Journal of Hazardous Materials 162 (2009) 1171–1177

Contents lists available at ScienceDirect

Journal of Hazardous Materials

journal homepage: www.elsevier.com/locate/jhazmat

Emission of airborne fibers from mechanically impacted asbestos-cement sheets and concentration of fibrous aerosol in the home environment in Upper Silesia, Poland

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ARTICLE INFO

Article history:
Received 13 September 2007
Received in revised form 2 June 2008
Accepted 3 June 2008
Available online 20 June 2008

Keywords:
Asbestos
Fiber-containing materials
Emission factor
Fibrous aerosol

ABSTRACT

The emission rate (€_S) of fibers released from asbestos-cement plates due to mechanical impact was determined experimentally. The emission rate has been defined as a number of fibers (F) emitted from a unit area (m^2) due to the unit impact energy (J). For fiber longer than 5 μm the obtained surface emission factor for asbestos-cement slabs slightly increased with deteriorating surface, changing from 2.7×10^3 F/(m^2 J) for samples with a very good surface to 6.9×10^3 F/(m^2 J) for the sample with worn surface (in the SI system the emission rate unit should be ($m^{-2}\,J^{-1}$)). The emission rate for short fibers ($L \leq 5$ μm) was little higher compared with emission of long fibers for all studied asbestos materials. The averaged emission rate for all studied samples was about 5000 and 6000 of long and short fibers, respectively, emitted per square meter (because of the impact energy equal to 1 J). The dominating population of emitted fibers ranged from 2 to around 8 μm in length. The second part of this work constitutes the report on the concentration of airborne respirable fibers, and their length distribution in two different groups of homes in Upper Silesia, Poland. Mean concentration level of the respirable fibers, longer than 5 μm, was found to be 850 F/m^3 (according to the SI system the fiber concentration unit is (m^{-3})) in the buildings covered with asbestos-cement sheets and 280 F/m^3 in the homes without asbestos-containing facades, located away from other asbestos sources. Although the laboratory and field measurements have been made by using the MIE Laser Fiber Monitor FM-7400 only, the obtained results indicate that the outdoor asbestos-cement building facades are significant sources of airborne fibers inside the dwellings in Upper Silesian towns.

1. Introduction

People in homes may be exposed to different kinds of fibrous aerosols. Fibers with diameters of less than 3 μm can penetrate deep into the human respiratory system constituting a potential threat to health. There are various diseases, including lung cancer, which can be caused by the inhalation of airborne fibrous dust clouds [1–4]. Especially, the asbestos group of naturally occurring hydrated mineral silicates has been shown to induce fibrosis, lung cancer, mesothelioma, and probably other kinds of intestinal cancer.

Over the past two decades a great deal has been learned about how and why asbestos fibers cause pulmonary diseases (example: [5]). There are three essential factors that are required to develop such disease [6]: adequate dose, dimensions of the fibers in the alveolar region, and fiber biopersistence. Other fiber properties, such as presence of iron or other transition metals on fibers, ability of fibers to generate free radicals [7,8], and the ability of fibers to interact with and alter biologically relevant molecules, as well as, the ability of fibers to produce reactive oxygen/nitrogen species (ROS) may also be determinants of fiber toxicity [6], especially among biopersistent fibers. Fibers may catalyze the generation of oxidants directly from molecular oxygen or indirectly from reactive oxygen and nitrogen species released by inflammatory cells recruited to the lungs or pleura [9]. The fundamental property of the fiber toxicity is, that in contrast to chemicals, fibers are believed to cause disease through a physical/chemical interaction [10], which means that the health effects depend not only on the type of fiber but also upon its diameter and length. Typically, it is assumed that the most hazardous fibers are those longer than 5 μm and of diameter up to 3–4 μm [10]. It is possible that the physical form of a fiber is even more important than its chemical composition [6,11]. On the other hand, it is not fully understood whether the health impact is due to toxic compounds absorbed on the fibers. Such compounds could be, for example, PAHs but generally surface reactivity is related to biological reactivity. Surface

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doi:10.1016/j.jhazmat.2008.06.045

reactivity depends on the bioavailability of iron on the surface of the fiber. The source of this iron could be from asbestos ore, a trace contaminant, or endogenous deposition in the lungs [9]. Although some extremely important questions concerning the relationships between exposure to asbestos and adverse health effects still need precise answers, the World Health Organization officially recognized that asbestos is a proven human carcinogen (IARC Group 1). No safe level can be proposed for asbestos because a threshold is not known to exist [11]. Exposure should therefore be kept as low as possible.

