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Original Article

Measurements of airborne asbestos fibres during refurbishing

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Abstract

Although the use of asbestos fibres in building materials has been prohibited in Norway since 1985, asbestos-containing materials (ACMs) are still found in many buildings. Lack of knowledge and awareness of these materials may lead to exposure during refurbishing. The aim of this study was to investigate the airborne fibre concentration and classify fibres found during the abatement of various ACMs. The release of fibres during short-term work tasks, such as drilling and sawing, was also investigated. Parallel air samples were collected during asbestos abetment of different building materials and analysed with scanning electron microscope (SEM) and phase-contrast microscope (PCM), respectively. Material samples were analysed with SEM. A real-time fibre monitor was used to measure asbestos during short-term work. The highest fibre concentrations were measured for samples collected during the removal of asbestos insulating boards (1.5–4.5 fibres/cm^3 [f/cm^3]), and the numbers were relatively similar for SEM and PCM. A large difference in asbestos concentrations was found between SEM and PCM when analysing floor materials, which were probably caused by a high number of gypsum fibres that the PCM operator counted. Thin fibres (<0.2 μm in width) were included in the SEM count and constituted up to 50% of the total fibre concentration for the asbestos cement materials. The presence of other inorganic and organic fibres on these samples probably led to similar results between SEM and PCM. Short-term work led to peak concentrations above 30 f/cm^3.

Key words: asbestos; asbestos quantification; characterization; occupational exposure; phase-contrast microscopy; scanning electron microscopy.

What's Important About This Paper?

Many buildings and houses built with asbestos-containing materials are now due for refurbishment or demolishing, making it important to stress that asbestos air concentrations during such work operations may be relatively high. This study also demonstrates that thin fibres (<0.2 μm) not detected by phase contrast microscopy should be counted more frequently as these constitute a large share of the asbestos released from some materials.

Introduction

Due to its durability and excellent heat and weather resistance, asbestos-containing materials (ACMs) were popular building materials between the 1930s and the mid-1980s. ACMs are still frequently found in buildings and houses built in this period, even though it is more than 30 years since the use of these materials was prohibited in Norway.

Today, many of these buildings need to be refurbished or demolished. As in many other countries, the presence of asbestos in buildings in Norway is not fully mapped. This incomplete mapping of asbestos may result in unsafe handling of ACM. Construction workers are especially at risk of exposure to asbestos in these cases. The type and condition of the material, the character of the work and the environment, such as indoor or outdoor work, are factors that are important in

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exposure scenarios. Some previous studies have found low levels of ambient asbestos fibres (<0.01 fibres/cm^3 [f/cm^3]) during the demolition of residential dwellings (Perkins et al. 2008; Neitzel et al. 2020; Stevulova et al. 2020); however, other studies have indicated exposure levels well above 0.1 f/cm^3 (Eypert-Blaison et al. 2018). Weathering of ACMs has been well documented and may lead to higher asbestos fibre concentrations during asbestos abatement (Brown 1987; Spurny 1989; Obmiński 2020; Ervik et al. 2021).

Exposure to asbestos has traditionally been quantified by air sampling, where particulate matter including asbestos fibres, is filtered onto a cellulose ester filter that is further investigated in a phase-contrast microscope (PCM). Fibres that are longer than 5 µm and have a diameter of less than 3 µm, and a ratio of length to thickness of more than 3:1 are counted by PCM (WHO 1997). Counting asbestos fibres by PCM is a relatively inexpensive and rapid method which is probably why this method is still used to a large extent for asbestos quantification. The major disadvantage of this method is that it cannot be used to detect fibres thinner than 0.2 µm or obtain chemical information from the fibres. The counting of fibres is therefore highly dependent on the operator and the equipment used by the operator. Appropriate training and participation in inter-laboratory analyses are necessary to ensure reliable results. A scanning electron microscope (SEM) or transmission electron microscope (TEM) equipped with energy-dispersive X-ray (EDX) yield the possibility of investigating thinner fibres and determining the chemical composition of the fibres. It is possible to differentiate between the various asbestos types and to identify non-asbestos fibres only when the fibres' morphology and chemical composition are known.

This study aimed to measure airborne asbestos fibres during the abatement of asbestos-containing building materials and to classify and characterize the collected fibres with SEM-EDX. Additionally, the real-time fibre concentration was assessed to investigate the release of asbestos fibres during short-term work. To the best of our knowledge, there are no studies on the comparison between PCM and SEM measurements during abatement activities; therefore, parallel samples were collected for the two methods.

Materials and methods

Sampling

Personal and stationary samples were collected during the removal of ACM. Personal samples are air samples collected in the breathing zone of the workers. Stationary samples are stationed at a fixed location in the vicinity of the work or in the background. When feasible, these samples were positioned at a height corresponding to a worker's breathing zone at approximately 1.5 m (MAK 2005). The following interior ACMs were investigated in this work: asbestos insulating boards (trade name Asbestolux), pipe insulation, polyvinyl chloride (PVC) vinyl tiles, and one cork board floor. The following outdoor ACMs were investigated in this work: corrugated asbestos cement roof sheets, asbestos cement roof slate shingles, and asbestos cement wall shingles (trade name Eternit). The workers mostly used handheld equipment such as screwdrivers and crowbar for removing wall and roof sheets and floor scraper for removing floor tiles. A machine was used only when grinding floors.

