samplers with a duration of 30 min at each site at 5-day intervals; Workplace air sampling was done at the height of 1.5 m (in the human breathing zone). Five control samples were obtained from the different places at the control site. Details of the Sampling sites and the number of samples collected are shown in Online Resource 5(ESM_1)**.**

Methods of testing

The collected samples were subjected to physical and chemical analysis to determine the presence of asbestos in the industrial setting. The number of tested dust samples for each analysis and summary of the Asbestos sample analysis are summarised in Online Resources 6 and 7(ESM_1), respectively**.**

The presence of fibres and the morphology of grains

Air samples were taken on paper filters, after which the filters were weighed to determine the amount of collected particles. Filter papers prepared using acetone/triacetin (NIOSH 7400) were observed by phase contrast microscopy using an optical microscope Olympus BX50F4. The surface morphology of particles present in dust samples was determined by Field Emission Scanning Electron Microscopy (FESEM) at 15 kV (Hitachi SU6600, Japan). The same analysis was repeated for the control samples.

Mineral composition and particle size

X-ray diffraction (XRD) diffractograms for about 0.1 g of each sample, including the control sample, were obtained by using the Rigaku UltimaIV Diffractometer under Cu Kα radiation (λ = 1.5406 Å). The diffractogram was obtained with a step resolution of 0.02° at a step time of 2 s to ensure measurement stability over changes in angular coordinates and time resolution. A total of 25 dust samples were analysed using XRD. X-ray diffraction spectra (diffraction patterns) were obtained and plotted using OriginPro 9 software. As a result, the positions of diffraction peaks, their intensities and the values of interplanar distances were established. The obtained diffractograms were compared with the available reference diffractograms of chrysotile and amphibole asbestos. The collected samples and control samples were analysed for particle size determination using Horiba Scientific SZ-100 particle size analyser with deionized water as the dispersion medium and Fritsch Analysette 22 Micro Tec plus particle size analyser.

FTIR analysis

Potential organic chemical bonds were interpreted by infrared spectroscopy using a Fourier-transform infrared spectrometer (FTIR, Nicolet iS50 FT-IR) with 64 scans and a resolution rate of 4 cm^{-1}.

Elemental analysis

About 0.25 g was taken from each sample and was digested with 5.0 mL of analytical grade HNO_3 (Suprapur HNO_3 65%, Merck KGaA, Germany) using a microwave digester (MARS 6 Microwave Digestion System, iWave ready 240 V/50 Hz) to liquefy the samples. Next, the digested samples were filtered with 0.45 µm syringe filters and were subjected to an inductively coupled plasma–optical emission spectrophotometer (ICP-OES, ICPA 7000, Thermo, USA). The elements were divided into two groups, major elements and trace metals, for the convenience of the graphical illustration of the data. The standard material (Multielement Standard for ICP) for the metal analysis was purchased from Sigma Aldrich. The recovery rates of ICP-OES for major elements were within 79–115% except for Al, whereas recovery rates were within 85–103% for trace metals. Therefore, all element recoveries from ICP-OES were within the globally accepted range (80–120%). The metal analysis was carried out in triplicates, and the average values of the metal concentrations for each sampling site of the two plants of the factory premises were obtained. The same procedure was repeated for the control samples. The data were illustrated using bar charts.

Epidemiological survey and medical screening

Study population and data collection

The study population (n = 264) consisted of workers from Administration, Production (Cleaning, Machine Operators, and Production workers), yards and stores, Drivers, Quality assurance, Electrical workers and Mechanical. Written informed consent was taken from each worker, and information on demographic, behavioural and disease-specific characteristics was collected using an interviewer-administered questionnaire.

Medical screening

Two hundred and sixty-four workers from two production facilities were medically screened in the year 2019 from May to December. Investigations on workers' health were assessed with medical screening, including blood pressure measurements, heart sound listening, and a lung function test (LFT)-Spirometry (Spirolab 3 machine). Detailed analysis, including the values of the parameters assessed in the LFT, is shown in electronic supplementary material 2(ESM_2). A data set as a control sample for the lung function test for healthy volunteers living outside the factory was prepared from the two previous studies (Sooriyakanthan et al., 2019; Udupihille, 1995) conducted in Sri Lanka, and a comparative analysis was performed with the studied healthy factory employees (ESM_3).

In addition, out of 264 medically screened workers, 202 were subjected to chest X-ray analysis, as only 202 granted their consent for the analysis. The chest

X-ray reports were read by an independent radiologist following the guidelines for the use of radiographs of pneumoconiosis and Appendix E –summary of details of the ILO (2000) International classification of radiographs of pneumoconiosis.

Statistical analysis

Data were double-entered, validated using EpiData v3.1, and analyzed using EpiData v2.2.2.183 (EpiData Association, Odense, Denmark). Frequencies were calculated for categorical variables. Continuous variables were summarized using means and standard deviation. The chi-square test was used to assess the differences in the proportions. The level of significance was set at $P < 0.05$.

Statistical analysis was performed to assess the relationship between the epidemiological data and the characteristics of suspended mineral particles.