Estimation of the exposure to fibrous aerosol requires knowledge about the emission of fibers, their atmospheric and indoor transport, and penetration from outdoor into indoor environment, as well as, deposition and resuspension. This knowledge is still very poor. This has been largely due to the enormous numbers of variables present in the outdoor environment and the nearly impossible feasibility to reproduce all of them in a laboratory. Another reason is the lack of a method to inexpensively produce length and diameter mono-dispersive fibers. Only recently Gilbertson et al. [12] have developed such a method, which produces straight fibers with controllable lengths, using thin film grown by physical vapor deposition. Besides, since the aerodynamic behavior of airborne fibers depends on the orientation of these fibers in the flow, theories and data valid for spherical particles are not applicable for fibers [13].

On the other hand, the health effects of inhalation of fibrous aerosol can concern huge groups of people becoming very important for some local populations. For example, many buildings in Central Europe are covered with thermal insulation containing asbestos-cement sheets, which weather and corrode. Cement particles, asbestos fibers and agglomerates of both particles and fibers are released from the plate surface and become dispersed in the air [14]. These airborne asbestos fibers can create a health risk, including a lung cancer risk. The problem of exposure to asbestos is, therefore, still actual. Asbestos will become airborne also from coatings, mastics, and adhesives used in the insulation industry from about 1930 to the present [15]. This fact creates exposure to the asbestos in these products during the application, spill, cleanup, sanding, cutting and removal. Also vermiculite, a naturally occurring material, from the mine that operated near Libby, Montana, USA, from the early 1920s until 1990 was contaminated with asbestos and other amphibole minerals. The historical cohort mortality study carried out recently by Sullivan [16] indicated significant elevations in standardized mortality ratios for asbestosis, lung cancer, and cancer of the pleura among Libby vermiculite workers. Unfortunately, the exposed population is much larger. Since vermiculite from Libby mine was used to make loose-fill attic insulation that remains in millions of homes, these findings highlight the need for control of exposures that currently occur when homeowners or such workers like cable installers, electricians, insulators, and so on, disturb these insulation materials made with asbestos-contaminated vermiculite [16]. Generally, in the world scale a correlation between national asbestos consumption and the incidence of asbestos diseases has been observed [17].

It should be noted that asbestos fiber-containing materials outside and even inside a building become dangerous only when the microscopic fibers are emitted from these materials into air. Such phenomenon appears if the asbestos materials become friable (crumbling), for example due to the atmospheric weather, or if building maintenance, repair, renovation or other activities (vibration and vandalism) disturb these materials. Therefore, it can be concluded that the important factor that generates, or considerably increases the emission of fibers from these fibers-containing materials used in buildings is the mechanical impact. The risk of human exposure to asbestos-containing material (ACM) is also directly related with the condition of this material. Unfortunately, till now the phenomenon of the mechanically generated emission of fibers from fiber-containing slabs is not satisfactorily recognized. After the pioneering work of Spurny [14] on the release of asbestos fibers from weathered and corroded asbestos-cement products no similar paper appeared in the available literature although some works describing in qualitative way the process of fibers emission have been published. For example, the release of asbestos fibers from the brake pads of overhead industrial cranes has been described by Spencer et al. [18]. The preliminary study of the resuspension of fibrous particles (mainly asbestos) from the carpet, generated by the physical activity of children, was carried out in 1993 [19], and some years later USEPA prepared the memorandum on the testing carpet, being the asbestos reservoir [20]. Crossman et al. [21] reported the quantification of fiber releases for various floor tile removal methods. They documented that fibers are released when floor tile is broken and/or abraded during removal procedures. They established that fiber levels vary with the aggressiveness of the procedures but they did not study the emission rate (€_S).

The aim of this work was to determine the emission rate of fibers released from the asbestos-cement plates due to the mechanical impact, and to estimate the range and typical values of the concentration of airborne fibers in homes in Upper Silesia, especially in the buildings with asbestos-cement facades. Upper Silesia Industrial Zone is an extensively urbanized and industrialized province in southern Poland where coal mining and metallurgy, as well as chemical industry are still the major industrial activities. These kinds of activities, especially the underground coal mining, significantly influence the quality of the building facades. The reason is the location of these coalmines—exactly under the cities what causes frequent vibration of the surface of the land area in Upper Silesia resulting in damages of the buildings. Hence, many of the asbestos-cement buildings' facades show breakdown likely to cause release of asbestos fibers into the environment. Therefore, asbestos can enter the homes as fibers suspended in outdoor air. Once such fibers are indoors, they can be resuspended by normal household activities, including even vacuuming (as many fibers will simply pass through vacuum cleaner bags).

