Chapter 16
Human Health Hazards Associated with Asbestos in Building Materials

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Abstract Asbestos is a fibrous natural material that possesses outstanding technological properties exploited since the time of its discovery for the manufacture of various building materials. Unfortunately, as known since the mid-1950s, both humans and animals exposed to asbestos fibres may develop a number of lethal respiratory diseases. Consequently, international medical and health organizations have classified asbestos as a human carcinogen and many countries worldwide have banned its use. Besides a short historical chronicle, this chapter provides a classification of asbestos minerals, applications in building materials, as well as its toxicity and pathogenicity mechanisms. The global asbestos issue and its use as a building material today will be the core of the chapter. In addition, a section is dedicated to the description of the reclaim, disposal and recycling of asbestos containing materials and a description of the substitutes of asbestos used today in building materials.

Keywords ACBM · Asbestos · Asbestos substitutes · Disposal · Pathogenicity · Reclamation · Recycling · Toxicity

16.1 Introduction

The word *asbestos* refers to a family of mineral fibres known and used for millennia (Dilek and Newcomb 2003; Ross and Nolan 2003). It was discovered that anthophyllite asbestos, one of the five amphibole asbestos minerals, was utilized to manufacture fireproof pottery and ceramics in Northern Finland (Lapland) during the Stone Age, some like 7,000–10,000 years ago and more commonly during the Early Metal Age, ca. 2,000 B.C. to 300 A.D. (Gualtieri 2017). Chrysotile, the only serpentine asbestos mineral, was utilized for the first time on the island of Cyprus about 5,000 years ago

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for weaving clothes (Gualtieri 2017 and references therein). Greeks and Romans knew asbestos and praised this magic fibre in many different ancient scripts. In the first century A.D. the Roman philosopher Pliny the Elder wrote about asbestos in his *Naturalis Historia* calling it as *linumvivum* (living linen) (Rosselli 2014). Over time, asbestos continued to attract noblemen, alchemists, and magicians from Western Europe to the Far East. Legend has it that Charlemagne, the Emperor of the Sacred Roman Empire from 800, possessed a fireproof tablecloth very likely made of asbestos that he was using to impress his guests by cleaning it into the fire (Rosselli 2014). In the sixteenth century, Georg Agricola provided the first scientific explanations to the magical properties of asbestos (Alleman and Mossman 1997).

The industrial age of asbestos dates back to about 1850 when manufacturing sites opened in Germany and the United Kingdom. Mining activity of white (chrysotile) asbestos in Quebec (Canada) began in 1878 in the Thetford district. Since then, asbestos rapidly became an invaluable resource and every-day life commodity all over the world (Gualtieri 2017). At that time, in countries like the Russian Empire where asbestos from the Ural deposits had been extensively exploited since 1884 (Shcherbakov et al. 2001) and used for the manufacture of various building materials, it was truly considered a marvel material. Asbestos was such a wonder that in 1908 Aleksandr Aleksandrovič Bogdanov, in his fiction book Краснаязвезда (The red star), narrates that the Martians weaved their clothes using *"fibrous minerals of the asbestos type"*.

In 1915, the Russian Empire was second only to Canada as far as the production of asbestos in the world.The period across the nineteenth and twentieth century saw the birth of other asbestos mine districts all over the world. Among them, the South African mines soon became of paramount importance as two different amphibole asbestos species were mined there: crocidolite and amosite (A=asbestos M=mines O=of S=South Africa) whose exploitation began in 1893 (Beukes and Dryer 1986) andin 1907 (Bowles 1955), respectively. Even Italy had its own natural source of asbestos from the mining district of Balangero and Corio, ca. 20 km northwest of Torino, where the exploitation of chrysotile began in 1918 and ended in 1990. Primo Levi, one of the most famous Italian writers of the twentieth century, also worked for some time at the Balangero chrysotile mine. In one of his books, Levi reports a fragment of his infernal experience there: "*There was asbestos everywhere, like gray snow: if you left a book on a table for a few hours and then removed it, you would find its negative profile.*" (Levi 1975). Figure 16.1 is an image of the abandoned Balangero mine which is now a reclaimed superfund site of national interest.