Environmental exposure to asbestos – Residents living in a 1 km vicinity

The effect of the asbestos on the inhabitants living close to the factory was studied by selecting ten houses within a 1 km radius of the two-factory premises. Air samples from chosen homes were collected using Envirotec APM550 Fine Particulate Air Sampler. The conditions of the breathing air and the status of the residents of the houses were also recorded. Four of the collected samples were subjected to SEM analysis. All ten samples were subjected to optical microscopic analysis to observe the availability of asbestos fibres in the breathing air of the houses situated within a 1km vicinity.

Results and discussion

Air quality monitoring

Microscopic analysis of dust samples

Phase contrast microscopic images for dust samples taken near to pulverizing machine sites of Plant 1 and 2 are presented in Fig. 1a and b, demonstrating the fibrous nature of the particulate matter indicating the presence of chrysotile. From the collected deposition samples, asbestos fibres were observed in seven sites out of ten sites (1^{st} production facility (PF)—Production Plant ($F_1$2), Pulverizer ($F_1$3), Loading area ($F_1$5), 2^{nd} PF—Production Plant 1 ($F_2$2) and 4 ($F_2$3), Pulverizer ($F_2$4) and Loading area ($F_2$5)). No airborne asbestos fibres were observed from the breathing air samples collected inside the factory. Sampling sites with the availability of asbestos fibres are summarized in Table 1. Fibrous formations (particles elongated in one direction) were found in the settled dust samples.

According to the Table 1, the range of available fibre concentrations in Facility 1 was 0–81 fibres/mm^2 whereas the average fibre concentration for the entire facility environment was 27.5 fibres/mm^2. Those values for the Facility 2 were 0–94 and 44 fibres/mm^2, respectively. Except for one sampling site (Defective sheets storage area), atmosphere of all other sites in Facility 2 were contaminated with fibres. Nevertheless, air collected at 50% of tested sampling sites in Facility 1 did not consist of fibres. From the asbestos fibres observed in sampling sites, the highest average values were obtained near the pulverizing machine of both production facilities. This was because of the higher emission of asbestos dust during the pulverizing process.

SEM analysis

Fibrous (needle-like) structures and cement particles were observed in the sample under the SEM (Fig. 1c and d). The fibrous structures observed could potentially be asbestos fibres (Belluso et al., 2017; Hofmann, 2023). Some fibres were observed as bundles, and some were observed as single fibres which are straight and thin. Fibre sizes ranged from about 30 µm to 300 µm. Accordingly, the straight and thin fibrous particles observed under the SEM analysis confirmed the presence of asbestos fibres in the atmospheric depositions collected at both facilities.

EDX analysis

The EDX spectra of tested air samples showed the characteristic peaks for the several elements such as C, O, Mg, Si, Ca, K, Al, and Fe. The EDX spectra in Fig. 1e and f, exhibit the presence of those elements in the samples collected at broken sheet dumping area and the pulverizing site in both Facilities. Chrysotile asbestos's most prevalent elements are Mg, Si, H, and