2. Experimental

A simple experimental set-up has been developed to measure the emission of fibers from the asbestos-containing materials. The samples of studied materials having a surface area between 0.02 and 0.03 m^2 have been placed inside of the AURA 2000 M.A.C. Cabinet, specially adapted for this study. During the experiments the ventilation system, as well as UV lamps was switched off. The basic principle of the experiments was as follows: the falling weight (10 iron balls of 19 g each, or one iron weight of 450 g) generated the emission of fibers from the samples of fiber-containing materials. Since the falling height was 23 cm the impact energy was 0.4 and 1.0 J, respectively. Such low impact energy values were selected because it was assumed that factors such as vibrations of the slabs caused by the turbulence of wind can generate an emission of fibers from the asbestos-containing building facades.

The increasing concentration of fibers in the cabinet volume has been measured by the Laser Fiber Monitor (MIE, Inc., Billerica, MA). The method used in this monitor is based on the electric field-induced alignment and oscillation of particles, combined with light scattering, resulting in highly selective detection of individual fibers, even in the presence of a population of predominantly non-fibrous particles. The field-induced periodic oscillation of a fiber passing through the optical sensing region generates light scattering pulses at a photomultiplier detector. Each passing fiber produces a train of pulses whose sharpness (i.e. the ratio of ampli-

Fig. 1. Photograph of the Laser Fiber Monitor (right) connected with the AURA Cabinet (left), here adapted for the fiber emission experiments.

tude to area) is proportional to fiber length, independently of fiber diameter and index of refraction [22] for fibers with aspect ratios exceeding 3, approximately. Fibers with a diameter as small as 0.2 and 2 μm length can be detected by this instrument [22]. The device used in our experiments was calibrated for the asbestos fibers by the MIE, Inc. technicians in Billerica, MA. It should be noted that this instrument like other optical techniques can easily detect well-formed fibers. Unfortunately, when curved or more complex fibers are detected, these methods may become less efficient [23]. Since fiber detection instruments are usually compared with the filter collection/PCM counting method, it can be difficult to calibrate such an instrument for all types and sizes of fibers [23]. Anyway, Laser Fiber Monitor has been used previously in field and laboratory studies [22,24,25].

In our study after every experiment the cabinet was cleaned using the ventilation system with HEPA filter. Fig. 1 shows the Laser Fiber Monitor connected with the cabinet adapted for the fiber emission experiments. During all experiments the air temperature and humidity inside the cabinet were almost constant, keeping the level 24–25 °C and 30–31%, respectively.

The emission rate is defined in this study as a number of fibers (F) emitted from the unit area of a material due to the impact of a unit energy. This factor was calculated using the following equation:

$$\text{€}_{\mathrm{S}} = \frac{\rightleftarrows \Delta C_{\max} V}{SE}$$

where €_{S} (F/(m^2 J)) (using SI system: (m^{-2} J^{-1}))—is the surface emission factor; $\Delta C_{\max}$ (F/m^3) (using SI system: (m^{-3}))—is the highest increase in the measured concentration of fibers inside the cabinet after impaction of 10 balls or one iron weight; V (m^3)—is the volume of the cabinet; S (m^2)—is the surface of the sample; E (J)—is the impact energy.

The emission rate has been determined for the selected samples of asbestos-cement sheets.

The length distributions of the emitted fibers have also been investigated using the Laser Fiber Monitor.

The second part of this study was carried out in two groups of dwellings: in buildings covered with asbestos-cement sheets (Group I), and in the control group of homes without such sheets, located in suburban areas with a slightly higher preponderance of trees and shrubs than the urban sites (Group II). The reference group of homes was arbitrarily obtained, with the residents of approximately 40% of those homes initially contacted agreeing to participate in this study. The test homes had to meet the requirement that they are located away from busy roads and crossroads because the brake linings in cars are another important source of asbestos in towns [18,26]. All studied homes (from both groups) had no air conditioner but were equipped with the central heating system using warm water. During our study campaign the air temperature and relative humidity inside the buildings were 21–25 °C and 30–40%, respectively.

Time-averaged fiber concentrations and the length distribution of airborne fibers were measured with a Laser Fiber Monitor FM-7400. It was the same device used in the laboratory experiments described above, as well as, in the previously carried out preliminary study of fibrous aerosol in homes in Sosnowiec [26]. The duration of each measurement was 24 h. The Laser Fiber Monitor was situated in the center of the living room, which very often was also one of the bedrooms, at the height of 1–1.5 m above the floor.

