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Original Article

European harmonization of asbestos exposure assessment: comparing PCM, SEM, and TEM to derive conversion factors

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Abstract

After the European ban on the use of asbestos, exposure assessment of asbestos became imperative for ensuring compliance with safety standards. However, each European country has their own legislation and requirements, including measurement strategies, analytical techniques such as the microscope used as well as occupational exposure limits (OELs). The recent EU directive (EU) 2023/2668 significantly lowered the OEL for asbestos from 100,000 fibres/m³ 8-h time-weighted average to either 2,000 fibres/m³ when counting fibres between 0.2 and 3 µm in diameter, or 10,000 fibres/m³ when counting fibres thinner than 0.2 µm and dictates a transition from optical to electron microscopy analysis by the end of 2029. This change impacts Member States that rely on phase-contrast microscopy (PCM) to quantify asbestos concentrations, prompting the need for a standardized comparison between different analytical methods. Therefore, our study investigated whether conversion factors could be developed, enabling comparison of results obtained with different analytical techniques. To achieve this, a phased approach was applied, involving a survey of measurement strategies implemented by different countries in Europe, a literature search, and analysis of in-house data to explore differences between analytical techniques. Standardized conversion factors were developed *via* (i) direct comparison of concentrations from analysis with scanning electron microscopy (SEM), transmission electron microscopy (TEM), and/or PCM, (ii) a multiple linear regression model, and (iii) *via* log probability plots from raw data on fibre dimensions. Ten institutes from the 'Partnership for European Research in Occupational Safety and Health' (PEROSH) asbestos network participated in this study. The results showed that SEM and PCM were the most commonly used analytical techniques, with TEM also being used in 3 countries. OELs and measurement standards/protocols varied across countries, and most employed national derived standards for measurements. Conversion factors overall showed that measurements analysed by TEM resulted in higher fibre concentrations followed by PCM and SEM. Although conversion factors were developed, these were influenced by factors such as material type, applied energy, and local controls, preventing the derivation of a general conversion method.

Key words: asbestos; comparison analytical methods; conversion factors; exposure assessment; PCM; SEM; TEM; workplace safety.

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What's Important About This Paper?

This study reports on a comparative analysis of different analytical techniques for measuring asbestos employed in European countries. Overall, the methods compared were found to yield different results, and while conversion factors were developed, they were influenced by many factors limiting their generalizability.

Introduction

The use of asbestos dates back to 4,500 years ago, gaining industrial significance in the early 1800s. By 1977, global asbestos production peaked at almost 4.8 million tons annually across 25 countries (Virta 2006). In the 1920s to 1940s, the first associations between asbestos exposure and asbestosis were observed. Subsequent research established links between asbestos exposure and severe diseases such as mesothelioma, fibrosis, and lung cancer (Selikoff and Lee 1978; Stanton *et al.* 1981; EPA 1986), leading to public opposition and increased liabilities. This prompted a decline in asbestos use in most industrialized countries after the mid-1970s due to phase-out strategies and national banning, culminating in an EU-wide ban in 2005 (Virta 2006). However, asbestos-containing materials (ACMs) are still present in numerous residential, public, industrial buildings, or installations, and exposure to asbestos fibres may occur when these ACMs are disturbed, damaged, or removed (eg Brostrøm *et al.* 2025; Ervik *et al.* 2023). Due to the ageing buildings and installations, as well as missions in the Green Deal on energy and to make European buildings asbestos-free, asbestos sanitation is expected to increase in the coming years, increasing the risk of worker asbestos exposure (EC-JRC 2022).

Following the EU-wide ban, accurate asbestos exposure assessments became imperative. As a result, exposure measurements are performed in most European countries. However, each European country has its own legislation and requirements for performing these measurements, which has resulted in different requirements to measure and the use of different measurement strategies and analytical methods. The 3 most commonly used analytical techniques are phase-contrast optical microscopy (PCM), scanning electron microscopy (SEM), and transmission electron microscopy (TEM). Each method has its own characteristics, and thus distinct advantages and limitations (see Table 1). For instance, with PCM it is possible to detect fibres > 0.25 µm in diameter, but it cannot distinguish different fibre types (in other words: all fibres are normally measured, including non-asbestos fibres). When using SEM in combination with energy dispersive X-ray spectroscopy (EDS), asbestos fibres are identified by their elemental composition, with a lower limit of visibility between 0.1 and 0.2 µm at the prescribed magnification for fibre counting. However, modern analytical SEMs can achieve a resolution below 0.01 µm, though the analysis cannot identify the crystalline structure of asbestos fibres. TEM, in combination with selected area electron diffraction (SAED) and EDS, allows for the detection and identification of fibres with widths down to 0.01 µm (Baron 2001). Moreover, the rules for fibre counting that are applied with these techniques vary. SEM and PCM follow the WHO criteria, defining hazardous asbestos fibres as having lengths > 5 µm, widths between 0.25 and 3 µm, and a minimum aspect ratio of 3:1 (WHO 1986). For TEM, fibre definitions according to ISO 10312 and ISO 13794 regard an aspect ratio equal to or greater than 5:1 with a minimum length of 0.5 µm (ISO 2019a, 2019b). However, according to the French standard for the indirect TEM method, an aspect ratio equal to or greater than 3:1 with a minimum length of 0.5 µm is required (AFNOR 2021). The lack of harmonization between the different European countries prevent direct comparison of measured asbestos concentrations (Baron 2001; Eypert-Blaison *et al.* 2018). This hampers the possibility to compare the results of exposure measurements across Europe directly, which in turn limit insights in exposure levels and development of control strategies in Europe.

As of November 2023, the EU Directive 2009/148/EC on the protection of workers from the risks related to exposure to asbestos at work has been amended by EU Directive 2023/2668. A key change introduces a 6-year transition from optical to electron microscopy analysis, which has significant implications for Member States that currently use PCM for quantifying asbestos concentrations in air samples. In addition, the occupational exposure limit (OEL) of 100,000 fibres/m³ 8-h time-weighted average (TWA) is lowered substantially to 1 of 2 options: (i) lowering the OEL to 2,000 fibres/m³ when counting fibres with a diameter between 0.2 and 3 µm (WHO fibre dimensions), or (ii) lowering the OEL to 10,000 fibres/m³ if including fibres with a diameter less than 0.2 µm (EP 2023). The lowered asbestos OEL must be implemented within a 2-year period, by November 2025.

Given the evolving regulations and methodological changes, this study focuses on the comparability of analysis results obtained by the different analytical

Table 1. Summary of key characteristics of analytical techniques used for measuring personal exposure to asbestos in the workplace.