The outstanding technological properties of commercial asbestos have been extensively exploited at industrial scale since the beginning of the twentieth century. It is possible to claim that asbestos minerals have been utilized to create more than 3,000 different asbestos containing materials (ACMs) used in practical and industrial applications (Gualtieri 2012). Among the asbestos minerals, chrysotile is by far the most exploited one. The asbestos-cement industry is the largest user of chrysotile fibres (about 85% of all applications) and it is estimated that about 95% of mining activity regards chrysotile asbestos (Ross et al. 2008).

Fig. 16.1 The reclaimed Balangero mine; an asbestos remediation Italian superfund site

The state of the art of the definitions of asbestos, pinpointing the gaps in this sphere of knowledge, and classification of asbestos minerals are described in Sect. 16.2 with the goal to deliver a synthetic clear picture of the complex area. Another goal of this chapter will be to describe what we know today about the toxicity and pathogenicity effects of asbestos (Sect. 16.3) within an uncertain and conflicting global scenario (Sect. 16.5).

As described in a dedicated paragraph of this chapter (Sect. 16.4), a number of building materials were or are actually made of composite mixtures including asbestos. ACMs used in buildings are classified as *loose* (or *friable*) and *compact*. *Loose* or *friable* asbestos building materials are mechanically crushed or pulverized with little effort with fibres (usually 70–95 wt.% of the product) that can be easily released into the surrounding environment. *Compact* asbestos building materials are made of a cement or polymeric material added with asbestos fibres (about 4–15 wt. %). Asbestos fibres are well fixed to the matrix and are released only if the material is damaged by mechanical tools. Common examples of *friable* asbestos in building materials are: suspended ceilings and floors, coal stoves, fireproofing spray and fire door interiors, insulating boards/panels, acoustical panels and finishes, lagging like steam pipes, boilers, pipework, asbestos blanket or asbestos paper tape, anti-vibration gaiters, ducts, walls and soundproofing or decorative spray coatings (Gualtieri 2012, 2013). Selected examples of *compact* asbestos in building materials are: masonry fillers, mortars, planar or corrugated roofing (by far the most common ACMs), shingles, vinyl asbestos, pipes, and water tanks (Gualtieri 2012, 2013). Figure 16.2 portrays selected examples of asbestos containing building materials (ACBMs): corrugated cement-asbestos roofing of a building in an urban industrial

Fig. 16.2 Examples of asbestos containing building materials (ACBMs) **a** corrugated cement-asbestos roofing of a building in an urban industrial area; **b** bent corrugated cement-asbestos roofing of a building in a rural industrial area; **c** a grain silo in a rural area. Original pictures taken by A.F.G

area (a); bent corrugated cement-asbestos roofing of a building in a rural industrial area (b); a grain silo in a rural area (c).

One of the objectives of this chapter is to deliver an updated classification of ACMs and discuss the problems related to their reclamation and disposal, with special attention to the differences in the existing directives and laws (Sect. 16.6). A further objective of the chapter is to report an updated list of asbestos substitutes that are used nowadays in building materials with an unbiased analysis of their pros and cons, especially in terms of toxicity/pathogenicity effects.

16.2 Classification of Asbestos Minerals

Although most of the outstanding technological properties and health hazards of asbestos are known, there is no consensus to date on a single definition of this term (Mossman and Gualtieri 2020). Depending on the context (commercial, regulatory, mineralogical, etc.), there are many ways to define the word "asbestos". Asbestos is often used as a generic term to identify minerals that can be mechanically ground to generate thin flexible fibre bundles of single fibres (Case et al. 2011). According to the commercial definition, asbestos are mineral fibres that possess exceptional properties (like heat resistance, mechanical strength and many more) that make them valuable materials for industrial purposes (Niklinski et al. 2004). As concerns the regulatory