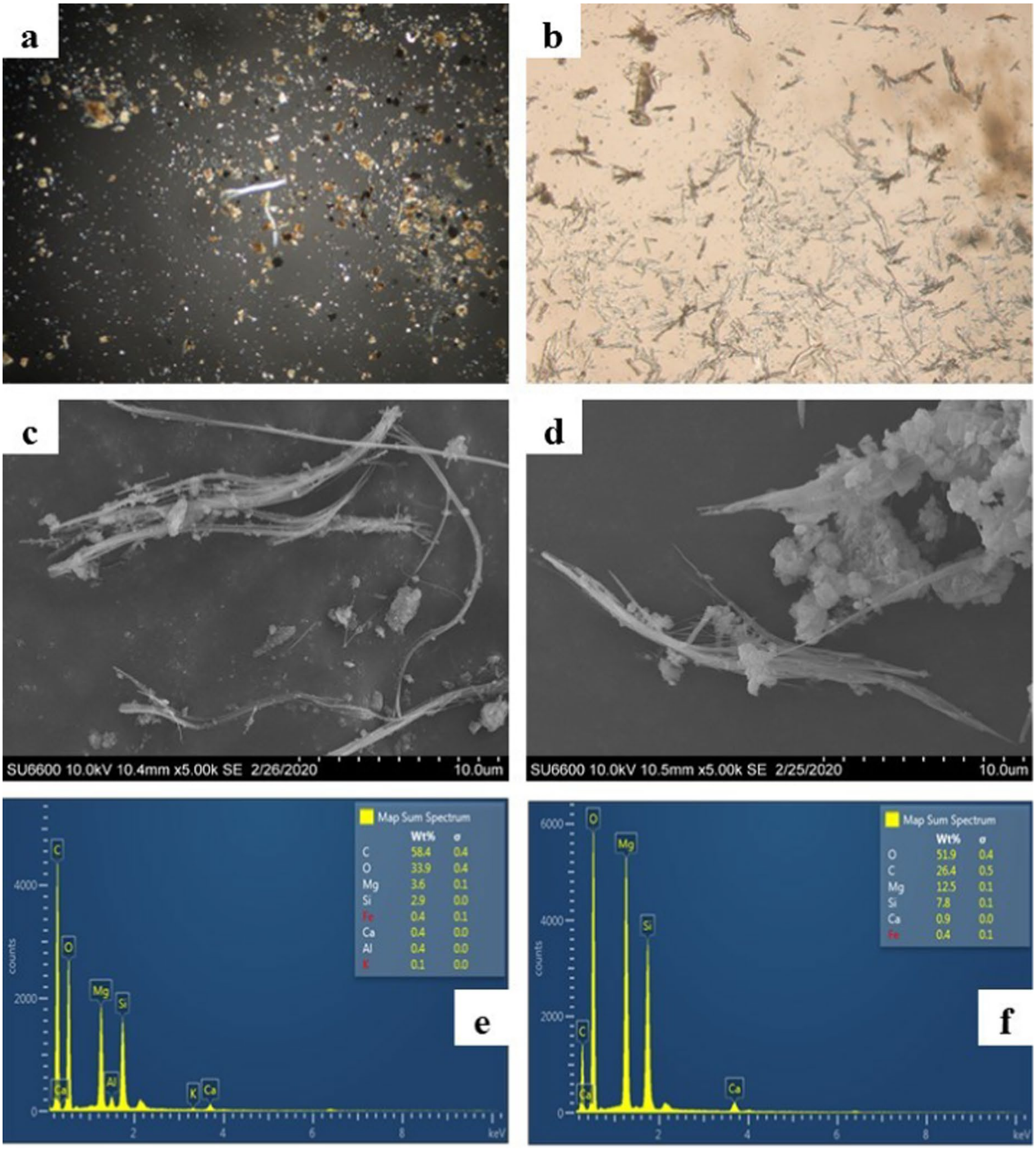

Fig. 1 Microscopic images of deposition samples collected at **a** Facility 1 and **b** Facility 2 near the pulverizing machine (4×10), **c** SEM and **e** EDX images for the dust particles near the broken sheets dumping area, Facility 1, **d** SEM and **f** EDX images for the dust particles near the pulverizing machine, Facility 2

O ($[Mg_3(Si_2O_5)(OH)]_{4n}$) (Peña-Castro et al., 2023). EDX analysis confirmed the presence of Chrysotile fibres in the atmospheric samples inside the factories. Depending on the sample composition, the most three concentrated elements per weight for all the tested samples were C, O, and Mg. The resultant higher weight percentage values of C might be due to the carbon strip for the sample mounting.

Table 1 Asbestos fibre availability and average counts from deposited samples collected from sampling sites of two roofing sheet production facilities, Sri Lanka

Production facility	Sampling site	Fibres availability	Average fibre count (fibres/ mm^2)
Facility 1	Inside the plant	Present	49
	Cement silo	Absent	0
	Loading Area	Present	35
	Near the Pulverising machine	Present	81
	Defective Sheets Storage	Absent	0
	Admin Complex	Absent	0
Facility 2	Inside the plant 1	Present	43
	Inside the plant 4	Present	52
	Near the Pulverizing machine	Present	94
	Defective Sheets Storage	Absent	0
	Loading Area	Present	31

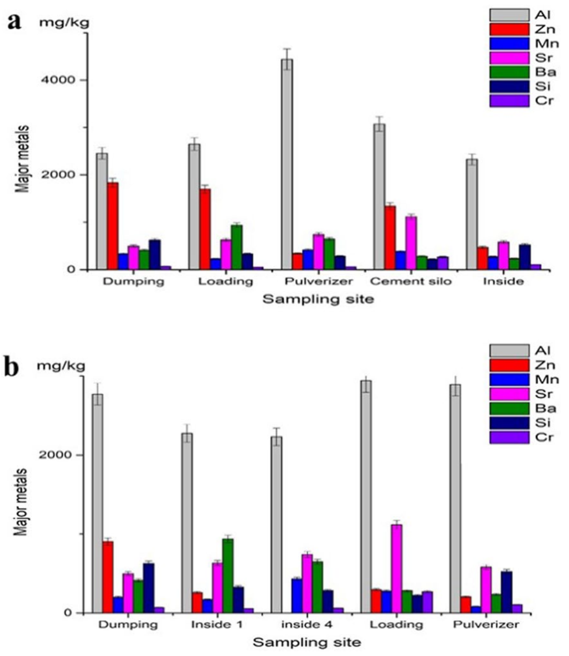

Fig. 2 Major and trace element concentrations (mg/kg) in dust samples collected from different sampling sites at **a** Facility 1 and **b** Facility 2 of the asbestos factory

Major and trace element abundances in dust samples

Figure 2a and b illustrate the most abundant major and trace metal found in deposition samples in Facility 1 and 2. The major elements, Zn, Al, Mg, and Fe, were reported high in the deposition samples, and their concentrations were 0.2–12, 1.9–4.8, 57–163 and 12–112 g/kg, respectively. As per the data obtained for the major metal concentration analysis Al and Zn were the most dominant elements in all dust samples. Aluminum is a major element present in the cement industry. The bulk Al_2O_3 concentration in ordinary and white Portland cement normally ranges from 1 to 6 weight percent, with the majority of the aluminium present in the calcium aluminate ($Ca_3Al_2O_6$) and aluminoferrite ($Ca_2Al_xFe_{2-x}O_5$, $0 \le x \le 1.4$) ($_{2x2x5}$) minerals (Andersen et al., 2006). It has been observed that the metal ions present in cement possibly leach into water. Hence, cement is the main source of Al present in the dust (Fig. 2a and b).