Parameter	PCM	SEM (EDS)	TEM (SAED and EDS)
Filter	Membrane filter of cellulose ester (mixed ester or cellulose nitrate), pore size 0.8 to 1.2 µm	Gold-coated capillary-pore polycarbonate filter, max. pore size 0.8 µm	Capillary-pore polycarbonate filter (max. pore size 0.4 µm) or membrane filter of cellulose ester (average equivalent pore diameter of 0.45 µm)
Distinction between types of (asbestos) fibres	No	Yes, with EDS (elemental composition)	Yes, with EDS (elemental composition) and SAED (crystallinity)
Lower limit of visibility (resolution)*	0.2 to 0.25 µm (0.2 to 0.25 µm)	0.1 to 0.2 µm (0.02 µm)	0.01 to 0.02 µm (0.001 µm)
Limit of detection**	Approx. 2,000 fibres/m³***	Approx. 100 to 200 fibres/m³	Approx. 1,000 fibres/m³
Relevant standards or protocols and counting rules	WHO 1997; NIOSH 7400: 1994; HSE 2021 WHO (>5 µm length and <3 µm width; aspect ratio 3:1)	ISO 14966: 2019; VDI 3492: 2013 WHO (>5 µm length and <3 µm width; aspect ratio 3:1)	ISO 10312: 2019; ISO 13794: 2019 (aspect ratio 5:1, minimum length 0.5 µm) AFNOR NF X43-269: 2017; AFNOR NF X43-050: 2021 (aspect ratio 3:1, minimum length 0.5 µm)

PCM: phase contrast microscopy, SEM: scanning electron microscopy, TEM: transmission electron microscopy, EDS: energy dispersive X-ray spectroscopy, SAED: selected area electron diffraction.
*Resolution: thinnest measurable fibre with prescribed microscope magnification for fibre counting and between parenthesis thinnest measurable fibre at highest magnification.
**Limit of detection: the lowest concentration that can be measured with 95% certainty (based on Poisson distribution) with standard microscope settings for fibre counting (Ogden 1982).
***The limit of detection of PCM is, in theory, approximately 2,000 fibres/m³, but in practice measuring asbestos fibre concentrations lower than approximately 5,000 fibres/m³ is not suitable due to the presence of other fibres (ISO 2014).

techniques. As part of this, the main objective was to investigate whether methods can be developed to facilitate comparison of the outcomes between different asbestos exposure assessment strategies. While being important in the coming 6 years transition period, such a strategy also would be beneficial from a perspective of using past exposure measurements (eg Fonseca *et al.* 2022) and reduce uncertainty in epidemiological studies.

Methods

This study was conducted by the PEROSH (Partnership for European Research in Occupational Safety and Health) asbestos network with participants from 10 of the 14 European Occupational Safety and Health (OSH) institutes in the organization. The work was completed as part of a PEROSH research project on the harmonization of asbestos workplace exposure assessment.

A phased approach for information gathering and analysis was applied, comprising an initial survey among participating PEROSH members with expertise in measuring asbestos fibre concentrations in air. Subsequently, a literature search was conducted and in-house data from members of the PEROSH network were collected to assess differences in reported asbestos fibre concentrations as a result of the different analytical techniques. Finally, it was attempted to develop standardized conversion factors to facilitate meaningful comparisons. This was done using 3 approaches:

1. Conversion factors were obtained by direct comparison of concentrations from analysis with SEM, TEM, and/or PCM.
2. Conversion factors were modelled with the use of multiple linear regression.
3. Conversion factors were estimated *via* log probability plots from raw data on fibre dimensions.

For all 3 routes, the focus was on 3 representative ACMs: asbestos cement (chrysotile and/or crocidolite), insulation/fire-resistant board (amosite and/or chrysotile), and spray-on asbestos (crocidolite). For all routes, only measurements with an analytical result above the limit of detection (LOD) were included in the analysis, as the differences in OELs between countries resulted in different LOD values in the data sets. For example, in the Netherlands, LOD values by SEM are typically lower than <300 f/m³ while LOD values from, eg, the United Kingdom could range between <5,000 and <50,000 f/m³. This complicated the use of values below the LOD and consequently, these were excluded from the analysis.

All data management, cleaning, and statistical analyses were conducted using R version 4.2.0 (2022-04-22).

Survey

A tailored survey was performed to map variations in methods for sample collection (measuring), preparation, and asbestos fibre analysis used for personal exposure assessment. The survey encompassed details such as; which (inter)national standards are employed, if any modifications are made in relation to the procedures described in (inter)national standards, if additional national requirements are defined (eg minimal sample volume), if filter overload protocols are used, which counting rules are applied, what type of microscope is used, and how results are reported and journalized.

Approach 1: direct comparison of SEM, TEM, and/or PCM concentrations

This approach involved a direct comparison of asbestos concentrations measured from air samples either collected in parallel or divided and analysed using different microscopy techniques. Hereby variations are minimized, resulting from the exposure scenario (eg type of ACM handled, and activities performed) and within and between persons. An example of a study with parallel sample collection and analysis by 2 different microscopy techniques (SEM and PCM) is described in detail in Ervik *et al.* (2023), or by directly comparing the same sampling filters where ½ of the filter was evaluated by TEM (indirect method) and ½ filter by PCM (Eypert-Blaison *et al.* 2018).

Initially, studies reporting conversion factors between asbestos concentrations measured with different sampling and analytical techniques were identified through a literature review.

Subsequently, data shared by participating research institutes were combined into 1 data set, containing results from air measurements that allowed for a direct comparison of asbestos concentrations measured with different exposure assessment strategies. This data underwent thorough cleaning and recoding to ensure a uniform data format. The analysis involved calculating conversion factors (based on the difference between the parallel obtained results analysed with different analytical techniques), categorized by type of asbestos in the material (amphibole asbestos and/or chrysotile) and several general factors.

Approach 2: regression modelling of conversion factors

The goal of this approach was to investigate whether statistical models could be developed to calculate conversion factors between results from different analytical techniques, including fibre-counting rules. The analysis was performed using measurement data from in-house databases as shared by participating institutes. The focus was on 3 representative asbestos-containing materials: asbestos cement, insulation/fire-resistant board, and spray-on asbestos. A harmonized data template was developed to facilitate comparability of the results, including contextual information about material type, asbestos content, activity, control measures, measurement strategy, and details about the analytical method.

The data mostly consisted of individual personal task-based measurements, but 1 institute shared a large data set with aggregated results of exposure measurements. In this case, the descriptive statistics per group of measurements (average concentration, standard deviation, and number of measurements) were used to simulate results of the individual measurements in this group, to match the other individual measurements. All data sets were combined and harmonized on terminology, type of controls, type of ACM, and type of activity to facilitate the analysis.