Conductive field-monitor cassettes (Pall Corporation, New York, NY, USA) equipped with 25 mm 0.8 µm mixed cellulose ester (MCE) filters for PCM samples and 25 mm gold coated 0.8 µm polycarbonate (PC) filters for SEM samples were used. A cellulose pad was used as backing for both MCE and PC filters. In-house-built pumps, for asbestos sampling, were connected to the sampling cassettes with a plastic tube. The flow rate was adjusted to 2 L/min before sampling and held constant during sampling. Sample collections were performed during asbestos abatement where one type of ACM was removed or dismantled. In very dusty environments, the sampling time was reduced to prevent overloading. The sampling time for personal and stationary samples was 20–280 min and 20–500 min, respectively. An overview of all collected samples and the sampling duration can be found in the Supplementary Materials. During exterior wall and roof abatement, most measurements were performed during an abatement in which the house was covered by a scaffold with plastic covering with fans to provide negative pressure according to the regulations for enclosures for asbestos abatement. This allowed for a more controlled and comparable environment when measuring asbestos release during several days of work. The specific house was a real house (single family—one story [14.5 m × 10.5 m × 4.7 m]) built in 1942. The house was later used as a residential building and had been renovated and fitted with asbestos-containing materials on exterior roofs and walls in the 1960s. In addition to the measurements performed at this house, a few samples (n = 6) were collected during the removal of exterior wall and roof without a plastic cover (indicated in the Supplementary Materials). These measurements were performed during abatements at two different locations, where one was a residential house (n = 2) from the 1960s in the central part of Norway, and the other was a hotel from the 1970s (n = 4) on the west coast of Norway. Material samples from ACM were collected from the investigated abatement projects. The existence of asbestos fibres was investigated in the material samples; however, the fibre content was not quantified.

Sample preparation of air samples

Filters were examined in a stereomicroscope prior to SEM to verify that the distribution of particles was homogenous. A piece of approximately 8 × 8 mm was cut out of the gold-coated filter with a scalpel and fixed to a carbon tab on an aluminium (Al) stub. Organic material was removed in a low-temperature plasma ashing apparatus (Diener Electronic GmbH & Co. KG, Ebhausen, Germany). Spots of carbon cement (Leit-C, Agar Scientific Ltd, Stansted, UK) were added to the sides of the stub to ensure good conductivity between the filter and the stub. Overloaded filters were rejected according to the criteria in the ISO 14966 standard (ISO 2019). The preparation of PCM samples was performed in a commercial laboratory following the NIOSH 7400 method (NIOSH 2019). The microscope slides were prepared by using the vaporized acetone and triacetin technique.

Sample preparation of material samples

Material samples from abatement sites were examined using a stereomicroscope before sample preparation. The sample preparation method is based on the sample treatment specified in ISO 22262-1 (ISO 2012). Material samples were drilled with a handheld drill in a fume hood. The generated dust was dispersed in water with a low concentration of hydrochloric acid (HCl) to dissolve calcium carbonate ($CaCO_3$) and calcium sulphates ($CaSO_4$ and $CaSO_4*2H_2O$) and sonicated for 1 min in a Sonorex Super (Bandelin GmbH, Berlin, Germany). A polycarbonate (Isopore, Merck Millipore, Massachusetts, USA) filter with a pore size of 0.8 µm was placed on a sintered glass disc in a Büchner filtration apparatus, and the sonicated sample was filtrated with the help of a vacuum pump. An approximately 8 × 8 mm piece of the filter was cut out and fixed on a 10 mm Al stub covered with double-sided carbon adhesive discs (Agar Scientific Ltd, Stansted, UK). Spots of carbon cement were added to the sides of the stub. Finally, samples were coated with a 10 nm platinum layer in a Cressington 208HR sputter coater (Cressington Scientific Instruments Ltd., Watford, UK) before the qualitative analysis with SEM-EDX. In addition, small pieces of floor material samples were investigated directly in SEM to study the floor surface and the nature of asbestos fibres inside the material. Floor samples were prepared by carefully cutting out small pieces from the material sample and mounting them on Al stubs. One vinyl asbestos floor cross-section was prepared by fixing a piece of the floor in a clamp. A section of the floor piece was broken off with a plier to reveal the cross-section. The pieces were covered by 20 nm Pt in the sputter coater before the investigation in SEM.

Analysis of air samples

Samples were examined at a magnification of 2000× by a SU6600 field emission scanning electron microscope (Hitachi High Technologies, Tokyo, Japan) equipped with a Quantax 200 EDX detector (Bruker Nano GmbH, Berlin, Germany). An accelerating voltage of 15 keV was used during the analysis. The ISO 14966:2019 method for determining the numerical concentration of inorganic fibrous particles was followed for quantification (ISO 2019). Counting was terminated after an area of 1 mm^2 had been evaluated or when 50 fibres were counted inside a minimum area of 0.25 mm^2. If no fibres were found on 1 mm^2, another 0.25 mm^2 of the filter was evaluated. According to the ISO 14966 standard, fibres fulfilling the following criteria: length >5 µm, diameter ≥0.2 µm, and a length/diameter ratio ≥3 were counted. The ISO 14966 states that the microscope should be adjusted so that a fibre of width 0.2 µm is just visible at the counting magnification of 2000×. In this study, the SEM was adjusted to observe as much as possible at 2000×. Thin fibres (diameter <0.2 µm) were therefore counted and listed separately, whereas short fibres (length <5 µm) were not counted. The length and width of all fibres were measured and recorded. Thin fibres were listed as <0.2 µm and not with accurate width. Fibres were classified as specified in the ISO 14966 standard as (i) fibres with a chemical composition consistent with those of serpentine asbestos, (ii) fibres with a chemical composition consistent with those of amphibole asbestos, (iii) calcium sulphate fibres, such as gypsum ($CaSO_4*2H_2O$) and anhydrite ($CaSO_4$), and (iv) other inorganic fibres. The detection limit (LOD) was calculated according to ISO 14966. Image fields and samples were rejected according to the following criteria in ISO 14966: When fibres or particles covered more than approximately one-eight of the area of an image field, the image field was rejected. The sample was rejected when more than 10% of the image fields of a filter sample were rejected (ISO 2019). Parallel samples analysed with PCM were counted at a commercial laboratory following the NIOSH 7400 standard (NIOSH 2019).

Analysis of material samples

In secondary electron (SE) imaging mode, samples were investigated at a working distance of 10 mm and acceleration voltage of 15 kV. The asbestos fibres were analysed by point analysis in SEM-EDX and classified as amphibolic or serpentine asbestos.