Because it was assumed that data obtained during this study would be used in further health risk assessment, the 24 h measurements of the fibers concentrations were carried out under the typical exposure conditions. Residents were required to keep the windows opened for the usual period of time (mainly it was 2–3 h a day).

Additionally, in the three studied dwellings both Laser Fiber Monitor and Phase Contrast Microscopy (NIOSH 7400 PCM) were used to quantify the fibers longer than 5 μm present in the air.

3. Results and discussion

3.1. *Emission of fibers from the asbestos-cement sheets*

3.1.1. *Visual inspection of the samples*

In these experiments the 6 samples detached from the buildings' facades, aged between 15 and 35 years, have been studied. The short characterization of these samples is contained in Table 1. As it can be seen surface quality of three samples was very good without any visible cracks. Surface quality of two samples was classified as good because small cracks were seen on these surfaces. Only the surface of the sample No. 6 was little corroded and has been classified as bad. Besides, the white sediment of gypsum was seen on this surface. Such formation of Ca-sulfates (gypsum) was earlier observed by Heide and Rottenbacher [27] on the plate surface after exposure in a corrosion chamber of the asbestos-cement sheets to SO_2, CO_2, high humidity, frost and water, among other weathering conditions. Therefore, it can be concluded that sample No. 6 comes from the plate highly influenced by SO_2 and/or CO_2.

Although it could be expected that the surface quality of the building facade sheet highly depends on the using/exposure time, the analysis of Table 1 indicates that the surface quality of the collected samples seems to be independent of their age. However, this paradox can be easily explained. German studies have shown that the corrosion mean velocity for the uncoated asbestos-cement roof-

Table 1
Characterization of the samples detached from the buildings' asbestos-cement facades

No. of the sample	Slab age (years)	Sample sizes		Sample mass (g)	Origin	Characteristics of the sample surface
		Area (m^2)	Thickness (cm)			
1	15	0.024	0.5	295	10-stories apartment house in the Sosnowca downtown	Surface quality: good (only small cracks are seen)
2	35	0.030	0.5	320	Roof of the apartment house	Surface quality: good (only small cracks and crannies are seen)
3	30	0.037	0.5	440	Building of the hospital hot water installation	Surface quality: very good (without any cracks)
4	25	0.022	0.5	240	Apartment house in Pogon, Sosnowiec suburbia	Surface quality: very good (without any cracks)
5	20	0.027	0.5	250	Apartment house near the Sosnowiec downtown	Surface quality: very good (without an cracks)
6	15	0.033	0.5	400	4-stories apartment house in the Sosnowiec downtown	Surface quality: bad (some cracks and little crannies are seen). The sample looks little corroded. White sediment of gypsum on the surface is seen

ing tiles was about 0.01 mm/year [28]. Applying this value to our asbestos-cement sheets it can be obtained that the expected corrosion layer should be 0.15 mm and 0.35 mm for the sheets of 15 and 35 years old, respectively. Therefore, the studied asbestos-cement sheets can have different corrosion layers, weather origin, but the maximal difference is equal to 0.20 mm that is 4% of the plate thickness. Such difference seems to be too small to be found by the visual inspection. The surface quality of our samples depends probably much more on the exposure to air pollution (which is locally different) and on the vibration caused, for example, by the underground coalmine activity and vandalism rather than the weather conditions.

3.1.2. *Emission of fibers*

The mechanically induced emission of the fibers from asbestos-cement slabs, averaged for all the samples is presented in Table 2. It should be noted, again, that in the laboratory the observed emission of fibers has been generated by relatively low impact energy: 0.4 and 1.0 J. This confirms that factors such as vibrations of the slabs caused by the turbulence/gust of wind can cause emission of fibers from the elevation of buildings made from the asbestos-cement. In Upper Silesia also weak, local earthquakes generated by the underground coalmines could cause such fibers emission.

It can be seen (Table 2) that the mean value of the emission rate, averaged for all studied sheets is practically in the same order for both short and long fibers. The averaged value of the surface emission rate is equal to $5.1 \times 10^3\ m^{-2}\ J^{-1}$ for long fibers ($L > 5\ \mu m$) and $5.7 \times 10^3\ m^{-2}\ J^{-1}$ for $L \leq 5\ \mu m$. Using more traditional units, especially popular in the industrial hygiene, the above data can be written as 5.1×10^3 F/(m^2 J) and 5.7×10^3 F/(m^2 J) for long and short fibers, respectively. The medians of the emission rate for both population of emitted fibers are almost the same (Table 2).