Multiple linear regression analysis was employed to analyse the data, for which 2 models were used. The first model was constructed to investigate whether the different analytical techniques had a significant effect on the measured exposure levels when considering type of ACM, local controls, and the energy level applied during abatement activities. It must be noted that some important factors, such as asbestos content (%) in the materials, whether the work was conducted indoors or outdoors, and asbestos fibre types, were not included in the model due to missing information. The energy level applied during abatement was recorded as either low or high energy, where high-energy activities involved the use of mechanical tools. It was assumed that high-energy activities could release more and smaller fibres (<5 μm) than low-energy activities. Equation (1) describes the linear relationship between the coefficients derived for the analytical technique (β_{at}), the material category (β_{m}), the local control measure in place (β_{LC}), the energy level applied during abatement (β_{e}), the baseline exposure or the intercept (β_{0}), and the predicted asbestos fibre concentration (γ).

$$\ln(\gamma) = \beta_0 + \beta_{at} + \beta_m + \beta_{LC} + \beta_e \qquad (1)$$

The second model was developed to investigate any interaction effects between the analytical techniques and the other dependent variables (type of ACM, local controls, and energy applied) as incorporated in the first model. This model is denoted in Equation (2).

Interaction effects in this context refer to how the impact of one variable on exposure measurements might change depending on the level of another variable. By incorporating these interaction terms into our regression model, we can gain additional insights into

Table 2. Microscope, sampling methods and OEL for characterization of asbestos fibres on national level.

Country	Analytical method	Standard/method for exposure assessment
United Kingdom	PCM (to a lesser extend SEM or TEM [direct])	HSG 248
Spain	PCM	MTA/MA-051/A04
Norway	PCM and SEM	PCM: WHO (1997) SEM: ISO 14966
Finland	SEM and PCM	In-house method and ISO 14966
Italy	SEM and PCM	PCM: WHO (1997) SEM: ISO 14966
The Netherlands	SEM	NEN 2991, NEN 2939, NEN-EN-ISO 16000-7, ISO 14966
Germany	SEM	DGUV information 213-546
Switzerland	SEM	ISO 14966
Denmark	PCM, SEM*, TEM*	PCM: WHO (1997)*, HSG 248, DS 2169:1981 (used, but not specified in regulations)
France	TEM (indirect)	AFNOR NF X 43-269

*Denmark; 2015 to 2022: PCM or other method giving similar results [Executive order: BEK nr 1792; 18/12/2015]; from 2022: PCM, SEM, or TEM using a suitable and acknowledged method [Executive order: BEK nr. 744; 18/6 2024].

how different combinations of these variables influence exposure levels. For instance, an interaction effect might reveal that a particular analytical technique's effectiveness in measuring exposure is significantly altered when higher energy levels are applied during abatement.

$$\ln(\gamma) = \beta_0 + \beta_{at} + \beta_m + \beta_{LC} + \beta_e + (\beta_{at} * \beta_m) + (\beta_{at} * \beta_{LC}) + (\beta_{at} * \beta_e) \quad (2)$$

Approach 3: comparison of fibre length and diameter distributions

For this approach, some institutes shared their raw analysis data on fibre dimensions (length and diameter) from exposure measurements during asbestos removal activities involving specific types of ACM (scenarios), ie asbestos cement with chrysotile a/o crocidolite, insulation, and fire-resistant board with amosite. The raw data were used to compare length and diameter distributions of the counted fibres analysed with different microscopy techniques. Size distributions of fibre length and width generally follow a lognormal distribution (Cheng 1986; Baron 2001). Cumulative lognormal probability plots were used to estimate the percentage of nonobserved/nonanalysed (thin or short) fibres. A lognormal probability plot is a scatter plot that uses a logarithmic horizontal scale and a standard normal inverse of the cumulative probability for the vertical axis. Data that follow a lognormal distribution will tend to follow a straight line on such plots. The trend allows one to project the cumulative probabilities and to estimate the percentage of thin (<0.2 µm) and short (<5 µm) fibres for each scenario and microscopy technique.

Results

Survey

With regards to the survey, data from 10 different European countries were gathered and summarized in Table 2. The results show a large variation in microscopy methods, with mostly PCM and/or SEM, and 3 countries (also) employing or accepting TEM (where France makes use of the indirect method, and the United Kingdom the direct method, while Denmark does not legally define specifics). In the direct method, a film of carbon is directly applied on the surface of the sampling filter by vacuum evaporation. Small areas of the carbon-coated filter are transferred to TEM grids after which the filter medium is dissolved away. In the indirect method, first the filter is ashed in an oxygen plasma, and the residual ash is dispersed in water and filtered. From this filter TEM grids are prepared in the same way as in the direct method (Eypert-Blaison *et al.* 2010). Some countries use the WHO method (1997) or ISO standards for characterizing exposure to airborne asbestos fibres; however, most countries have developed national standards/methods.

Approach 1: direct comparison of SEM, TEM, and/or PCM concentrations

In total, 27 studies involving direct comparisons between the different analysis techniques were identified, from both the literature search (n = 17) and studies

Table 3. Overview of conversion factors from literature or derived by direct comparison of parallel exposure measurement data analysed with different methods obtained from literature and shared by project partners.

Study	ACM	Asbestos type	Operation	Number of samples	Fibre dimensions	STEM/PCM	SEM/PCM	TEM/PCM	TEM/SEM	Min to max
Dement *et al.* (2008)	Textile	Chrysotile	Preparation, carding, spinning, winding, twisting, weaving, finishing	84	WHO + TAF			1.5		1.02 to 2.17
Health Council of the Netherlands (2010)		Chrysotile and amphibole	Not specified	-	WHO			2		
National Research Council (NRC) (1984)				-	ALL			60		
Marconi (1984)	Asbestos tapes, paper boards, cement boards, brake and clutch	Not specified	Not specified	30	WHO			1.17		0.24 to 2.57
					WHO + TAF			1.28		0.1 to 2.7
					ALL			3.61		0.58 to 10.8
EPA (1986)					WHO			2 - 4		
Verma (1995)	Raw asbestos	Chrysotile	Mining, crushing, milling, tailing, dumping/loading, brake manufacturing	65	WHO + TAF			5.4		1.8 to 17.6
					ALL			42.4		12 to 144
					WHO			2.6		1.2 to 10.4
Winer and Cossette (1979)			Various	11	ALL			66.3		
Marconi *et al.* (1993)	Spray-on asbestos	Amosite		23	WHO		1.3			1.1 to 1.5
Pang *et al.* (1984)	Generated standard samples				WHO + TAF			2.1		
Hwang and Wang (1983)			Various	25	WHO			4.8		
Bottino *et al.* (2002)			Removal asbestos Marine ship and location in harbour	16	WHO		1.53			0.4 to 2.5