Real-time fibre monitoring

A real-time fibre monitor (Fibre Monitor 7400, TSI, Shoreview, MN, USA) calibrated for chrysotile fibres was applied during different work to measure the air concentration of released fibres during careless handling of ACM. This included 1 min of drilling or bayonet sawing on three different ACMs: wall shingles, corrugated roof sheets, and roof slate shingles. Additionally, breaking and smashing wall shingles and roof shingles and sheets and friction between them were tested. Released fibre air concentration, which may result when handling ACM, was also investigated. This included breaking or causing friction of wall or roof materials.

Figures 6 is made in R studio with the use of the CRAN packages "ggplot2" and "ggpubr."

Results and discussion

A total of 57 air samples for SEM analysis were collected during asbestos removal work of which 41 were personal samples and 16 were stationary. Eleven samples were rejected due to overloading; of these, 8 samples were collected during floor removal and 3 during the removal of roof felt and batten. This resulted in 35 personal and 11 stationary samples. At the same time as the collection of SEM samples, samples for PCM were also collected. This gave 27 parallel samples of SEM and PCM that could be compared. Asbestos fibres were identified in all ACM material samples collected at the asbestos abatement sites.

Indoor ACM removal

All air concentration measurements for indoor removal of walls and floors were carried out in enclosed areas where fans provided negative pressure to limit the spread of asbestos fibres from the contaminated zone. This may result in an underestimation of the fibre concentration, especially for the stationary samples, since these were collected approximately 2–3 m from the work activity. The airborne fibre concentrations measured for personal and stationary samples during indoor ACM removal are summarized in Table 1. The percentage of the different asbestos fibre types is presented to show the relative fibre composition within samples.

Interior wall—asbestos insulating boards

The highest fibre concentrations were measured during the abatement of asbestos insulation boards (Asbestolux). Asbestos insulating boards usually contain 15–25% amosite or a mixture of amosite and chrysotile in a calcium silicate plaster (HSE 2012). This type of material is friable and crumbles easily, making fibre release likely. A high amphibole content was found in the material sample collected on site with amosite fibres as the dominant fibre type. Thin fibres accounted for 5–15% of the asbestos fibre of the total SEM count for the various air samples. The width and length measurements of counted fibres are shown in Fig. 1. All fibres were included in the figure, also those with only one end in the image field. The width and length of the measured fibres can be found in the Supplementary Materials. Considering fibre width, most amphibole asbestos fibres were found to be in the size bin 0.3–0.39 µm, whereas thin fibres (<0.2 µm) dominated chrysotile. The width and length results for the amphibole asbestos fibres shown in Fig. 1 are largely dominated by amosite fibres. These results seem to be in accordance with asbestos widths reported earlier for amosite and chrysotile from asbestos collections in ambient air and in an asbestos factory (Kohyama et al. 1996; Besson et al. 1999). The same authors pointed out the importance of knowing the size distribution of airborne fibres in various environments and settings, as carcinogenicity depends on the fibre size. As others pointed out earlier, amphibole asbestos fibres are straighter and less prone to generate fine fibrils than serpentine asbestos (Eypert-Blaison et al. 2018).

Interior floor—Vinyl asbestos tiles and corkboard

All air samples quantified with SEM during indoor floor removal and floor grinding were below LOD (0.04 f/cm^3) concerning asbestos fibres. The vinyl tiles and the cork board were removed using a floor scraper. Material samples from the sites confirmed that asbestos fibres existed in the materials (Fig. 2), and a chorine peak in the EDX spectrum proved that the tiles consisted of a polyvinyl chloride matrix. Asbestos vinyl tiles are often reported to have asbestos content of less than 10% (Kominsky et al. 1998a; Lange et al. 2000; HSE 2012), although there exist reports stating that the asbestos content may be as high as 30% (Anderson et al. 1982). Chrysotile fibres were observed protruding from the matrix on fracture edges on vinyl floor tiles (Fig. 2a). In addition, chrysotile fibres were observed in the adhering mastics on some of these floor materials (Fig. 2b). One of the samples was collected during the grinding of asbestos-containing mastics. However, this sample was also below LOD (0.04 f/cm^3). During the SEM counting analysis, a high number of calcium sulphate fibres, presumably gypsum, was observed even though the material itself did not contain gypsum fibres. Median concentrations of calcium sulphate fibres were 0.1–1.0 f/cm^3 (Table 1). SEM observations on the surface of floor material samples confirmed that calcium sulphate fibres and other particles were covering the floor surface (Fig. 2c). Other types of renovation work, for example, gypsum board removal, could have taken place before the floor removal or in close vicinity to

Table 1. Summary of personal and stationary air samples for indoor ACMs asbestos abatement analysed with SEM.

Personal samples

	Material	Activity	n	Asbestos fibres: Median ($f_{WHOasbestos}/cm^3$)	Min and max (f/cm³)	Median (f_{thin}/cm^3) <0.2 μm	Chrysotile (%)	Amphibole (%)	Non-asbestos fibres: Median ($f_{non\text{-}asbestos}/cm^3$)	Calcium sulphate (%)	Other inorganic (%)
Interior wall	Asbestos insulating boards	Dismantling	5	2.6	1.5–4.5	0.3	<10	>90	<LOD[a]	N/A	N/A
		Cleaning	1	0.9	N/A	0.1	10	80	0.1	>90	N/A
Interior floor	Vinyl tiles	Scraping with spatula	3	<LOD[b]	N/A	<LOD[b]	N/A	N/A	1.0	>90	<10
		Grinding	1	<LOD[b]	N/A	<LOD[b]	N/A	N/A	0.1	>90	<10
	Corkboard	Packing corkboards	2	<LOD[b]	N/A	<LOD[b]	N/A	N/A	1.0	>75	<25
Pipes	Pipe insulation	Sawing and dismantling	1	0.02	N/A	0.01	20	80	0.1	10	90