The obtained results indicate that from the unit area (1 m^2) of asbestos-cement slabs under the impact of energy 1 J some thousands of long (i.e. carcinogenic) asbestos fibers are released. This statement may also be formulated by using the mass (instead of the surface) unit. According to the data presented in Table 2, and making a simple calculation it can be estimated that from 1 kg of these asbestos-cement sheets some hundreds of long asbestos fibers are emitted due to the impact with unit energy of 1 J.

Analysis of the emission rate for the individual samples has shown that the emission rate is not strongly related with the slab age but significantly depends on the surface quality. The relation between the surface emission factor $€_S$ and the surface quality, expressed as: very good (samples from asbestos-cement sheets No.: 3, 4 and 5), good (samples from the slabs No.: 1 and 2) and bad (samples from the slab No.: 6 only), is presented in Fig. 2. It can be seen that the factor $€_S$ for both, long and short fibers increases with deteriorate of the surface quality, changing (long fibers) from $2.7 \times 10^3\ m^{-2}\ J^{-1}$ for the samples with very good surface to $6.9 \times 10^3\ m^{-2}\ J^{-1}$ for the sample with a bad surface. The emission rate for the short fibers is slightly higher than for the long fibers.

It should be noted that the averaged emission rate obtained for the sample No.: 5, with originally very good surface, was $3.1 \times 10^3\ m^{-2}\ J^{-1}$ for long fibers. Next, this sample has been mechanically broken and the emission rate for this destructed sample rapidly increased, reaching $2.0 \times 10^4\ m^{-2}\ J^{-1}$ what confirms, once again, the previous remark that a mechanical destruction of the fiber-containing sheets (for example due to vandalism) has much more influence on the emission of fibers than the atmo-

Table 2
The averaged emission rate of the long ($L > 5\ \mu m$) and short ($L \leq 5\ \mu m$) fibers emitted from the asbestos-cement sheets

$€_S$ ($m^{-2}\ J^{-1}$)[a]		
	$L > 5\ \mu m$	$L \leq 5\ \mu m$
Mean	5.1×10^3	5.7×10^3
Standard deviation	1.9×10^3	3.1×10^3
Median	5.2×10^3	5.1×10^3
N (samples)	6	6

[a] In traditional units (F/(m^2 J)).

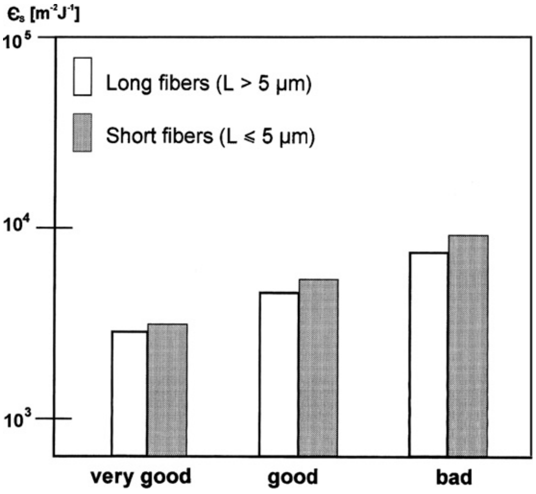

Fig. 2. The asbestos-cement slabs surface quality dependence of the emission rate.

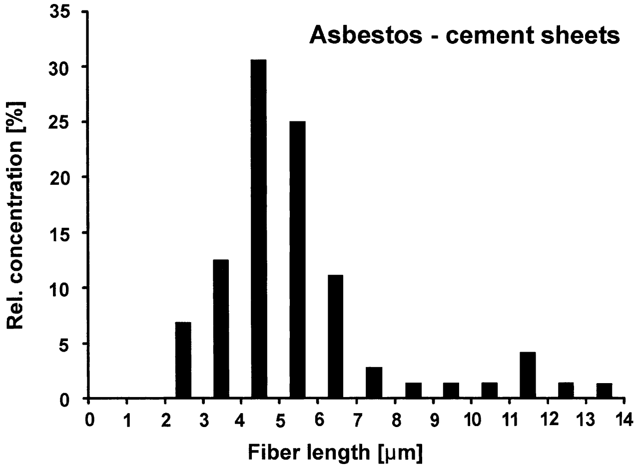

Fig. 3. Length distribution of the fibrous aerosol generated from the asbestos-cement sheets by the mechanical impaction.

spheric corrosion. It follows that coating asbestos-cement facades with a thin layer of some plastics material can prevent such facades from emitting asbestos. This procedure can significantly delay the necessity of dismantling the asbestos-cement slabs from residential buildings.