Table 3. Continued

Study	ACM	Asbestos type	Operation	Number of samples	Fibre dimensions	STEM/PCM	SEM/PCM	TEM/PCM	TEM/SEM	Min to max
Longo *et al.* (2002)	Flanges and gaskets	Chrysotile (65% to 85%)	Scraping and hand wire brushing of small (study 1) and large (study 2) flange assemblies; power wire brushing of large flange assembly	103	WHO + TAF					1.8 to 52.8
Snyder *et al.* (1987)**		Chrysotile		9	ALL		25.9			3.0 to 53.1
		Amosite		4	ALL		4.5			3.9 to 5.1
Eypert-Blaison *et al.* (2018)	Adhesives, coating, sprayed asbestos, plasters, paints/coatings	Asbestos	Dismantling/loosing/pulling, grinding/sanding, hydroblasting VHP-UHP, cutting/sawing/chain sawing		WHO			4.56		0.19 to 15.1
					WHO + TAF			15.2		0.85 to 124
		Chrysotile			WHO			4.31		
					WHO + TAF			14.9		
		Amphibole			WHO			0.39		
					WHO + TAF			0.58		
Dement and Wallingford (1990)	Textile, friction, AC	Chrysotile	Industrial situation	9	WHO + TAF		1.07			
Crossman *et al.* (1996)	Floor tiles	Chrysotile	Removal, dry hand spud bar, dry pneumatic spud bar, dry hand scraper, dry ice, propane torch, mastic remover, wet mastic scraper	25	WHO			5.0		0.5 to 17.3
					ALL			19.4		4.1 to 60.2
Kominsky *et al.* (1992)	Floor tiles	Chrysotile	Spray buffing and wet striping	25	ALL			22.6		1.3 to 97.8
Boulanger *et al.* (2014)					WHO			1.7 to 4.0		Max. 30
TNO (1993/1994)*	Vinyl, board, asbestos cement	Chrysotile and amosite	Removal	33	WHO		0.81			0.11 to 1.6
STAMI (2018 to 2022)*	Board, pipe, asbestos cement	Chrysotile and amosite	Removal	16	WHO		0.95			0.2 to 1.5
				5	WHO + TAF			2.6	2.5	1.4 to 5.1
HSE (2016 - 2019)*	Insulation board, sprayed asbestos	Mainly amositie	Removal, clearance, dismantling enclosure	29	WHO			1.37		0.3 to 4.2

Table 3. Continued

Study	ACM	Asbestos type	Operation	Number of samples	Fibre dimensions	STEM/ PCM	SEM/PCM	TEM/PCM	TEM/ SEM	Min to max
Combination of all studies	All	All		S(T)EM/ PCM: 2 TEM/ PCM: 10	ALL	-	15.2 (4.5 to 25.9)	41.6 (2.9 to 88)	-	-
				SEM/ PCM: 1 TEM/ PCM: 10	WHO + TAF	-	1.07	7.3 (0.6 to 21.6)	-	-
				SEM/ PCM: 4 TEM/ PCM: 13	WHO	-	1.1 (0.8 to 1.5)	2.8 (0.4 to 4.8)	-	-
		Chrysotile		6	ALL	-	-	33.1 (19.4 to 47.5)	-	-
				5	WHO + TAF	-	-	10.1 (2.5 to 21.6)	-	-
				3	WHO	-	-	4 (2.6 to 5)	-	-
		Amosite		1	ALL	-	-	2.9	-	-
				TEM/ PCM: 2 TEM/ SEM: 5	WHO + TAF	-	-	1.6 (0.6 to 2.6)	2.5 (1.4 to 5.1)	-
				3	WHO	-	-	0.9 (0.4 to 1.4)	-	-

WHO: fibre length (L) > 5 µm; 0.25 µm < diameter (D) < 3 µm; L/D aspect ratio = 3. TAF: thin asbestos fibres (L > 5 µm; 0.01 µm < D < 0.2 µm; L/D aspect ratio >= 3). SAF: short asbestos fibres (1 µm < L < 5 µm). ALL: all fibres: WHO + thin (TAF) + short (SAF). AM: arithmetic mean. GM: geometric mean.
*Data shared by project partner, not published.
**Analysis with scanning transmission electron microscopy (STEM).

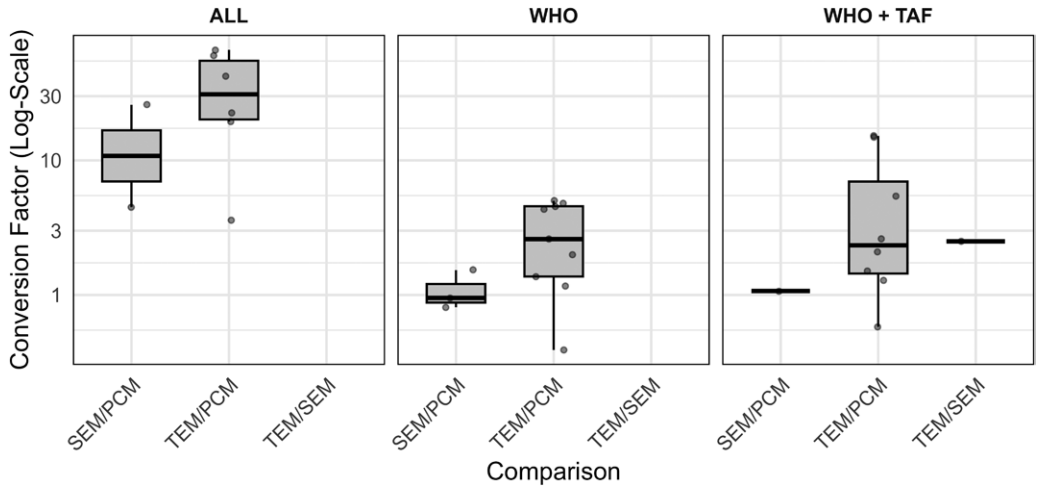

Fig. 1. Overview of conversion factors by fibre dimensions.

from the individual participating institutes (n = 4). Table 3 shows the summary statistics for the conversion factors derived in the different studies for different combinations of analytical technique, asbestos type, and counting rules. It can be observed that most data were available for the direct comparison of TEM and PCM, and almost no data are available for the direct comparison of TEM and SEM. Overall, variability in conversion factors is considered high (see Fig. 1), ranging from 0.3 to 140 across all fibre types. When comparing TEM and PCM, the conversion factors for chrysotile fibres were generally higher than for amosite fibres. Unfortunately, this type of comparison cannot be made for the other pairs of analytical techniques due to lack of data. When considering the level of energy based on the type of tools that are applied, average conversion factors for TEM/PCM are higher, indicating higher fibre counts for results analysed with TEM compared to PCM when high-energy activities were performed. Unfortunately, insufficient data were available to make this distinction for SEM/PCM or TEM/SEM as well. Lastly, a decrease of conversion factors for TEM/PCM can be observed over the period 1980 to 2020 (based on study age).