framework, asbestos is a group of fibrous minerals with length >5 μm and aspect ratio (length/width) ≥ 3 (National Institute for Occupational Safety and Health 2019). Unfortunately, the incomplete and inadequate definition of asbestos led to general confusion in scientific, social, health, and legal frameworks (Mossman and Gualtieri 2020). In this chapter, we will refer to the general definition adopted by international health and regulatory agencies (such as International Agency for Research on Cancer and the International Labour Organization) for which chrysotile and five fibrous amphiboles form the family of "asbestos" minerals (Gualtieri 2017). The amphibole asbestos species are amosite (asbestos grunerite), crocidolite (asbestos riebeckite), fibrous actinolite, fibrous anthophyllite and fibrous tremolite (Gualtieri 2012) (Table 16.1).

Asbestos minerals are silicates classified based on their crystalline chemistry and structural features (Ballirano et al. 2017). Amphiboles are double chain silicates with Si/O=4:11. These chains are linked to a layer of octahedral sites: $M(1)$, $M(2)$, $M(3)$ are regular octahedral cavities and $M(4)$ is a large and distorted 6- to eightfold cavity (Fig. 16.3a). In addition, there is an even larger 10- to 12-fold A site (Fig. 16.3b). OH^- groups occur in the interiors of the rings in the double chains (Fig. 16.3a). The structure of amphiboles has the general formula $A_{0-1}B_2C_5T_8O_{22}W_2$ (Hawthorne et al. 2007). A=Ca^{2+}, K^+, Na^+, Li^+, with 6 to 12-fold coordination (i.e., A site); B=Ca^{2+}, Mg^{2+}, Na^+, Fe^{2+}, Mn^{2+}, Li^+, with distorted eightfold coordination (i.e.,

Table 16.1 The ideal chemical composition and crystal symmetry of the six asbestos minerals (adapted from: Gualtieri 2012)