Because the health impact of the inhalation of the dose of the thin fibers strongly depends on the length of these fibers the length distribution is a very important feature of the fibrous aerosol. The average length distribution of fibers emitted during the laboratory experiments, and presented in Fig. 3, is seen to have a peak concentration level in the 4–5 μm length range.

3.2. Study of fibrous aerosol in dwellings

The concentration levels of fibers longer than 5 μm found in the studied dwellings are presented in Table 3. Mean concentration of fibers in buildings covered with asbestos-cement sheets (Group I) was 850 fibers per cubic meter what was three times higher than in Group II of control dwellings (280 fibers/m^3). These data indicate, especially in the context of the presented above results of the laboratory studies, that significant sources of fibrous aerosol in the indoor environment in Upper Silesia are outdoor asbestos materials (mainly asbestos-cement buildings facades).

The obtained results agree with the previous, preliminary studies of concentration of airborne asbestos in Polish dwellings obtained using the Laser Fiber Monitor [19,26,29,30]. Only Wozniak et al. [31] who used the Laser Fiber Monitor FM-7400 (MIE, Inc., USA) in their indoor study in Wroclaw reported that the concentration of fibers >5 μm reached the level of 11,100 m^{-3} but their measurements were carried out in the flat located in the vicinity of the playground covered with serpentinite.

Since the length of the asbestos fibers is an important factor of its toxicity, the average length distribution of fibers for the two groups of dwellings are shown in Figs. 4 and 5. The fiber length distributions are seen to have a peak concentration level in the 3–5 μm length range, representing most of the total concentration in studied dwellings. In homes covered with asbestos-cement sheets a peak was observed in the 4–5 μm length range (Fig. 4) while in the reference homes (Group II), a peak appeared in the 3–4 μm length range (Fig. 5). It seems to be very important to note, once again, the significant contribution of short fibers to the total concentration of fibrous aerosol in the dwellings in Upper Silesia, because some papers have recently appeared in literature, indicating that short asbestos fibers could be also carcinogenic (example: [32]). Besides, from Figs. 4 and 3 it can be seen that the length distribution of airborne fibers obtained in the buildings with asbestos-cement facades and in the laboratory experiments, where fibers were emitted from asbestos-cement sheets due to the mechanical impact, are very similar.

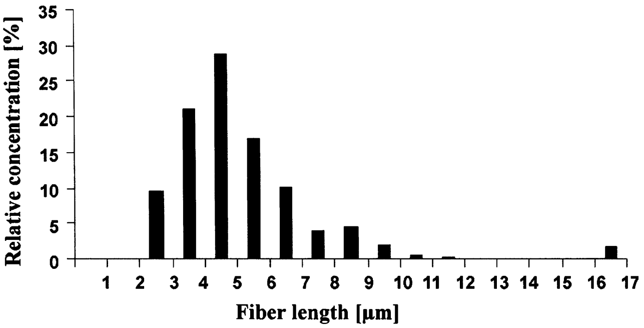

Fig. 4. Length distribution of the fibrous aerosol in buildings with asbestos-cement facades.

It should be remarked that till now most of the investigations of airborne asbestos level indoors have been made with the Phase Contrast Microscopy (PCM). In fact, the PCM method is used by U.S. EPA as a screening tool since it is less costly than the reference method based on the Electron Transmission Microscopy (ETM) with an X-ray analyzer. Therefore, the parallel measurements were carried out in three studied dwellings and in two outside points

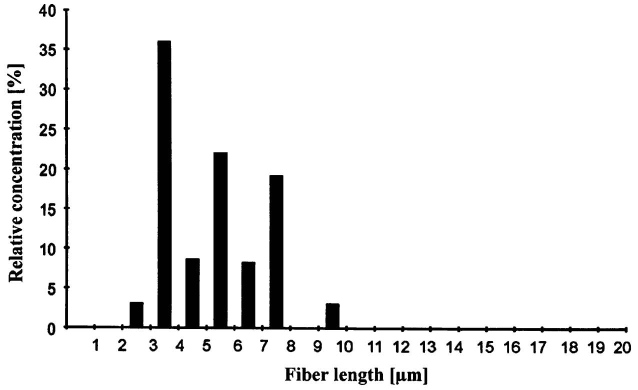

Fig. 5. Length distribution of the fibrous aerosol in the reference buildings.