Approach 2: regression modelling of conversion factors

In total, 40,002 individual personal measurements were available for analysis, of which 72 measurements originated from Denmark, 15 from Norway, 25 from Spain, 216 from the United Kingdom, 272 from the Netherlands, and 39,402 from France. 219 of the measurements were analysed with PCM, 239 with SEM, and 39,424 with TEM (indirect). Table 4 shows the distribution of measurements over the different analytical techniques, energy level of the abatement process, the ACM, and whether any control measures were applied during the abatement. Both the energy level of the abatement tools and the type of control measure applied are not evenly distributed over the data available for the different analytical techniques.

Figure 2 illustrates the results of the linear regression model (Equation (1)), trained on 39,776 measurements (excluding values below the limit of detection), which explained 52% of the variance in exposure, as indicated by the R-squared value of 0.52. This implies that 52% of the variability in exposure concentrations can be accounted for by the factors included in the model. Notably, SEM analysis estimates lower fibre concentrations compared to PCM, while TEM analysis yields higher fibre concentrations than both PCM and SEM techniques. Regarding materials, insulation debris shows no significant difference compared to asbestos cement, but loosely bound materials and spray-on asbestos/insulation materials result in significantly higher exposure estimates. The difference between high-energy and low-energy activities is minimal. Unexpectedly, the use of local exhaust ventilation (LEV) shows higher exposure estimates compared to situations without controls. Similarly, thorough wetting (a process where the water fully saturates the material) results in higher exposure estimates, contrary to theoretical expectations.

The model is used to calculate conversion factors between the different analytical techniques. For example, to estimate exposure for analysis with SEM or TEM for loosely bound materials, while leaving other parameters the same as the intercept parameters (low-energy activity and no controls), exposure is calculated for SEM as follows:

Table 4. Data contribution from different countries for the different routes and materials.

Analytical technique	Energy applied	ACM	Control measures	*N*
PCM	Low	Asbestos cement	No controls	1
			Surface wetting	7
		Insulation debris	Unknown	47
		Loosely bound materials	Surface wetting	52
			Unknown	13
		Spray-on asbestos/insulation	Surface wetting	61
			Unknown	21
SEM	Low	Asbestos cement	No controls	34
			Surface wetting	9
			Foam	61
		Loosely bound materials	No controls	61
			LEV	7
			Surface wetting	39
			Foam	19
	High	Asbestos cement	Foam	1
		Loosely bound materials	No controls	5
			LEV	3
TEM	Low	Asbestos cement	No controls	5,457
			Surface wetting	25,491
			Thorough wetting	473
			Unknown	1,669
		Insulation debris	Unknown	3
		Loosely bound materials	No controls	430
			Surface wetting	2,266
			Thorough wetting	10
			Unknown	343
		Spray-on asbestos/insulation	No controls	121
			Surface wetting	964
			Thorough wetting	245
			Unknown	388
	High	Asbestos cement	No controls	144
			Surface wetting	661
			Unknown	341
		Loosely bound materials	No controls	29
			Surface wetting	95
			Unknown	51
		Spray-on asbestos/insulation	Surface wetting	49
			Thorough wetting	32
			Unknown	162
Total				40,002

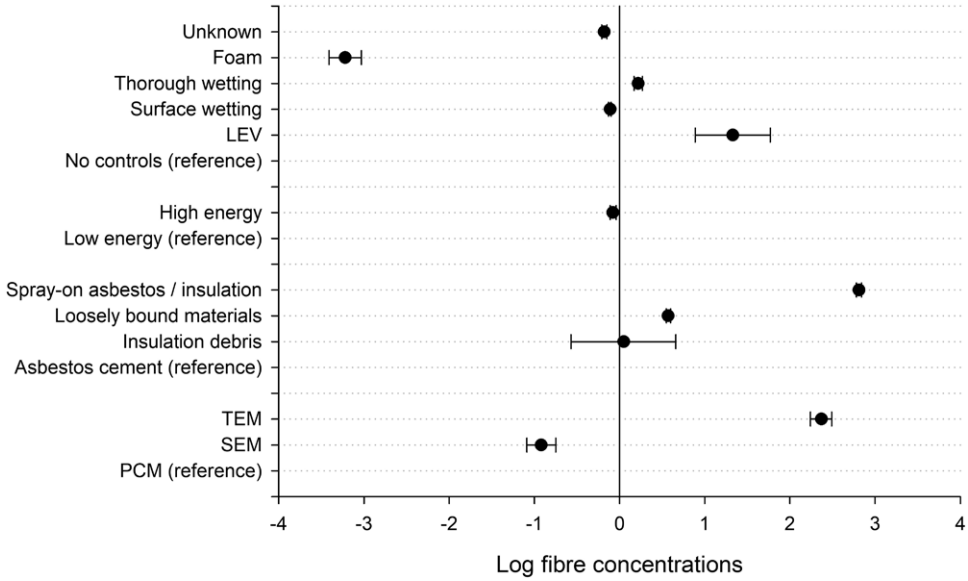

Fig. 2. Results of the multiple linear regression analysis of Equation (1).

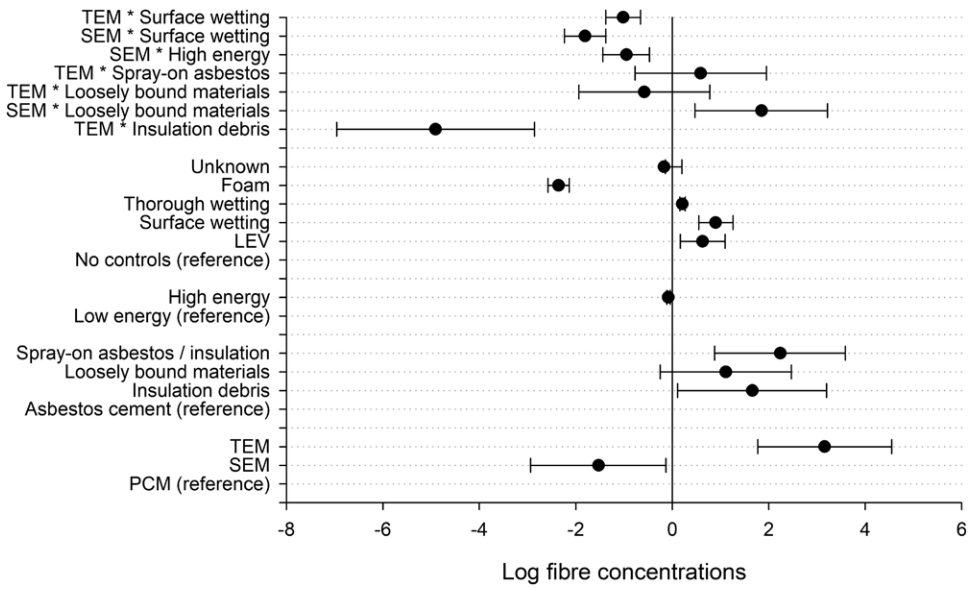

Fig. 3. Results of the multiple linear regression analysis of Equation (2).