The most prevalent airborne trace elements were Cd, Cr, Pb, Cu, As, and Ni, and their concentrations were negligible (Online Resource 1(ESM_1)). The average concentrations of the trace metals in the samples were; Cd- 2.74, Pb- 17.18, Ni- 46.68, Cr- 81.01, As- 7.12, Co- 6.77 and Cu- 43.04 mg/kg. However, Hg was not detected in any of the samples. When considering Facility 1, the least abundant metal was Mo (<5 mg/kg) for all sampling sites, whereas it was as (<5 mg/kg) for Dumping, Inside1, and Inside 4 sampling sites and Mo (<5 mg/kg) for Loading and Pulverizing sampling sites and Facility 2. The evidence of trace metal contamination might be due to the production materials. Trace elements are naturally present in varying proportions in the primary raw materials for cement and both primary and secondary fuels used in the industries (Vollpracht & Brameshuber, 2016). Because of this, Portland cement contains a range of trace metals.

X-ray diffraction analysis

The diffraction peaks of the dust samples demonstrate the characteristic chrysotile asbestos peaks—24.3, 32.2, 34.2, 43.1, 60.1 (2θ)) and of natural asbestos (Ahmad, 2015)(Fig. 3). The peaks with highest intensities around 30° 2θ angle in the following two XRD diffractogram showed the existence of calcite in the deposited dust samples (Witek et al., 2019). The characteristic diffraction peaks of chrysolite were not detected for two and one sampling sites in Facility 1 and Facility 2, respectively (Online Resource 8(ESM_1)). Remarkably, none of the chrysotile diffraction peaks were in the XRD patterns obtained for the samples collected at dumping sites at both facilities. Deposited dust samples obtained from the Cement silo sampling site at Facility 1 also did not consist of characteristic chrysotile asbestos peaks. As well, amphibole peaks were not previewed for all tested dust samples, revealing the abundance of serpentine chrysolites in the atmosphere of both facilities (Kusiorowski et al., 2012).

Particle size analysis

All the samples collected from the Factory premises showed the presence of particles in sizes between 2 and 8 µm (Online Resource 2, (ESM_1)). The particles observed in the PM analysis can be cement and other dust particles. Control sample PM10 and PM2.5 values were 46 µ gm^{-3} and 23 µ gm^{-3} and are lesser than the WHO maximum limit of 50 µ gm^{-3} and 25 µ gm^{-3}, respectively. The highest PM2.5 value was observed near the Pulverizing machine of PF2 (258 µ gm^{-3}), while the lowest value was observed from the admin complex in PF1 (37 µ gm^{-3}). The highest and the lowest PM10 values were observed from the same sites as PM2.5 (387 µ gm^{-3}, 67 µ gm^{-3}). The highest PM10 values were more than 8 times higher than that of the control sample whereas the highest PM2.5 was 10 times higher compared to the control sample. The highest average values were obtained near the pulverizing machine of both production facilities same as of fibre counts. This was due to the continuous breakage of waste roofing sheets, while the PM values were lower at the Admin complex due to the concealed conditions.

A possibility could be the larger sizes of the fibres, and due to the weight, those fibres won't be available in the breathing air for a long duration, thereby not getting captured by the air sampler, and at times the sampling sites were not functioning during the sampling. Therefore, the asbestos fibres were unavailable in the breathing air of those areas.

FTIR analysis

The sites which confirmed the presence or absence of chrysotile bands are listed in Online Resource 9(ESM_1). The FTIR spectra for the samples collected at three sites and four sites (out of 5) in Facility 1 and 2, respectively consisted of chrysotile bands. Consequently, the existence of Chrysotile asbestos was further confirmed by the FTIR analysis with the existence of their characteristic bands. Figure 4a–d shows the FTIR spectra obtained for the samples collected from the selective sites at two facilities (pulverizing machine and inside the production plant). The existences of surface Mg–OH and Si–O bonds were confirmed by the strong bands around 3750 cm^{-1}, which is attributed to OH stretching vibrations, and broad band around 1000 cm^{-1}, which is attributed to the symmetric stretching vibration of Si–O–Si and Si–O bonds of the mineral's tridymite