| Commercial term	Mineral species	Idealized chemical formula	Space group	References
Amphibole asbestos				
Amosite/brown asbestos	Grunerite	$(Fe^{2+},Mg)_7Si_8O_{22}(OH)_2$	$C2/m$	Pollastri et al. (2017a)
Crocidolite/blue asbestos	Riebeckite	$Na_2(Fe^{2+},Mg)_3Fe_2^{3+}Si_8O_{22}(OH)_2$	$C2/m$	Pacella et al. (2019)
Actinolite asbestos	Actinolite	$Ca_2(Mg,Fe^{2+})_5Si_8O_{22}(OH)_2$	$C2/m$	Pollastri et al. (2017b)
Anthophyllite asbestos	Anthophyllite	$(Mg, Fe^{2+})_7Si_8O_{22}(OH)_2$	$Pnma$	Pollastri et al. (2017a)
Tremolite asbestos	Tremolite	$Ca_2Mg_5Si_8O_{22}(OH)_2$	$C2/m$	Giacobbe et al. (2018)
Serpentine asbestos				
White asbestos	Chrysotile	$Mg_3(OH)_4Si_2O_5$	Cc	Pollastri et al. (2016)
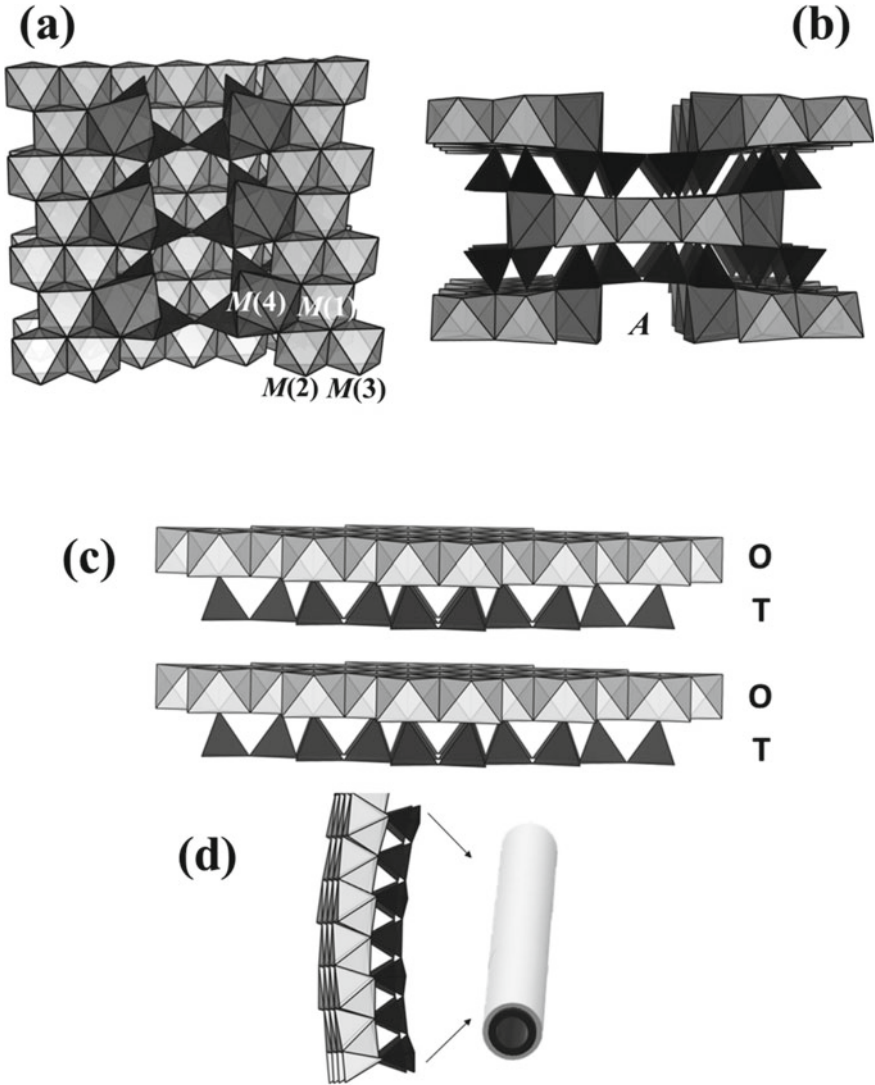
Fig. 16.3 Schematic representation of amphibole and serpentine structures; **a** the (100) plane of the monoclinic structure of amphiboles, **b** the (001) plane of the monoclinic structure of amphiboles.The black polyhedra are the tetrahedral *T* sites. The light grey polyhedra are the *M*(1), *M*(2), *M*(3) octahedral positions whereas *M*(4) positions are coloured in dark grey. **c** The ideal layer unit of serpentine lying on (001) crystallographic plane; tetrahedral sites are coloured in black; octahedral sites are coloured in light grey. **d** The rolling of the TO layers forms a cylindrical structure typical of the chrysotile fibres

the $M(4)$ sites); C=Mg^{2+}, Fe^{3+}, Fe^{2+}, Al^{3+}, Mn^{3+}, Mn^{2+}, Ti^{4+}, Li^+, with regular sixfold coordination(i.e., $M(1)$, $M(2)$ and $M(3)$ sites); T=Si^{4+}, Al^{3+}, Ti^{4+}, at the tetrahedral sites $T(1)$ and $T(2)$ running along the chains; W=OH^-, Cl^-, F^-, O^{2-}. These minerals preferentially crystallize along the c-axis and mono-dimensional growth determines their fibrous crystal habit (Gualtieri 2012). Amphiboles crystallize in different space groups (Hawthorne et al. 2007) but, apart from anthophyllite, the asbestos varieties are monoclinic with space group $C2/m$ (Table 16.1). Idealized chemical formulas of amphibole asbestos are shown in Table 16.1. For detailed information regarding the classification, crystal chemistry and structural characteristics of amphiboles, the reader can refer to the work of Hawthorne et al. (2007).