Ln(exposure) = (β_0 = 9.76) + (β_{at} SEM = -0.92) + (β_m loosely bound material = 0.57) = 9.41

$e^{9.41}$ = 12,210 f/m³

The same calculation for TEM is performed by:

9.76 + (β_{at} TEM = 2.37) + (β_m loosely bound material = 0.57) = 12.7

$e^{12.7}$ = 327,748 f/m³

Using the estimates resulting from the regression model, a conversion factor of 26.8 was determined for TEM to SEM results ($e^{9.76 + 2.37}/e^{9.76 + (-0.92)}$ = 185,350/6,905 = 26.8). In other words, airborne asbestos concentrations measured by TEM were estimated to be 26.8 times higher than those determined by SEM. The conversion factor from SEM to PCM was 2.5, and the conversion factor for PCM to TEM was 10.7.

Figure 3 displays the results of the linear regression model incorporating interactive effects between the analytical technique and all other determinants

in the model (energy, control measure, type of ACM; Equation (2)). Interaction effects in this context refer to how the impact of one variable (analytical technique) might change depending on the level of another variable (eg the energy level of the abatement activity or the presence of local controls). The second model explained 53% of the variance in exposure and shows trends similar to those for Equation (1) as shown in Fig. 2. Noteworthy is the variation in the effects of local controls compared to the first model. Significant interactive effects suggest that conversion factors derived from the second model vary between 2 techniques depending on the exposure situation, offering a nuanced perspective compared to the first model with a fixed conversion factor. However, it is not possible to calculate a single, uniform conversion factor between the different analytical techniques with the second model. Instead, conversion factors vary depending on the specific scenario due to the interaction effects influenced by the varying levels of other parameters.

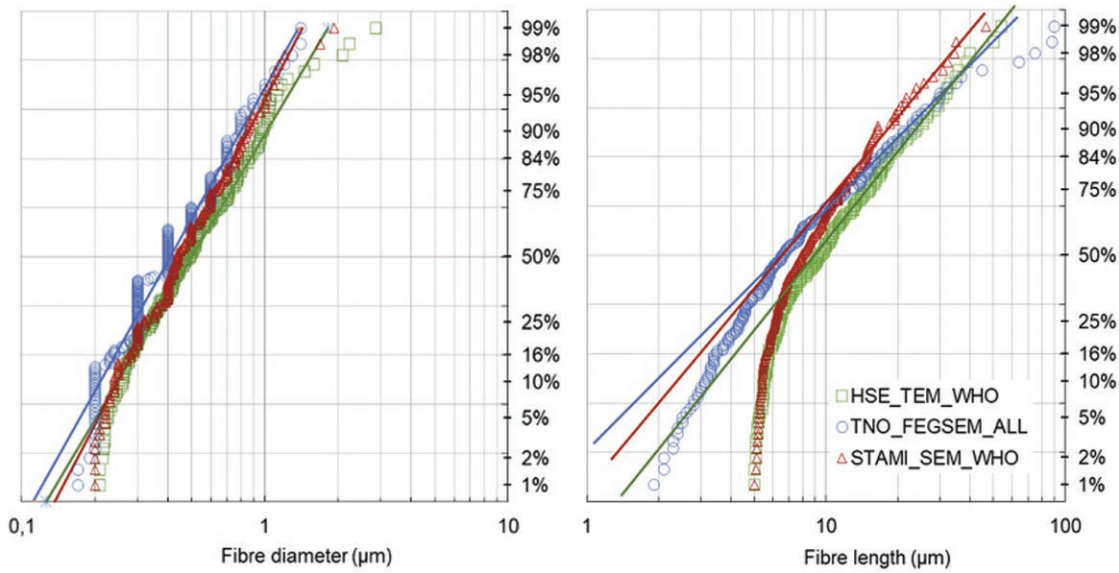

Fig. 4. Cumulative log normal probability plots of fibre diameter and fibre length, based on the raw fibre-counting data of TNO (all fibres counted) and HSE and STAMI (only WHO fibres counted) from personal air samples collected during removal activities of amosite insulation boards.

Table 5. Percentage of fibres with diameters < 0.2 µm and length < 5 µm, derived from the cumulative lognormal probability plots of raw fibre-counting data of TNO, HSE, and STAMI from personal air samples collected during removal activities of amosite insulation board chrysotile/crocidolite asbestos cement and chrysotile flang/gasket.

ACM	Fibre type	Partner	Analytical technique	Counting rules	Counted fibres	Percentage of fibres	
						$D < 0.2$ µm	$L < 5$ µm
Insulation board	Amosite	TNO	FEG–SEM	All	202	5% to 10%	30% to 45%
		STAMI	SEM	WHO	709	5% to 10%	25% to 40%
		HSE	TEM	WHO	223	5% to 10%	20% to 30%
	Chrysotile	STAMI	SEM	WHO	35	30% to 45%	20% to 30%
Asbestos cement	Chrysotile	TNO	FEG–SEM	All	172	30% to 45%	20% to 30%
		STAMI	SEM	WHO	173	30% to 45%	20% to 30%
	Crocidolite	TNO	FEG–SEM	All	24	30% to 45%	20% to 35%
		STAMI	SEM	WHO	92	15% to 30%	30% to 45%
Flange/gasket	Chrysotile	TNO	FEG–SEM	All	45	30% to 45%	20% to 30%

We can calculate conversion factors for SEM using the second model similarly to the example from the first model:

Ln(exposure) = (β_0 = 8.97) + (β_{at} SEM = -1.53) + (β_m loosely bound material = 1.11) + (β_{at} SEM * β_m loosely bound material = 1.85) = $e^{10.4}$ = 32,860 f/m³

And for TEM:

Ln(exposure) = (β_0 = 8.97) + (β_{at} TEM = 3.16) + (β_m loosely bound material = 1.11) + (β_{at} TEM * β_m loosely bound material = -0.58) = $e^{12.66}$ = 314,897 f/m³

Resulting in a SEM/TEM conversion factor of 314,897/32,860 = 9.6. A significant positive effect can be observed for the interaction between SEM analysis and loosely bound materials. This suggests that when analysing asbestos in materials characterized as loosely bound, SEM yields higher exposure estimates compared to other scenarios. Interestingly, the interaction between TEM analysis and loosely bound materials shows an almost significant negative effect. This implies that, in contrast to SEM, TEM analysis tends to result in lower exposure estimates when dealing with loosely bound materials.