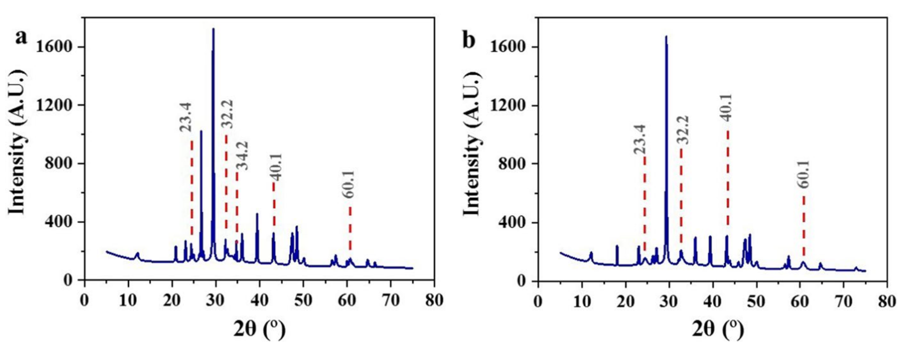

Fig. 3 X-ray Diffractogram of the dust collected near the pulverizing machine of **a** Factory 1 and **b** Factory 2

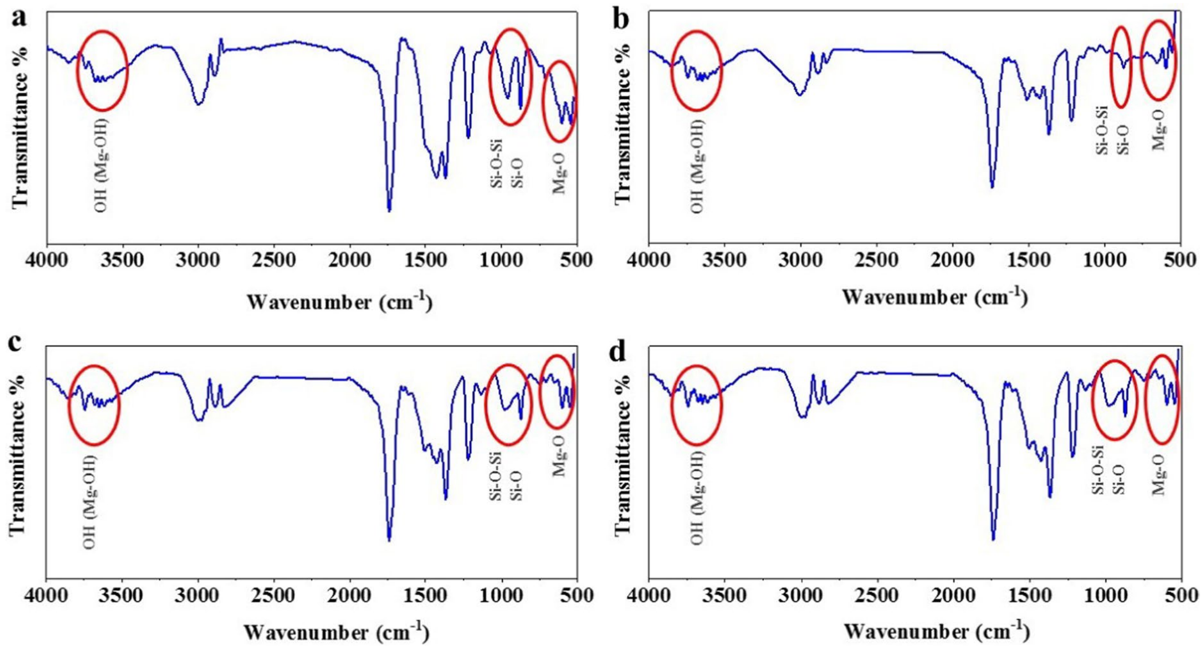

Fig. 4 FTIR spectra of dust particles collected near pulverizing machine at **a** Facility 1, **b** Facility 2, and inside the production plant at **c** Facility 1, and **d** Facility 2

layer, respectively (Borges et al., 2023). Also, the weak bands between 500 and 750 cm^{-1} confirmed the existence of internal vibration of the Mg–O bond in the tested samples Field(Borges et al., 2023; Valouma et al., 2016). The strong band at 1750 cm^{-1} and the broad band around 1500 cm^{-1} might be due to the water molecules absorbed or adsorbed on chrysotile fibres (Wypych et al., 2004).

Overall air quality in the factory setting

Based on the findings, no free chrysotile fibres could be detected from the breathing air samples collected from the two Asbestos factories. Tiny and lightweight Asbestos fibres normally remain suspended in the air (Ansari et al., 2010). In 1986, OSHA, in Standard 29 CFR 1910.1001, established the current permissible exposure limit (PEL) for asbestos in the workplace as 0.1 fibres/cm^3 of air as an eight-hour time-weighted average (TWA) over a 30-min period (Tucker, 2014).

However, free chrysotile fibres were observed in the settled dust (deposition) samples collected at both facilities. Seven out of ten sampling sites showed the presence of fibres, except in three locations. These sites, loading area, admin complex, and cement silo are generally the places where the asbestos-related activities are lower than the other areas inside the factory. In industry, Asbestos cement products are manufactured using mechanized processes with 10–20% chrysotile mixed with Portland cement slurry. Chrysotile fibres are fine fibres (< 0.5 μm) in white to grayish green color and have $[Mg_3(Si_2O_5)(OH)]_{4n}$ of chemical composition (Peña-Castro et al., 2023). In thin sections, asbestos cement typically consists of finely divided asbestos fibre dispersed in a matrix of Portland cement, including abundant partially hydrated relict cement grains. Accordingly, Asbestos fibres can be available in these deposition samples due to the fibres' size and the longer duration (5 days) of sample collection in this sampling method.