Table 3
Concentration of the airborne fibers in two groups of dwellings in four towns in Upper Silesia, Poland (Katowice, Chorzów, Sosnowiec, Bytom)

Group of dwellings	Concentration level (m^{-3})[a] of airborne fibers			
	Longer than 5 μm		Equal to 5 μm or shorter	
	Mean	Range	Mean	Range
I (Buildings covered with asbestos-cement sheets) *n* = 25	850	300–1800	1290	600–3400
II (Reference buildings) *n* = 20	280	<70–700	580	<70–1500

[a] In traditional units (F/m^3).

Table 4
Comparison of the concentration levels of airborne fibers longer than 5 μm obtained from parallel measurements by using the Laser Fiber Monitor and PCM (NIOSH FM 7400)

No. of dwelling	Concentration (m^{-3})[a] obtained by using	
	Laser fiber monitor	PCM
1	540	3215
2	400	958
3	500	1816
4	600	690
5	800	920

1–3 Indoor measurements (homes), 4–5 Outdoor measurements.
[a] In traditional units (F/m^3).

using the Laser Fiber Monitor and the PCM. Unfortunately, Table 4 shows rather weak correlation between the results obtained by using these two methods (although the correlation for the outdoor data does not look so bad). On the other hand, our indoor data seem to be in a good agreement with the results obtained by Janeczek et al. [33] who measured the concentration of asbestos fibers in ambient air in Sosnowiec, Upper Silesia, Poland, using the Phase Contrast Microscope. The lowest concentrations of respirable asbestos fibers were found in Sosnowiec suburb ranging from 0 to 533 fibers per cubic meter while the highest concentrations were recorded near the crossroads (768–1646 fibers/m^3). In the residential districts of Sosnowiec the asbestos concentration was reported to be 768–1067 fibers/m^3. All these microscopic data were obtained for the samples collected 70–12 min only what means that the 24-h levels would probably be slightly lower. It should be noted, however, that PCM cannot distinguish asbestos fibers, hence the further studies using ETM method are needed to confirm the results obtained in Upper Silesia flats.

Recently some studies of asbestos structures suspended in ambient air in Katowice, the capital town of Upper Silesia, have been performed by the use of an electron transmission microscope with an X-ray analyzer [34]. These results indicate that the mean level of asbestos in outdoor air in the residential districts of Katowice (where a great number of buildings with asbestos-cement facades is located) is between 510 and 2532 asbestos structures, longer than 5 μm, per cubic meter. However, “structure” refers to asbestos fiber, cluster, bundle and matrix. Therefore, these data are not fully comparable with the concentration of individual, clearly separate fibers indoors.

It is also rather difficult to compare our results with data obtained abroad due to the difference in the kind of asbestos emitters influencing the airborne fibers indoors. Especially, the asbestos-containing materials used in buildings in different countries are different. For this reason and because the reported measurements were carried out, as a rule, under different conditions, the range of published data is from almost zero up to 10^6 m^{-3}. For example, Crump and Ferrar [35] made the statistical analysis of the data from a EPA study of airborne asbestos levels in 49 buildings occupied by the General Service Administrations. They detected no statistically significant differences in asbestos levels among three categories of buildings: (1) with no ACM, (2) with ACM in good conditions, and (3) in buildings contained damaged ACM. The average indoor concentration of asbestos was 70 m^{-3} for fibers 5 micrometers or longer. Corn [36] determined the concentration of asbestos in air from analysis of samples collected in over 300 buildings involved in litigation and found that concentrations of fibers >5 μm were generally less than 500 m^{-3}. Much higher levels were obtained by Ganor et al. [37] who measured the concentrations of asbestos in the air of a communal dining room in Israel in which the damaged ceiling had a sprayed on coating of insulation containing asbestos. They obtained the concentration 4×10^6 m^{-3}. It should be noted that the literature data presented above were obtained in 1990s. Towards the end of the 20th century, governments in many developed countries banned or seriously restricted the use of asbestos. Unfortunately, consumption of asbestos is increasing in Asia, Latin America and the Commonwealth of Independent States [17]. In most of the countries there is little, if any, control of hazardous asbestos exposures from occupational, environmental and domestic sources [17]. The illustration of this thesis can be the result of the study recently made by Ansari et al. [38] in India where around 60% of total production of asbestos is processed there in unorganized sectors including milling and manufacturing of asbestos-based products. Asbestos fibers levels in the range of $(2–16) \times 10^6$ m^{-3} were found in air at work zone areas of asbestos milling units [38] but due to the specific situation in India (people living close to the industrial sectors of the towns) also part of the general population is exposed to the similar concentration of asbestos.