Approach 3: comparison of fibre length and width distributions

Based on the raw fibre-counting data of TNO (the Netherlands Organisation for Applied Scientific Research), HSE (Health and Safety Executive), and STAMI (the National Institute of Occupational Health in Norway), in Fig. 4, 2 cumulative lognormal probability plots for amosite fibre length and fibre diameter are illustrated. Despite being sourced from different projects and analysed with different microscopy techniques, the distributions of amosite fibre diameters are lognormal and nearly identical. This means that the diameter distribution depends on the asbestos properties and less on the activity and microscope technique. It should be noted that in all removal projects, no high-energy tools were used. When comparing the fibre lengths, a slightly different phenomenon was observed, where fibre lengths deviate from a lognormal distribution. For the data from HSE and STAMI, this is caused by the WHO fibre-counting protocol; only fibres > 5 µm were counted. For TNO data, where all fibres were counted, the cause lies more with the fibre definition (aspect ratio > 3:1). When comparing the raw data of TNO and STAMI coming from removal projects with chrysotile asbestos cement, similar fibre diameter and fibre length distributions were observed (see Figure S1). Also, here the difference between the data from STAMI and TNO is mainly caused by the WHO fibre-counting protocol; by STAMI only fibres with diameters > 0.2 µm were counted. In addition, as chrysotile fibres are much thinner than amosite fibres, the resolution of the scanning electron microscope with the chosen magnification also starts to play a role, especially with fibre diameters below 0.1 µm.

Assuming a lognormal distribution for fibre diameter and fibre length, the percentage of fibres with a diameter < 0.2 µm and fibres with a length < 5 µm can be derived from the cumulative probability plots. Based on the results in Table 5, similar percentages were obtained for the same scenarios (removal activities with low-energy tools). Based on the raw fibre-counting data of TNO, HSE, and STAMI, a clear distinction in the fibre diameter distribution can be made between amosite at one hand and chrysotile and crocidolite at the other. For chrysotile and crocidolite, a much higher percentage of the fibres are thinner than 0.2 µm (30% to 45%) than for amosite (5% to 10%). For the fibre length this clear distinction is not observed; for all fibre types ca. 30% (20% to 45%) of the fibres are shorter than 5 µm. These values allowed for the derivation of a theoretical conversion factor of 2.2 (range = 1.7 to 2.8) for chrysotile and crocidolite fibres, and 1.6 (range = 1.3 to 2.0) for amosite fibres, to calculate the total fibre count from WHO fibres. For the derivation of all fibres > 5 µm (WHO + TAF) from WHO fibres, the theoretical conversion factors are 1.4 (1.2 to 1.8) for chrysotile and crocidolite fibres and 1.1 (1.0 to 1.2) for amosite fibres.

Discussion

The objective of the current study was to investigate the effect of different measurement and analytical methods used across Europe for measuring airborne asbestos concentrations. Ideally, the determined conversion factors would allow comparison of results measured with different analytical methods, and therefore also between exposure levels across Europe. However, results show high variation in conversion factors for all approaches, meaning that a generic conversion factor between methods could not be established.

While the conversion factors varied greatly between analytical techniques, they did show similar trends. Overall, analysis with TEM generally leads to higher asbestos fibre concentrations compared to PCM and SEM. This is consistent with the higher resolution of TEM allowing smaller and thinner fibres to be detected (Baron 2001). Furthermore, *via* direct comparison of concentrations (Approach 1) approximately the same exposure results were obtained with PCM and SEM analysis. This agrees with Ervik *et al.* (2023)'s research, who studied the differences between SEM (following ISO 14966) and PCM (following NIOSH:7400) with parallel collected samples. They expected SEM analysis to lead to higher fibre counts due to the presence of fibres with smaller dimensions but did not observe significant differences between samples analysed with

SEM and PCM. They attributed this to the presence of other inorganic fibres, which were not counted with SEM but were contributing to the concentrations measured by PCM. In addition, variation between PCM and SEM results were further attributed to the difference in composition of asbestos materials and abatement conditions, such as outdoor abatement processes (Ervik *et al.* 2023). Unfortunately, few comparison studies (Approach 1) investigated the difference in measured concentrations between SEM and PCM methods, so the attribution factors could not be studied in more detail. However, looking at the differences in concentrations between TEM and PCM, the type of ACM and especially the types of asbestos present in the material has a major influence on the conversion factors. In general, with amosite containing materials, conversion factors are lower (0.9 to 2.9) than with chrysotile and crocidolite containing materials (4 to 33). This agrees with the dimensions of the asbestos fibres; the amount of thin amosite fibres (<0.2 µm) determined with the lognormal probability plots (Approach 3) is much lower (5% to 10%) compared to chrysotile and crocidolite fibres (30% to 45%). Lastly, a decrease in the determined TEM/PCM conversion factors were observed, when comparing factors calculated from historical compared to current date results (data not shown). This may introduce a bias in conversion factors for Approach 1 if older data are used. The reason for the difference over the years might be attributed to improved microscopes over time as well as lowered OELs resulting in improved analytical protocols and counting performance.

As was demonstrated within this study, great variability in conversion factors exists between analytical techniques. This variation is partly due to differences between the analytical techniques themselves (ie selectivity, resolution, direct/indirect), but more importantly due to the differences in counting rules. For example, with PCM and SEM, normally only WHO fibres ($D \geq 0.25$ µm, $L > 5$ µm, $L/D > 3$) are counted, while with TEM also thin asbestos fibres ($D < 0.2$ µm), which result in higher asbestos fibre concentrations. This is also demonstrated with the lognormal probability plots of the fibre diameter and fibre length (Approach 3), as well as the higher estimates in the statistical models for TEM (Approach 2) and the conversion factors from direct comparisons (Approach 1). Depending on the type of asbestos, the share of thin fibres and short fibres is, respectively, 5% to 45% and 20% to 45%, which leads to a theoretical conversion factor of 1.3 to 2.8 between SEM (WHO fibres) and TEM (all fibres). Moreover, these percentages are based on removal activities with low-energy (manual) tools. With high-energy (mechanic) tools, the number of short fibres is expected to increase, which makes for even higher conversion factors. This is shown via direct comparison of analytical techniques (Approach 1), where higher conversion factors between PCM and TEM are determined for high-energy activities (8.3 to 58) than for low-energy activities (2.3 to 11). Similar trends are reported in the literature, where for example airborne chrysotile fibre concentrations measured during mining and milling showed a significantly higher percentage of fibres less than 5 µm in length compared to textile facilities (Dement and Wallingford 1990). Similarly, Eypert-Blaison *et al.* (2018) suggested that the fraction of WHO fibres, thin asbestos fibres (TAF, <0.2 µm) and short asbestos fibres (SAF, <5 µm) are related to the type of ACM that is being removed as well as to the removal techniques that are employed. This is supported by observations, where removal of spray-on asbestos resulted in high concentrations of WHO asbestos fibres while thin and short asbestos fibres were more abundant when removing asbestos-containing plaster.