Environmental exposure to asbestos – Residents living in a 1km vicinity

According to the SEM and EDX analysis, no asbestos fibres were observed in the breathing air within 1 km of the factory (ESM_1, Online Resource 3. a and b). Similarly, with the Optical Microscopic analysis, no asbestos fibres were observed in the breathing air of the 1 km vicinity from the two plants (ESM_1, Online Resource 3. c and d). According to observations, it can be interpreted that individuals currently living in the same locality of the asbestos factory are not exposed to asbestos fibres through the breathing air. As the neighborhood's breathing air is free of asbestos fibres, residents living in close proximity to the factory might not subjected to undue respiratory health risks at present. However, to maintain the health and safety of the local community, constant monitoring of air quality is vital to prevent potential mishaps.

Epidemiological survey and medical screening

Medical screening and lung function tests

Of the 264 workers, 95.45% were males, and among them, 95 (37.69%) were smokers, while all the female employees were non-smokers. Using the measurements of LFT, the health conditions of the workers were categorized as Normal, Possible Mild Restrictions (PMR), Possible Moderate Restrictions (PMoR), Moderate obstructions (MO), Mild obstructions (MiO), Obstructions with possible restrictions (OwPR), and Possible Moderate, severe restrictions (PMSR) (Table 2). From LFT results,

Table 2 Demographical factors associated with Asbestos Related Occupational Health Problems Among Asbestos Industry workers and Medical Screening data of the Asbestos Roofing Sheets Production Factory workers (n = 264)

Socio-demographic data	Number of workers					
1. Total number of study participants	264					
Men	252					
Women	12					
2. Occupation and the age groups of the workers						
Age group	**20–29**	**30–39**	**40–49**	**50–59**	**> 59**	**Total**
Admin	13	15	2	5	0	35
Production (Cleaning, Machine operators, Production workers)	18	26	26	19	7	96
Yard	6	11	13	6	5	41
Driver	3	7	4	2	2	18
Quality	16	8	7	6	0	37
Electrical	4	4	4	3	2	17
Mechanical	4	4	6	4	2	20
Total	64	75	62	45	18	264
3. Chest X-ray test	202					
Normal	197					
Abnormal	05					
Mild Emphysema	03					
Mild fibrosis in B/L lower zones	01					
Early fibrosis in the left lower zone	01					
4. Lung Function test						
Total	264					
Normal	200					
With variations	64					
Possible mild restrictions	43					
Possible moderate restrictions	10					
Moderate obstructions	03					
Mild obstructions	04					
Obstruction and possible restrictions	03					
Psossible moderately severe restrictions	01					

24.24% of workers presented abnormal lung function (LF) conditions, and Table 3 details their work duration. Among them, 10 workers were suffering from Asthma. From the questionnaires, only five workers didn't use personal protective equipment (PPE) while working inside the factory. However, during the sample collection, it was observed that most of the workers didn't use the PPE continuously during the working period. Of the 264 workers, 44 (16.66%) indicated respiratory symptoms during the medical screening process. The workers who displayed respiratory symptoms along with abnormalities in LFT are shown in Online Resource 4(ESM_1). Among these employees, three were from the production, 02 were working in the quality assurance, while one each from admin, electrical and mechanical and the other was working as a driver. A machine operator was suffering from a lower respiratory tract infection with a cough, while the driver was suffering from Cough, Nasal discharge, Shortness of breath, Clubbing, and Plethoric.

Medical screening and X-ray analysis

Only 202 workers gave consent for chest X-rays. According to the analysis results obtained from the radiologist, from those 202 X-ray reports, only five workers showed any pulmonary abnormality (Table 4).

Analysis of correlation coefficients

Correlations between medical screening with behavioral factor

The correlation coefficient values (R) were calculated for the factors that can affect the workers' respiratory health using Epistat. R between the respiratory symptoms and the work duration is 0.04, R between the chest X-ray results and the work duration is 0.011, while R between the LFT results and the work duration of the workers is 0.022. R between the respiratory symptoms and the usage of PPE is 0.032, LFT results and the use of PPE is 0.045, while R between the work area of the workers and PPE usage is 0.0385.