The serpentine group of silicate minerals includes the fibrous polymorph chrysotile, and lamellar antigorite and lizardite (Ballirano et al. 2017). To a first approximation, the structure of serpentine species is characterized by units of tetrahedral (T) sheets centred by Si and octahedral (O) sheets centred by Mg with T/O=1:1 (Fig. 16.3c). Because the size of an ideal T sheet (b=9.10 Å) is smaller than the size of an ideal O sheet (b=9.43 Å), a mismatch between the T and O sheets occurs inducing a differential strain (Pollastri et al. 2016). To compensate for the size differences and strain of the sheets, structure distortions occur in the different polymorphs of serpentine (Ballirano et al. 2017). Concerning chrysotile, the rolling of the TO layer releases the strain and forms a cylindrical lattice (Pollastri et al. 2016). The curvature of the lattice propagates along a preferred axis leading to the formation of the tubular structure typical of chrysotile fibres (Fig. 16.3d). The general chemical formula of serpentine is $Mg_3(OH)_4Si_2O_5$. Ionic substitutions are usually limited in chrysotile compared to other serpentine minerals (Ballirano et al. 2017). The most common substitution occurs between Fe^{2+} and Mg^{2+}in the octahedral site (Ballirano et al. 2017). Moreover, Al^{3+} can replace Si^{4+} in the T sheet and Fe^{3+}can replace Mg^{2+} in the O sheet (Pollastri et al. 2016; Ballirano et al. 2017). Gualtieri et al. (2019a) recently found that Cr, Ni, Mn and V can replace Mg in the O sheet. The concentration of this group of metals in chrysotile is highly variable and depends on the geological origin (Bloise et al. 2016): 2,044 and 2,064 mg/kg for Italian chrysotile samples from Valmalenco and Balangero, respectively (Bloise et al. 2016); 1,704 mg/kg for a chrysotile sample from Quebec, Canada (Bloise et al. 2016); 13,473 mg/kg for a commercial sample of chrysotile from Orenburg, Russia (Di Giuseppe et al. 2021).

The peculiar structural features of asbestos minerals give them exceptional physical and chemical properties that building material manufacturers have found incredibly useful (Gualtieri 2012). The main properties of the asbestos fibres are: high tensile strength, non-flammable, sound isolation, low thermal conductivity, chemical resistance, high surface area, thermal stability and thermal resistance (Gualtieri 2012). Although all types of asbestos have these properties, amphibole asbestos and chrysotile are different. In particular, amphibole asbestos fibres are resistant to any type of chemical attack, while chrysotile fibres dissolve quickly in an acidic environment (Gualtieri et al. 2018a). Concerning chrysotile, the low pH induces the replacement of Mg^{2+} for H^+ or H_3O^+ and leads to the breakdown of the octahedral layer resulting in a form of amorphous silica (Gualtieri et al. 2018a, 2019b). In contrast, the substitution of octahedral cations for H^+ in amphibole species occurs

Fig. 16.4 Electron
micrograph images of
asbestos fibres. **a** Image of
chrysotile fibre bundles from
Balangero (Italy). Chrysotile
forms aggregates of very
long, thin and curvilinear
fibres that show a high
degree of flexibility.
b Micrograph images of
UICC standard crocidolite
from South Africa.
Crocidolite fibres show the
typical columnar and straight
aspect of amphibole asbestos
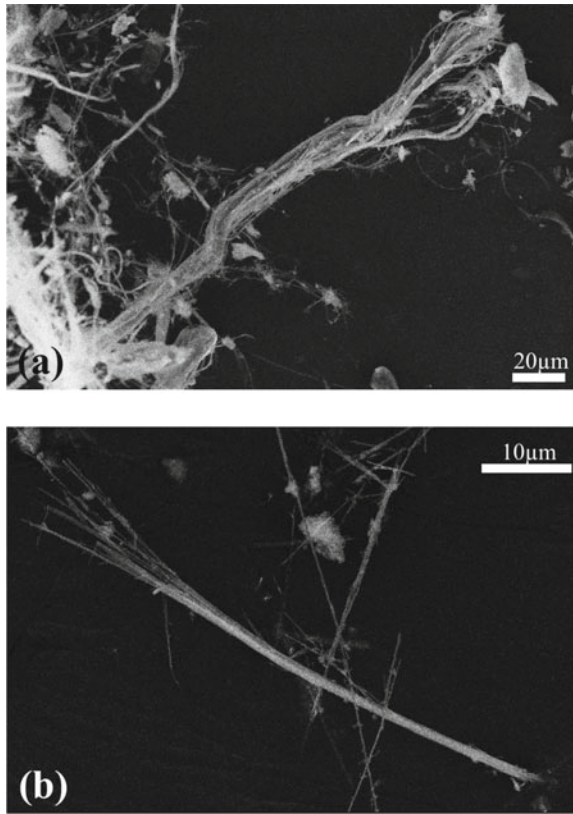
without major structural changes (Gualtieri et al. 2018a). The other main difference
between these two types of asbestos concerns their crystalline habit. As displayed in
Fig. 16.4, chrysotile is characterised by long, very thin and curled fibres (Pollastri
et al. 2016) whereas amphibole asbestos fibres commonly exhibit a quite rigid and
straight columnar aspect (Belluso et al. 2017).