Stationary samples

	Material	Location	n	Asbestos fibres: Median ($f_{WHOasbestos}/cm^3$)	Min and max (f/cm³)	Median (f_{thin}) <0.2 μm	Chrysotile (%)	Amphibole (%)	Non-asbestos fibres: Median ($f_{non\text{-}asbestos}/cm^3$)	Calcium sulphate (%)	Other inorganic (%)
Interior wall	Asbestos insulating boards	Contaminated zone	1	0.4	N/A	0.05	10	90	<LOD[d]	N/A	N/A
		Clean zone	2	<LOD[c]	N/A	<LOD[c]	N/A	N/A	<LOD[c]	N/A	N/A
Interior floor	Corkboard	Contaminated zone	1	<LOD[c]	N/A	<LOD[c]	N/A	N/A	2.1	80	20
Pipes	Pipe insulation	Contaminated zone	1	<LOD[d]	N/A	<LOD[d]	N/A	N/A	<LOD[d]	N/A	N/A

Asbestos fibre concentrations are shown for WHO asbestos ($f_{WHOasbestos}/cm^3$) and for thin fibres (f_{thin}/cm^3). Concentrations of other fibres are listed as ($f_{non\text{-}asbestos}/cm^3$).
N/A, not applicable.
Asbestos LOD: [a]0.03 f/cm³, [b]0.04 f/cm³, [c]0.002 f/cm³, [d]0.01 f/cm³.

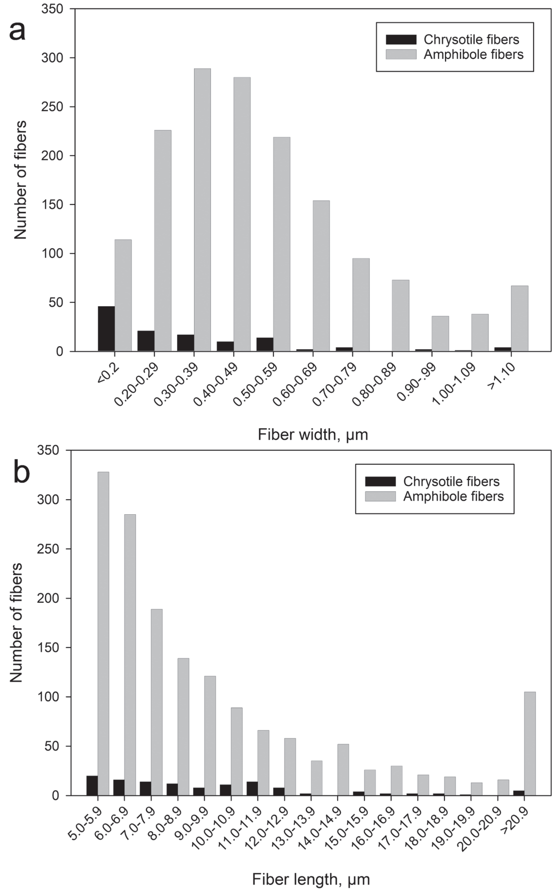

Fig. 1. SEM measurements of fibre width (a) and length (b) for chrysotile and amphibole asbestos fibres collected when interior wall boards were removed.

the floor. A typical count field of view in SEM (2000×) is shown, and a calcium sulphate fibre is indicated in Fig. 2d. Such debris from other building materials may settle on the floor and resuspend during floor removal. Consequently, the filters quickly became overloaded; thus, several of the floor removal samples in this study had to be rejected. The vinyl tile removal in our study was performed with a floor scraper, which resulted in low airborne asbestos concentrations measured with SEM. Other procedures or floor types may induce higher asbestos air concentrations, and variations can exist due to the technique used and/or to the floor conditions (Zichella et al. 2021). Publications related to work on asbestos-containing vinyl floor tiles with measurements performed during installation, maintenance, and removal are summarized in a meta-analysis by Perez et al. (2018). The airborne PCM fibre concentrations for personal samples varied in the reported studies from 0.001 f/cm^3 to 1.7 f/cm^3 depending on the work that was performed (Lundgren et al. 1991; Kominsky et al. 1998b; Lange et al. 2000, 2008; Lange 2001, 2002, 2004; Racine 2010). The highest PCM values in the meta-analysis (1.7 f/cm^3) were reported by Kominsky et al. (1998b) during ultra-high-speed burnishing. However, they also collected parallel samples that were analysed by TEM and found lower concentrations during the same maintenance operation. The difference was caused by a white powdery non-asbestos material with elongated particles that were counted by PCM. On the contrary, the same authors reported exposure concentrations during wet stripping and spray buffing that were underestimated by PCM because of a higher number of thin and short fibres not counted by PCM (Kominsky et al. 1998a). Short fibres (<5 µm) may have a high dominance in vinyl tiles (Kominsky et al. 1998a; Perez et al. 2018). Eypert-Blaison et al. (2018) reported very high air concentrations using TEM, with a maximum of 158 f/cm^3 of short asbestos fibres (average 13 f/cm^3) when vinyl floor tiles were removed by scraping with a spatula. An indirect TEM analysis method was used in their work where the filter is ashed, and the mineral particles are resuspended and filtered on a new filter. The ashing of the original filters may release short fibres embedded in particles of vinyl matrix and thereby lead to higher counts of short fibres which were not originally present as isolated fibres. Short asbestos fibres were not detected in our samples. However, when performing fibre counting in SEM on samples with a magnification of 2000× short fibres, less than 0.5 µm may have been missed if other particles covered them. A small-scale laboratory test was performed to provoke asbestos release where a small piece of a vinyl floor tile was sawed with a handheld tool. In air samples collected from this experiment, short asbestos fibres or structures were detected lying on or within larger particles (Fig. 3). These structures had a length in the range of 0.1–0.5 µm. Isolated fibres were not detected.

To our knowledge, little information about asbestos release from corkboard is reported in the literature. In general, corkboard materials are more porous than vinyl tiles. Unfortunately, several samples collected during the corkboard removal were overloaded. The asbestos fibre concentration was quantified in only three samples, where two personal samples were collected during the packing of the corkboard material into plastic bags and one stationary sample in the contaminated zone. Again, a high number of calcium sulphate fibres were observed on these filters.