Table 3 Number of workers with variations in Lung Function Test with no of years at employment

Duration of work (Years)	Possible Mild Restrictions (n = 43)	Possible Moderate Restrictions (n = 10)	Moderate obstructions (n = 3)	Mild obstructions (n = 4)	Obstructions with possible restrictions (n = 3)	Possible Moderate severe restrictions (n = 1)	Normal (n = 200)
0–5	19	8	0	1	0	1	70
6–10	12	2	2	2	2	0	68
11–15	7	0	0	1	0	0	30
16–20	3	0	0	0	1	0	8
21–25	1	0	1	0	0	0	15
26–30	0	0	0	0	0	0	9
31–35	1	0	0	0	0	0	0

Table 4 Details of the workers who presented abnormalities in their chest X-rays

Serial no	Job category	Work duration (Years)	X-ray	LFT
4	Gas plant operator	4	Mild emphysema	Normal
25	Yard and stores labourer	7	Mild fibrosis in B/L lower zones	Normal
160	Mechanical welder	12	Early fibrosis in the left lower zone	Normal
182	Yard and stores	14	Mild emphysema	Possible mild restriction
157	Mechanical filler	7	Mild emphysema	Possible mild restriction

Correlations between LFT abnormalities with the asbestos fibres availability

Around 0.47 correlation could be observed between the LFT abnormalities and the XRD, ICP-OES, FTIR, SEM and PSA data for deposition samples. However, there isn't any correlation with the Optical Microscopic data as there were no free asbestos fibres in the air samples.

Correlations between respiratory symptoms with the asbestos fibres availability

According to the calculations, a 0.24 correlation between the respiratory symptoms and the data obtained from XRD, ICP-OES, FTIR, SEM and PSA calculations could be observed. Nevertheless, there is no correlation with the Optical Microscopic data because no free asbestos fibres were observed in the breathing air samples.

Health status of the industry workers through medical screening and epidemiological survey

Though working in the same factory, asbestos exposure to workers varies with different factors, such as duration of exposure, fibre concentrations, inhalation rate, and also with weather conditions. Duration of exposure is diverse as direct and indirect, depending on the number of hours working in a particular site and being on the premises but not directly involved with work. Asbestos has been classified as a Group I carcinogen by International Agency for Research on Cancer and is acknowledged as a well-known carcinogen of lung cancer and malignant mesothelioma (Tiwari & Saha, 2014).

Employees (264) who gave consent were medically screened and were subjected to LFT (Spirometry) to check their LF. LFTs are a combination of studies conducted in clinical practice to determine lung capacity and the possible deterioration of the mechanical function of the lungs, respiratory muscles, and chest wall (Barroso et al., 2018). This test measures how much air human can breathe in and out of your lungs and how easily and fast you can blow the air out of your lungs (Association, 2021). Lung function traits, including forced expiratory volume in 1 s (FEV1), forced vital capacity (FVC) and FEV1/FVC, are helpful in the diagnosis or monitoring of lung diseases (Lee et al., 2017). The workers' health conditions were categorized accordingly with these measurements' aid. LFT results of the workers revealed that 75.75% didn't have any Lung Function Abnormalities. The comparison of LFT parameters for factory employees who recorded normal LFT values with a healthy study population (outside the factory), a created data set from published two Sri Lankan studies is shown in (ESM_3), and the values of normal LFT of factory employees agree with the findings of the previous Sri Lankan healthy data (Sooriyakanthan et al., 2019; Udupihille, 1995). Nevertheless, 64 of the factory workers had restrictions and obstructions: PMR (16.28%), PMoR (3.78%), MO (1.13%), MiO (1.51%), OwPR (1.13%), PMSR (0.37%). The highest number of workers had PMR. However, two workers suffering from PMR were suspected of emphysema from X-ray analysis. Reduced lung function among individuals with a history of asbestos exposure is common and has been well-recognized (Park et al., 2014). In pulmonary diseases, when certain patients are in the early stages of their illness, it may not be visible in chest X-ray results. Then, Horizontal Central Ray (HCR) X-ray tests should be done further to analyze the health conditions of the particular workers. However, both LFT and chest X-ray results can show positive results in severe health conditions. Of all the 264 workers, two workers showed positive results in both tests. The details of the five employees were informed to the factory management and for further testing, including HRCT at the Respiratory Unit of the National Hospital, to rule out Asbestosis and other respiratory diseases.

Numerous studies suggest that people who live in places with a high concentration of asbestos-bearing rocks and are consequently exposed to naturally occurring asbestos (NOA) discharged in the air may develop mesothelioma (Noonan, 2017). Nevertheless, the connection between exposure to natural environmental factors and the occurrence of this malignancy remains a subject of ongoing debate (Avataneo et al., 2022). Reduced lung function is a significant health indicator in respiratory illnesses and predicts mortality in the population as a whole (Schu et al., 2000). However, this test is mainly effort dependent. Hence, the psychological strength and muscle strength of the individual are the main factors that can affect the results. Therefore, sometimes, when the individual is not in a good health condition or not in a good mental state, a variation in the LFT results could be observed.

According to the literature, lung volumes in Sri Lankans compared to Europeans are smaller which is attributed to the smaller physique, but observed as same as to South Indians. Furthermore, differences in ethnicity cause variations in lung functioning, and the smoking causes a decrease in Lung function (Sooriyakanthan et al., 2019; Udupihille, 1995) Sri Lanka is a country with multi-ethnicity with the majority of 75% Sinhalese and 11% of the population being Tamils. According to the study population, 93.6% are Sinhalese. Yet, a comparison of LFT values of the Healthy workers in the current study with the two previous studies by Sooriyakanthan et al., (2019) and Udupihille, (1995) shows that ethnicity has no major influence on the lung function of factory workers. Of the 64 employees with LF disorders, approximately 37.5% were smokers, a risk factor for lung diseases. Cigarette smoking is the single most important modifiable risk factor for reduced lung function (Vollmer et al., 2000); smoking produced a proportional deficit in pulmonary function (Gold et al., 1996). Radiographic studies show that smoking increases the attack and the progression rate for Asbestosis (Mossman & Churg, 1998). Therefore, smoking can act as a co-factor with asbestos exposure for LF abnormalities.