16.3 Toxicity and Health Effects of Asbestos

We are aware of the potential risks of asbestos to human health since the end of the
nineteenth century (Alleman and Mossman 1997) and literature from the 1930 and
1940s reported health problems affecting workers exposed to asbestos (Niklinski
et al. 2004). However, the first unequivocal evidence of asbestos carcinogenicity was
delivered in the mid-1950s by Sir Richard Doll whose pioneering epidemiological
studies correlated lung cancer among asbestos workers to asbestos exposure (Doll
1955). Later, many more scientific evidences were found to prove that exposure

to asbestos is linked to the development of respiratory diseases such as lung cancer, malignant mesothelioma (MM) and asbestosis (pulmonary fibrosis affecting asbestos workers) (Mossman and Gualtieri 2020). The International Agency for Research on Cancer (IARC), after carefully evaluating available data (e.g., from epidemiological, in vivo and in vitro studies), determined in 2012 that all asbestos types (chrysotile and amphibole asbestos) are carcinogenic for a number of target organs including lung, pleura, peritoneum and larynx (International Agency for Research on Cancer 2012). Hence, chrysotile and amphibole asbestos are now included in Group 1 "carcinogen for humans" (International Agency for Research on Cancer 2012) and classified as Category 1A carcinogens (European Chemicals Agency 2015). According to the latest data available in the literature, asbestos causes approximately 255,000 deaths per year, of which 233,000 are related to occupational exposure (Furuya et al. 2018). In particular, MM is estimated to cause the deaths of 13,883 people annually in Asia, 3,354 in Africa and 2,794 in Europe (Odgerel 2017).

Exposure to asbestos fibres occurs through inhalation, mainly in the workplace but also in the vicinity of natural geologic occurrence of asbestos or inside buildings with ACM (Kamp 2009; Gualtieri 2020). According to the World Health Organization criteria, regulated asbestos fibres are longer than 5 μm, thinner than 3 μm and with an aspect ratio (length/width) $\geq$3 and can be airborne and inhaled (World Health Organization 1997). Once released into the air, these fibres easily penetrate the upper airways (i.e., nasal and oral cavities) and travel along the airflow pathway (Gualtieri et al. 2017). The fate of a fibre in the respiratory tract depends on its aerodynamic diameter D_{ae} (Gualtieri et al. 2017): when D_{ae}>5 μm, a fibre is filtered in the upper respiratory tract where it is cleared (Bustamante-Marin and Ostrowski 2017); when $3 \leq D_{ae} \leq 15$ μm, a fibre reaches the laryngeal/bronchial tracts; when $D_{ae} \approx 2$–3 and <0.2, a fibre reaches the lower alveolar respiratory section. The airways are covered with a mucus layer that is constantly moved by the ciliated epithelium from the lower to upper airways (Bustamante-Marin and Ostrowski 2017). Mucociliary escalator traps and carries particles to the pharynx where they can be expelled by coughing or swallowing (Bustamante-Marin and Ostrowski 2017). Particles that can bypass the mucociliary escalator and reach the alveolar spaces are cleared by alveolar macrophages (AMs) through phagocytosis (Oberdörster 1993). Phagocytosis involves several steps, from recognizing the exogenous particle (via a receptor-mediated mechanism) and engulfing it in a phagosome (i.e., a membrane-bound vacuole) to the maturation of phagosome into a phagolysosome (i.e., a new vacuole created by the fusion of phagosome with lysosome) and the dissolution of the internalized particle in the phagolysosome acidic environment (Rosales and Uribe-Querol 2017). Unfortunately, phagocytosis fails when AMs attempt to engulf fibres longer than the AM diameter (Fig. 16.5a), leading to frustrated phagocytosis (Donaldson et al. 2010). Toxicological studies on lung tissues from rodents and human subjects suggest that the fibre length threshold value for inducing frustrated phagocytosis is 5 μm (Mossman 2018; Roggli and Green 2019). Fibres that are not biodurable (i.e., with biodurability defined as the resistance of a particle to biochemical decomposition) such as chrysotile (Gualtieri 2018; Gualtieri et al. 2018a), are dissolved by the acidic environment of the phagolysosome, broken into small fragments and easily