Pipe segment—thermal insulation

For pipe asbestos removal, it is generally assumed that asbestos fibres are not released into the workplace atmosphere since the pipe section is covered in plastic before sawing and dismantling. Still, an asbestos fibre

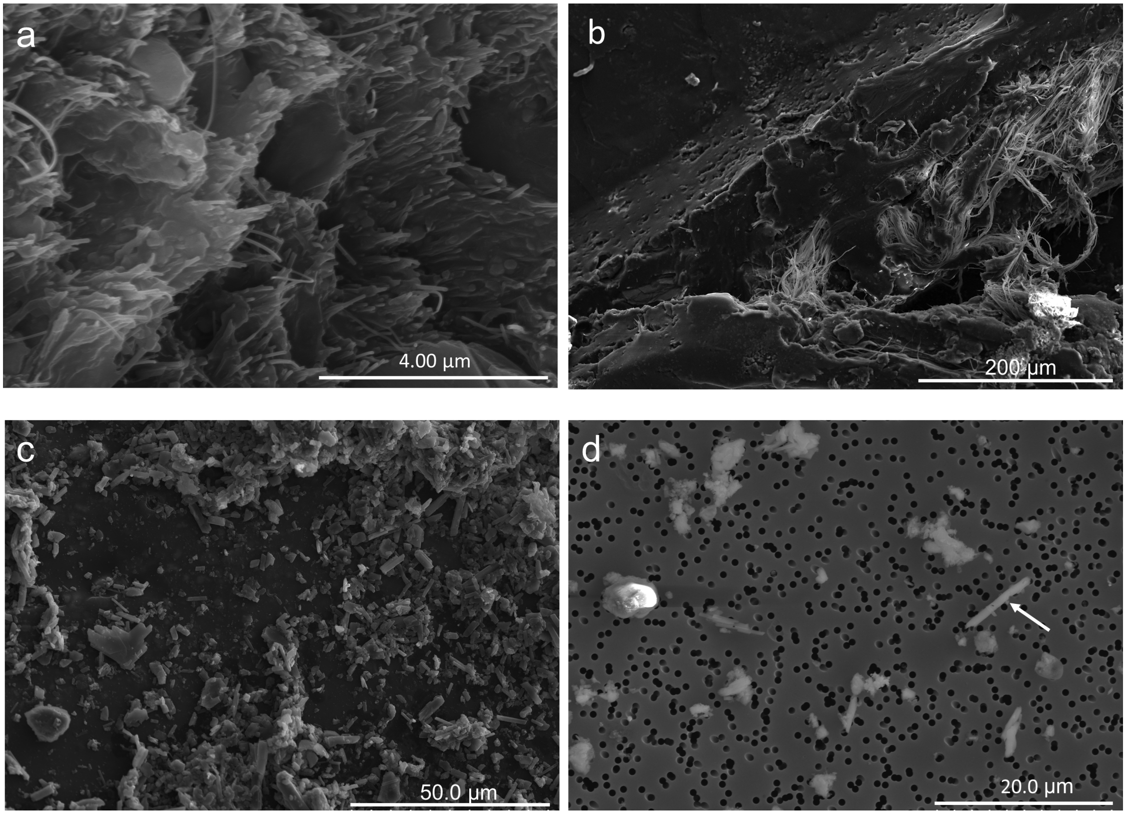

Fig. 2. SEM secondary electron images of a cross-section of a vinyl asbestos floor (a) remnant of mastics on floor tiles (b) surface of vinyl tiles (c) image field at 2,000× magnification. A calcium sulphate fibre is identified by the white arrow (d).

concentration of 0.02 f/cm^3 was quantified using SEM on the personal sample. This concentration is in the same range as sawing pipe thermal insulation in Eypert-Blaison et al. (2018); however, it is unclear whether the sawing occurred within a plastic cover in their study. Non-asbestos fibres, such as calcium sulphate and other inorganic fibres, were also observed in the air samples. Amosite fibres, chrysotile fibres and other inorganic fibres were observed in the material samples. The detected fibres may have been in settled dust not from the current pipe section removal. Nevertheless, it cannot be excluded that some of the detected fibres were released from the pipe segment removal despite the plastic cover.

Asbestos cement exterior wall and roof

The airborne fibre concentrations measured for personal and stationary samples during outdoor ACM removal are summarized in Table 2. All outdoor ACMs were asbestos cement materials products that usually contain 10–15% asbestos (HSE 2012). Chrysotile was the main asbestos fibre type present in the material samples from exterior roofing, both slate shingles and corrugated sheets, and wall shingles, which is typically for asbestos cement materials. However, amosite and crocidolite fibres were also identified. The composition of asbestos types in the building materials may depend on where and when the materials were produced.

Some of the measurements during asbestos abatement of outdoor walls and roofs were conducted during the abatement of a house with an enclosure built around it. Exterior asbestos abatement is usually not performed in an enclosure, and the air concentrations listed in Table 2 for these measurements are higher than the ones measured without coverage. Nevertheless, the air concentrations measured in the plastic-covered house represent air concentrations on calm and dry days without wind or in densely populated areas where other buildings surround the abatement object. Also, the background levels of 0.05 f/cm^3 measured during this asbestos abatement indicates that there is a risk of local contamination of asbestos fibres during the removal of exterior asbestos material. This will depend on the weather, as illustrated with background measurements on other outdoor ACM removals in Table 2 with low air concentrations