As mentioned in chapter 2, the only difference between the two studied groups of dwellings was that the homes belonging to Group I have asbestos-cement facades while the homes belonging to Group II have no asbestos-cement materials. Hence, it can be concluded that the observed elevated concentration of airborne fibers inside the homes of Group I is related with the migration of asbestos fibers from outdoor air, mainly released from the asbestos-cement sheets. The difference between the exposure to airborne fibers longer than 5 μm inside the buildings with asbestos-cement facades and in the reference buildings, calculated from Table 3 (as the difference between the averaged concentrations of fibers for the two studied groups of dwellings), is 570 m^{-3}. Because the health hazards of asbestos depend upon asbestos inhalation, the measurements of airborne concentrations enable the estimation of a risk. Unfortunately, the dose-risk relationships which could be used in such estimation have been obtained using mainly the workplace exposure. Only several studies have been performed to calculate the risk of mesothelioma resulting from nonoccupational exposure to asbestos. On the other hand, although in case of lung cancer, one of the most popular forms of cancer, there are many epidemiological studies, the extrapolation of risk and comparison between different studies is considerably complicated [11]. Apart from incomplete knowledge about the true workplace exposure, an additional complication is related with the fact that workplace concentrations were measured by means of an optical microscope. Anyway, assuming that our concentration levels obtained by the Laser Fiber Monitor are no higher than the concentration levels which can be obtained by PCM (see Table 4) and applying the risk assessment formula presented in [11], it may be estimated that for the lifetime exposure to about 500 m^{-3} in a population of whom 30% are smokers, the excess risk due to lung cancer will be in the order of 10^{-6}–10^{-5}. For the same lifetime exposure, the mesothelioma risk for the general population will be in the range 10^{-5}–10^{-4}. It should be noted that both these cancer risks are generated by residing in the homes with asbestos-containing outdoor facades.

4. Conclusions

Asbestos-cement slabs are susceptible to emitting fibrous particles generated by impact. Factors such as vibrations of the slabs caused by the turbulence/gust of wind can cause emission of fibers from the elevation of buildings made from asbestos-cement sheets.

Susceptibility of 15–35 years old asbestos-cement slabs to emitting fibrous particles caused by mechanical impact is practically not dependent on the age of the slabs, but it is highly dependent on the quality of the surface of the slabs. Mechanical destruction of the fiber-containing sheets (for example due to vandalism) much more influenced on the emission of fibers than atmospheric corrosion.

The emission factor for both, long and short fibers increases with deteriorate of the surface quality of the asbestos-cement facades, changing (for long fibers) from $2.7 \times 10^3\ \mathrm{m^{-2}\,J^{-1}}$ for the slabs with very good surface to $6.9 \times 10^3\ \mathrm{m^{-2}\,J^{-1}}$ for the slabs with worn surface (using more traditional units the emission factor is equal to $(2.7–6.9) \times 10^3\ \mathrm{F/(m^2\,J)}$).

The dominating population of fibers emitted during a mechanical impact from the examined materials contains fibers from 2 to around 8 μm of length.

The length-distribution of fibers emitted from asbestos-cement slabs seems to be one-modal with the maximum ranging from 4–5 μm of fiber length and is similar to the length-distribution of airborne fibers obtained in the buildings with asbestos-cement facades.

The indoor concentration about some hundred fibers per cubic meter (probably less than 300 fibers/m^3) could be assumed as a background value or normal concentration level of respirable fibers, longer than 5 μm in the towns in Upper Silesia, Poland.

Inside the buildings with asbestos-cement facades the mean concentration of respirable fibers, longer than 5 μm was higher than in reference dwellings by approximately three times. This elevated concentration of airborne fibers generates for the residents of these homes the lung cancer risk in the order of 10^{-6}–10^{-5} and the mesothelioma risk ranging from 10^{-5} to 10^{-4}.

The method of the estimation of the emission rate, described in this work, could be useful in the assessment of the health risk related with the human contact with the fiber-containing materials, as well as in the control measurements of the safety level of these materials.

Acknowledgements

This work was supported by the Polish Government under the grant 4PO5D02819. The laboratory experiments were carried out mostly in the Institute of Occupational Medicine and Environmental Health (IOMEH) in Sosnowiec, Poland.

Author also wishes to thank Professor Kyaw Tha Paw U, University of California, Davis, for the valuable discussions and Mrs. Beata Łudzeń-Izbińska, IOMEH, Sosnowiec, for helping with the experiments.

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