Whilst this study presents a comprehensive analysis on differences in exposure to asbestos fibres in EU context and potential conversion factors in general, some limitations must be considered. First, it must be noted that not all EU member states are represented within the PEROSH network, nor are all PEROSH institutes in EU member states, and therefore not in the scope of the survey and data sharing initiative. Next, while comparison data between TEM and PCM were abundant, limited data were available for comparison of SEM versus PCM or SEM versus TEM measurements. These data availability could have an impact on the results. For example, while the difference in results between PCM and TEM techniques can be considered conclusive the difference between SEM and PCM was not as pronounced. With respect to the regression models, insufficient data was available to derive coefficients for all interaction effects. Furthermore, existing data were unevenly spread amongst the different analysis techniques, with a very large number of samples analysed with TEM. Ideally, data should be more homogenously distributed over the different determinants in the model. Therefore, the development of a statistical model capable of predicting conversion factors based on specific circumstances is not possible with the current data set. Results from the regression models suggest some significant interaction effects, that could explain variation in conversion factors found between the different techniques. However, other outcomes of the model were not in line with the results from the direct comparison study (Approach 1). While direct comparison of concentrations showed no significant differences between SEM and PCM, the regression model showed lower values with SEM. This may be an effect of predominantly using data that came from the Netherlands where mainly low asbestos fibre

concentrations were measured due to a lower OEL compared to other countries at the time of measurement. In contrast, while the regression model showed no significant difference in measured concentrations between low- and high-energy activities, direct comparison of concentrations showed significantly higher values when using high-energy tools. Also, LEV and thorough wetting appeared to increase exposure estimates, which is contrary to typical expectations. These unexpected results may be due to ineffective application or maintenance of controls. Alternatively, sampling bias could have occurred if measurements were taken after wetting agents had evaporated, leading to an overestimation of exposure.

To further investigate the above findings in Approach 2, we examined univariate models for energy and local controls. The univariate model for energy indicated a slight but significant positive effect for high-energy activities on exposure. For local controls, the univariate model generally showed a reduction in exposure estimates across all controls, except for thorough wetting, which did not follow the expected trend. Both the univariate and multivariate models explained a relatively small portion of the variance in exposure (R^2 of 0.002 and 0.15, respectively). This limited explanatory power suggests that other unaccounted factors may influence exposure levels. A potential reason for these artefacts could be the imbalance in the data set, with a disproportionate contribution of data from 1 country. Specifically, 1 country provided approximately 39,000 individual measurements, while contributions from other countries ranged from approximately 20 to 300 individual measurements. This imbalance might have introduced bias into the model, affecting the observed relationships between variables. Lastly, variability in how high- or low-energy activities and local controls are implemented across different sites and countries could also result in inconsistent exposure estimates.

In conclusion, this study gained valuable insight in national asbestos regulatory frameworks of different European countries with regards to exposure assessment methods, which can differ significantly from each other. The implications of our study results extend beyond the scope of conversion factors within the context of EU regulations and harmonization efforts. The observed variability in measurement results between the different techniques underscore the challenges in achieving a harmonized approach for exposure assessment of asbestos fibres across EU member states. While it is recognized that the EU has made strides towards the harmonization of asbestos-related regulations, challenges will remain. While the EU intends to increase the accuracy of exposure assessment to asbestos fibres by limiting the analytical methods to electron microscopy, they do not extend further than the exclusion of the PCM method. Additionally, the EU has set 2 OELs for asbestos, of which one is related to WHO fibre dimensions (limit value of 2,000 f/m^3) and one to WHO + TAF fibre dimensions (limit value of 10,000 f/m^3). This factor 5 difference seems appropriate for amosite fibres when considering the results of direct comparisons between TEM and SEM from Approach 1, which range between a factor 1.4 to 5.1. For chrysotile, there was no direct comparison available in the literature between TEM and SEM; however, between TEM and PCM higher ranges of conversion factors were observed (ranging between 2.9 and 88). If the difference between chrysotile and amphibole fibres is similar between TEM and SEM, the EU factor of 5 between WHO and WHO + TAF fibres might not be appropriate for chrysotile, and perhaps also not for other amphibole fibre types. Furthermore, the EU has not defined a lower limit of the fibre diameter for TAF, and no discrimination between SEM and TEM either, while with TEM thinner fibres can be counted compared to SEM. In that sense, also the difference in resolution between conventional SEM and high-resolution SEM need to be considered. Final conclusions on the diameter distributions of the different asbestos fibres, require studies where the resolution of the microscopes are set sufficiently high to measure and count <200 nm diameter-size fibres. Historically, this has not been necessary in SEM analysis, because the lower count was 0.2 µm following the WHO criteria. As this diameter criterion is linked to the limited resolution of the PCM method and not based on the health hazard of fibre dimensions, with the exclusion of PCM, it could be considered to re-evaluate this criterion as well.

This study demonstrated the complexity of applying standardized conversion factors between analytical techniques and/or counting rules. There is a great variation in conversion factors, indicating the relevance of additional parameters such as the type of asbestos/ACM, activity/tools and possibly other conditions during the abatement process. Also, the measurement technique used is also of importance. Although in general, a standard combination of sampling, sample preparation, and analytical technique is used in each country, measurement strategies (eg measurement duration, flow, task-based versus workday measurements) that are applied differ between countries. This can also influence the measurement results. As asbestos exposure measurements are often performed in dusty environments, to prevent overloading of filters, relative short sampling durations and low flowrates are often applied, which may bias the result. With the current sampling methods in combination with the lowered OELs, the analytical effort that is necessary to reach the desired limit of detection (number of image fields to

be counted) will be very large, resulting in a longer duration of the analysis, higher costs, and possible higher uncertainty (due to a higher risk of human errors). This may cause difficulties in assessing compliance with the lower OELs.

For a proper comparison of measurement and analysis methods and the ability to derive (generic) conversion factors, specific research is needed, in which data are generated that allows a thorough comparison of results between TEM, SEM, and PCM. In this study, variation in, for example, type of ACM, type of asbestos in ACM, general dust level, work method (energy level, dust aspiration, wet or humidification), and control measures should be considered. In addition, the possible influence of differences in sampling equipment, sampling media, sampling duration, flow rate and sample preparation should be taken into account, as well as coordination on which fibre dimensions are included in the analysis with accompanying microscope settings.

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Conflict of interest

The authors declare no conflict of interest relating to the material presented in this article. Its contents, including any opinions and/or conclusions expressed, are solely those of the authors.

Data availability

The data underlying this article cannot be shared publicly as the data are owned by many different third parties who shared their data with TNO for the analysis.

Supplementary material

Supplementary material is available at *Annals of Work Exposures and Health* online.

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