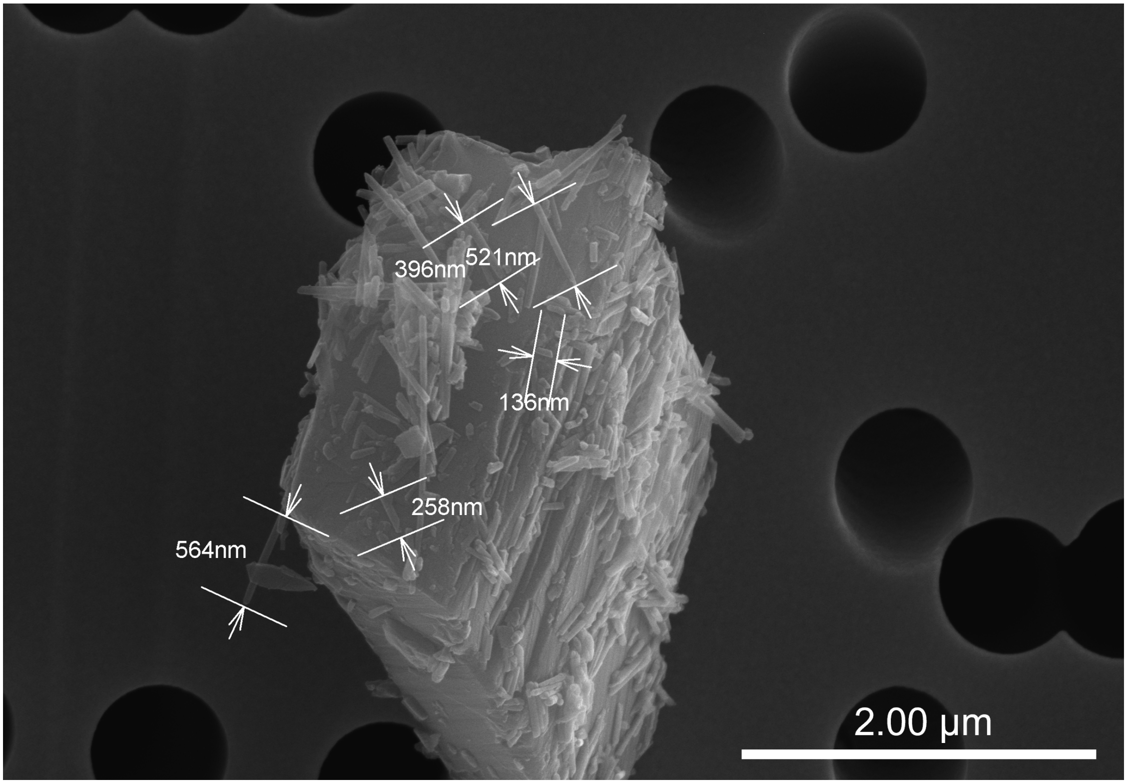

Fig. 3. SEM secondary electron image of short asbestos structures lying on a larger particle released during sawing of a floor tile with a handheld tool. Measures of fibre length are marked in the image.

of asbestos fibres, which were performed during winter in Norway, where snow and wind acted as natural protections. Brown (1987) investigated ACM sheet cleaning, sheet painting, roof replacement, and building demolition. The highest asbestos concentrations were found for workers demolishing weathered ACM roof sheets, and the values were in the range of 0.3–0.6 f/cm^3, measured by PCM (Brown 1987). ACM roof sheet replacement was on average 0.1 f/cm^3 over the full work operation. These samples were collected outdoors under ambient conditions, and the asbestos concentrations are comparable to the values reported in our study for the plastic-covered house.

Higher levels of asbestos fibres were found when removing old, corrugated cement roof sheets and slate shingles, probably because the material had started to deteriorate, exposing asbestos fibres on the surface (Ervik et al. 2021). This is similar to the observations in Brown (1987). An important result is that comparable levels of airborne asbestos fibres were also detected during the removal of roofing felt and the roof themselves. This is probably due to released asbestos fibres from the deteriorated corrugated cement roof, as the roofing felt itself did not contain any asbestos.

The size distribution of the collected fibres (Fig. 4) shows the dominance of thin fibres when chrysotile is the main asbestos type present. The high proportion of thin fibres suggests that counting thin fibres should be done more frequently, as these fibres may constitute a large fraction of the total fibre exposure. Information on the air concentrations of the thin fibres may be important for assessing the health risks of asbestos exposure (Stanton et al. 1981; Coin et al. 1994). The width distribution of amphibole asbestos shows the same trend as asbestos insulating boards, with most fibres in the 0.30–0.39 µm bin. The width and length of the measured fibres can be found in the Supplementary Materials.

Comparison between SEM and PCM

The SEM and PCM parallel sample counts are presented in the scatter plots in Fig. 5. An overview of parallel SEM and PCM samples is presented in the Supplementary Materials. Theoretically, if only asbestos fibres were present on the filters, PCM and SEM should have a 1:1 correspondence, whereas a steeper slope may be expected for the relationship between SEM + <0.2 and PCM, depending on the number of

Table 2. Summary of personal and stationary air samples for exterior wall and roof removal analysed with SEM.

Personal samples

				Asbestos fibres					Non-asbestos fibres		
	Material	Activity	n	Median ($f_{WHOasbestos}/cm^3$)	Min and max ($f_{WHOasbestos}/cm^3$)	Median (f_{thin}/cm^3) <0.2 µm	Chrysotile (%)	Amphibole (%)	Median ($f_{non\text{-}asbestos}/cm^3$)	Calcium sulphate (%)	Other inorganic (%)
Exterior wall	Wall shingles*	Dismantling	6	0.2	0.02–0.4	0.1	60–70	20–30	0.03	<10	>90
	Felt and batten*	Removal	2	0.1	0.1–0.1	0.04	70	0–10	0.04	<10	>90
	Wall shingles	Dismantling	1	<LOD[a]	N/A	<LOD[a]	N/A	N/A	<LOD[a]	N/A	N/A
Exterior Roof	Corrugated sheets and slate shingles*	Dismantling	8	0.2	0.1–0.4	0.1	60–70	30–40	0.02	<10	>90
	Felt and batten*	Removal	1	0.1	N/A	0.03	40	30	0.1	<10	>90
	Corrugated sheets	Dismantling	4	0.01	<LOD[b]-0.01	<LOD[b]-0.01	80	20	<LOD[b]	N/A	N/A

Stationary samples

				Asbestos fibers					Non-asbestos fibers		
	Material	Location	n	Median ($f_{WHOasbestos}/cm^3$)	Min and max ($f_{WHOasbestos}/cm^3$)	Median (f_{thin}) <0.2 µm	Chrysotile (%)	Amphibole (%)	Median ($f_{non\text{-}asbestos}/cm^3$)	Calcium sulphate (%)	Other inorganic (%)
Exterior wall and roof	Corrugated roof sheets, roof slate shingles and wall shingles	Background during activity*	2	0.05	0.01–0.1	0.03	50–60	30–40	0.01	<10	>90
		Close to activity*	3	0.1	0.02–0.08	0.03	60–70	20–30	0.02	<10	>90
		Background during activity	1	<LOD[a]	N/A	<LOD[a]	N/A	N/A	<LOD[a]	N/A	N/A

Asbestos fibre concentrations are shown for WHO asbestos ($f_{WHOasbestos}/cm^3$) and for thin fibres (f_{thin}/cm^3). Concentrations of other fibres are listed as ($f_{non\text{-}asbestos}/cm^3$).
N/A, not applicable.
*The work took place inside of a plastic cover, the percentage of fibre types is only shown when the number of fibres observed exceeded the LOD. Asbestos LOD: [a] 0.01 f/cm^3, [b] 0.004f/cm^3.