According to the findings, the number of workers with LF abnormalities who are smokers is less than the number of workers with LF abnormalities who are non-smokers. However, the correlation coefficient value between smoking and LF abnormalities is 0.032. Therefore, there is a correlation between smoking and LF abnormalities.

Of the 264 workers, 44 (16.66%) showed respiratory symptoms during the medical screening process. According to the literature, airway obstructions may be present in asymptomatic patients with asthma (Brand & Roorda, 2003). Also, workers with respiratory symptoms like breathlessness, chest tightness, runny nose and wheezing can have respiratory conditions like chronic obstructive pulmonary disease (COPD). The inflammatory response is accentuated in patients with COPD, and small airways become persistently inflamed. COPD also leads to decreased gas transfer. The vascular system is affected, with an increased risk of ischemic heart disease, congestive heart failure (CHF), pulmonary vascular changes and pulmonary embolism (PE) (Jögi et al., 2011).

Of the 64 workers with LFT abnormalities, according to questionnaire only 5 (7.81%) did not use any PPE while working inside the factory. Three were administration workers, and two were working at the loading area. Although the Admin complex areas did not show the availability of asbestos fibres in the breathing air, the Loading area had asbestos fibres. Therefore, those workers are at risk of being exposed to asbestos fibres in the breathing air while working. Also, the administration workers have the same above-mentioned risk. According to questionnaire though the other workers used PPE, they used only a cotton mask to cover their faces. That was also not used continuously due to the higher heat inside the factory premises and the breathing difficulties. Furthermore, during the sample collection, it was witnessed that most of the employees didn't use the PPE continuously during the working hours. Therefore, when we consider the usage of PPE, there is a discrepancy between the interpreted the data from questionnaire analysis and the actual numbers. According to the correlation coefficient values, both LFT results and respiratory symptoms showed positive correlations with PPE usage. Therefore, the usage of PPE is critical to avoid the possibility of getting respiratory diseases and reduce the effect on the workers' lung function while working in an asbestos-related production factory. As such using PPE is an essential health precaution for the workers in the asbestos industry because the only way of preventing asbestos exposure while working in an asbestos factory is to cover the potential tracks of asbestos exposure. Therefore, wearing masks and protecting the skin is essential and should be mandatory for asbestos-related industry workers and the factory should implement and adhere to the safety guidelines strictly.

Conclusion

The workers presently employed were medically screened in two facilities of the asbestos manufacturing factory in Sri Lanka to assess the safety of the occupational and atmospheric environment. Asbestos fibre counts were recorded from dust samples, at crucial working sites, but chrysotile fibres were not present in the breathing air samples. The atmospheric contamination of fibrous asbestos in the deposited samples was confirmed by the characteristic FTIR bands and the element composition of chrysotile. The air samples were contaminated with potentially toxic major (Average concentrations of Zn, Al, Mg, and Fe were 0.2–12, 1.9–4.8, 57–163, and 12–112 g/kg, respectively) and trace metals (Average concentrations of Cd, Pb, Ni, Cr, As, Co, and Cu were 2.74, 17.18, 46.68, 81.01, 7.12, 6.77, 43.04 mg/kg). The medical screening test confirmed that only 16.66% of workers showed respiratory symptoms. The habit of smoking would be a potential co-factor with asbestos exposure for LF abnormalities. Personal protective equipment was identified as a crucial thing that can mitigate the risk of respiratory illnesses and the impact on workers' lung function to a certain extent when they are working in an asbestos-related production facility.

The performed study was a cross-sectional study. Furthermore, we were unable to trace the health status of Ex-workers' and we could not contact them in person due to the pandemic COVID situation in the country. According to literature, the average latency period for Asbestosis, lung cancer, and mesothelioma is about 40 years. Therefore, there is a need for long-term follow-up of occupationally exposed workers.

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Author contribution All authors contributed to the study and take responsibility for the data's integrity and the data analysis's accuracy. WBCPW performed Experimentation, data interpretation, data validation, and writing of the first draft, MS wrote the final draft and manuscript preparation, ACW supervised analyzing crystallography, morphological features and particle sizes, RMDM supervised screening workers for respiratory diseases and overall medical investigations, MV supervised chemical analysis for bioavailable metals and risk assessment, reviewing and editing the manuscript, DNM conceptualization, conducting the epidemiological survey on workers, overall supervision, project administration, funding acquisition, writing, reviewing, and editing the manuscript. The manuscript was written with contributions from all authors. All authors have approved the final version of the manuscript.

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Declarations

Competing interests The authors declare no competing interests.

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