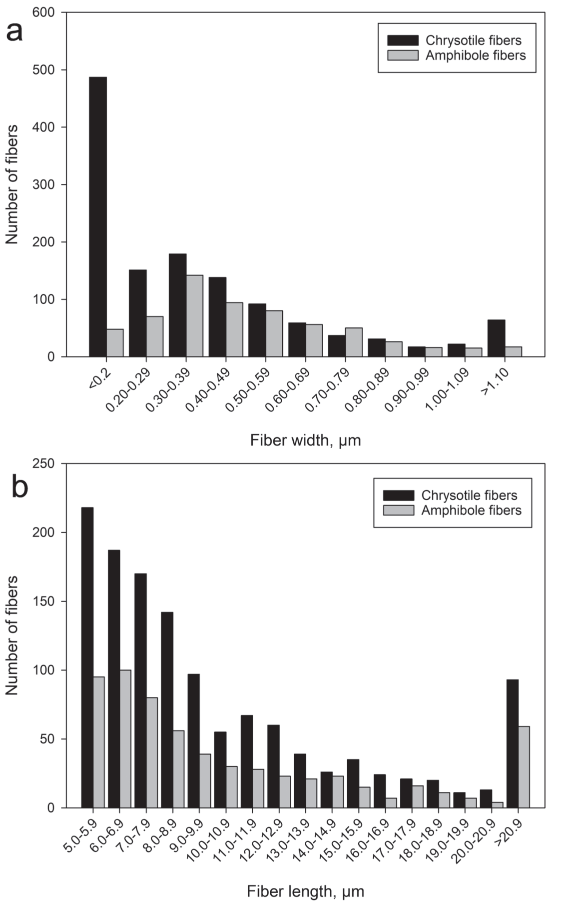

Fig. 4. SEM measurements of fibre width (a) and length (b) for chrysotile and amphibole asbestos fibres collected when exterior wall shingles, corrugated roof sheets and roof slate shingles were removed.

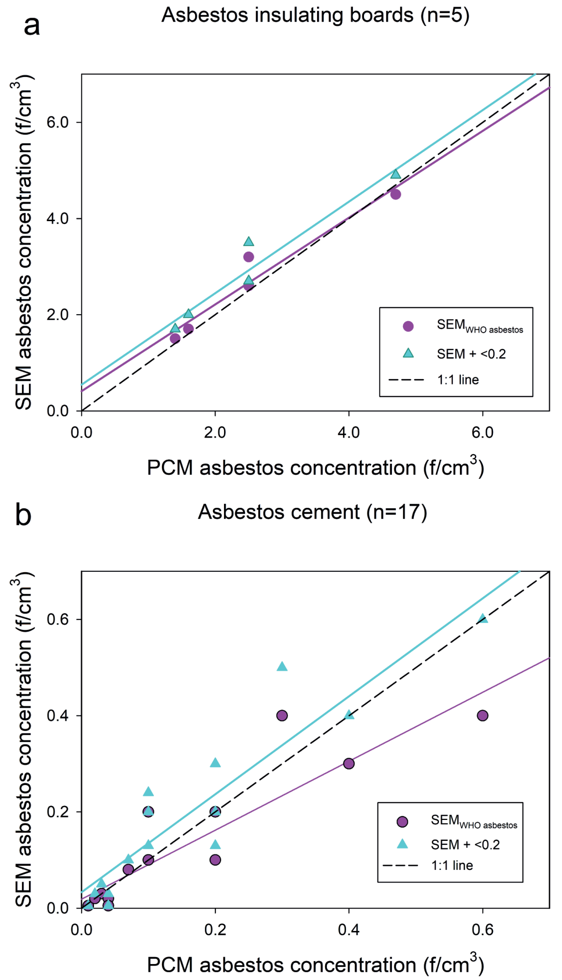

Fig. 5. Comparison between SEM and PCM, and SEM+<0.2 and PCM for removal of asbestos insulating boards (a) and asbestos cement materials (b). The 1:1 line is added in both graphs. The R^2 values for asbestos insulating boards are 0.94 and 0.93 for SEM: PCM and SEM+<0.2: PCM, respectively. The R^2 values for asbestos cement samples are 0.77 and 0.84 for SEM: PCM and SEM+<0.2: PCM, respectively.

thin fibres. Samples collected during asbestos insulating board removal are presented in Fig. 5a. These samples had a high amphibole content, and a small proportion of other inorganic fibres were observed on the filters. Thin fibres (<0.2 µm) are known to be less frequent when amphibole asbestos types dominate, and this is also observed in Fig. 1. Including thin fibres (SEM + <0.2) in the count altered the slope of the relationship only slightly. The absence of other inorganic fibres in addition to the small proportion of thin fibres probably led to the similar results between PCM, SEM and SEM+<0.2.

The comparison between PCM and SEM for asbestos cement materials (exterior wall and roof removal) is shown in Fig. 5b. The data points are seen to have a wider spread than for the asbestos insulating boards which is reasonable since these results are based on several types of asbestos cement materials, such as wall shingles, corrugated roof sheets, and slate shingles. In addition, the samples were collected over several days. Outdoor abatements may also be affected by weather conditions, although most of the asbestos cement samples were collected under a plastic cover. The slope of the relationship between PCM and SEM+ <0.2 has a value of 1.0, whereas the slope of the relationship between SEM and PCM has a value of 0.72. Up to 50 per cent thin fibres were found in the samples from the removal of exterior wall and roof, and Fig. 4 demonstrates the dominance of thin fibres released when such ACMs are dismantled. A larger discrepancy between the PCM and SEM+ <0.2 was therefore expected in this study. There were, however, relatively

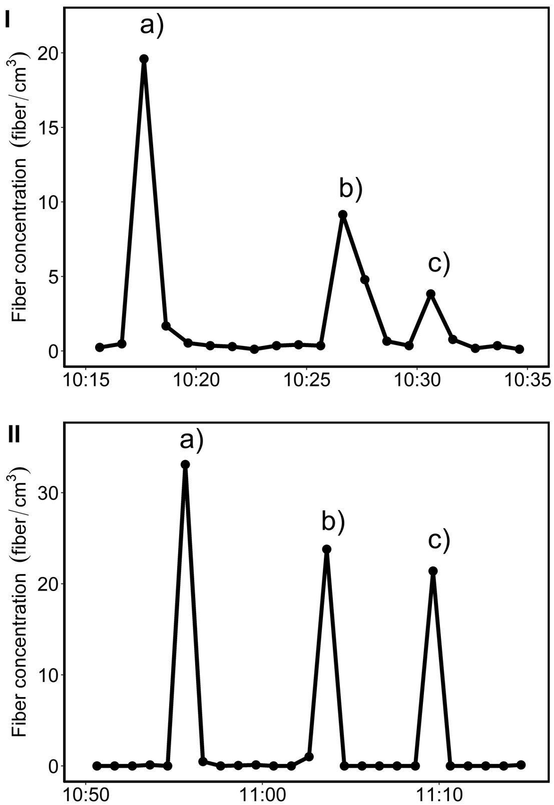

Fig. 6. Real-time fibre concentration during different work tasks, (I) drilling and (II) sawing with bayonet saw on (a) roof slate shingles (b) wall shingles, and (c) corrugated roof sheets. The concentration is given as average fibre concentration in air over 60 s marked as points.

high amounts of other inorganic fibres present in many of these air samples (Table 2) and some of these may have been included in the PCM count. Organic fibres, such as cellulose fibres or vegetable-derived fibres, may also have contributed. In the SEM analysis, organic fibres were removed by the asher procedure, and the prevalence of such fibres is therefore not known. Both inorganic and organic fibres may therefore have led to the deviation from the 1:1 line for the SEM and PCM relationship and likewise counteracted the impact from the thin fibres. The existence and concentrations of inorganic fibres are material and situation dependent. The presence of organic fibres may also depend on materials, and on season and weather conditions, especially in outdoor abatements. Hence, a high number of thin fibres may lead to a higher discrepancy between SEM and PCM when thin fibres are included in the SEM count.

The largest difference between PCM and SEM was found for interior floor materials, both vinyl tiles and the cork floor. The four samples analysed by PCM were all above 0.1 f/cm^3, with fibre concentrations ranging from 0.4 f/cm^3 to 2.1 f/cm^3, whereas the corresponding SEM samples were all below LOD. A scatter plot is therefore not included for these samples. The deviation between PCM and SEM may be explained by the high number of resuspended gypsum fibres, which were probably incorrectly counted as asbestos fibres by the PCM operator. Only one SEM and PCM parallel sample was collected during pipe segment removal. Removing the pipe segment with asbestos insulation led to fibre concentrations at 0.1 f/cm^3 when counted with PCM, whereas the SEM count was at 0.02 f/cm^3. Other fibre types, such as calcium sulphate and other inorganic fibres, were also present and may explain the discrepancy.

Fibre release during short-term work

The concentration of fibres released during short-term work on ACM is presented in Fig. 6. The highest concentration was measured when working on roof slate shingles, by drilling holes or sawing with a bayonet saw. Overall, the bayonet saw resulted in the highest peak concentrations of fibres. Air samples for SEM analysis were collected simultaneously with the fibre monitor. Numerous asbestos fibres were observed on these filters; however, asbestos fibres were not counted due to the very short sampling time. Additionally, small operations like breaking wall/roof shingles, or making friction between wall/ roof shingles also resulted in elevated concentrations of released asbestos fibres, albeit to a much lower extent, with peak concentrations of about 1.0 f/cm^3.

These results show that short-term work, which may be performed on ACM when the person is unaware of the nature of the material and the risk, results in high-peak episodes. Even short-term exposure to asbestos fibres is known to increase the risk of negative health effects (Seidman et al. 1979). Exposure to asbestos fibres may also occur if, for example, the dust settles and is resuspended or when handling the clothes worn during work on ACM. The fibre monitor was calibrated for chrysotile and the main fibre type found in these roof and wall shingles were chrysotile. The fibre monitor has previously been compared with the conventional PCM method and found to have a good agreement for a chrysotile aerosol (Kauffer et al. 2003). Nevertheless, we cannot exclude that the fibre monitor counted other non-asbestos fibres.

Conclusion

This study highlights the importance of mapping the presence of ACMs prior to renovation or before demolition work begins to protect workers from asbestos exposure. It is also important to give homeowners, who choose to do the asbestos removal themselves, good and easily accessible guidance for protective equipment, insofar as even short-term work resulted in a relatively high asbestos fibre release. The highest fibre concentrations during abatement operations were measured during the removal of asbestos insulating boards. The analysis of samples collected during floor removal demonstrated that the existence of common non-asbestos fibres, such as calcium sulphate fibres may lead to erroneous counts when using PCM. The PCM method is thus not recommended when many non-asbestos fibres occur in the samples, and this is also specified in the NIOSH 7400 method. Also, during the abatement of asbestos cement materials, a high proportion of thin fibres where observed. These results suggest that airborne asbestos quantification should be performed by methods capable of fibre identification and observing fibres thinner than 0.2 µm.

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Conflict of interest

The authors declare no conflict of interest.

Data availability

The data underlying this article are available in the article and in its online supplementary material.

Supplementary data

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

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