Fig. 16.5 a Electron micrograph showing an alveolar macrophage attempting (without success) to phagocytose a long asbestos fibre. **b** Sketch illustration of the chain process responsible for the onset of MM. (*1*) Thin and long asbestos fibres can reach the pleural surface. (*2*) In the pleural cavity, asbestos fibres induce frustrated phagocytosis and chronic inflammation that prompt programmed necrosis of mesothelial cells. (*3*) Necrotic cells release the proinflammatory protein HMGB1 which stimulates macrophages to secrete monocyte-derived cytokines. (*4*) Cytokines stimulate the survival of cells with damaged DNA and lead to the pathway of carcinogenesis of MM (*5*). (adapted from: Carbone and Yang 2012, 2017)
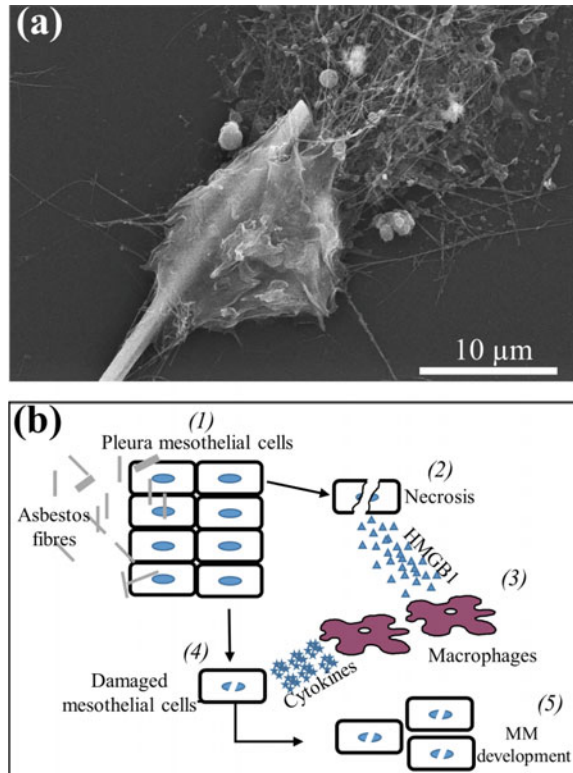
engulfed by the AMs (Bernstein et al. 2013; 2014, 2015). On the contrary, biodurable fibres, such as amphibole asbestos and fibrous zeolites (Gualtieri et al. 2018a), are designed to induce chronic frustrated phagocytosis (Donaldson et al. 2010).

Literature data shows that frustrated phagocytosis is pivotal in asbestos-induced toxicity (Carbone et al. 2019). During frustrated phagocytosis, in the attempt to clear the fibrous particles, AMs trigger respiratory bursts with production of reactive oxygen species (ROS). NADPH oxidase enzyme helps the macrophages to reduce O_2 to a superoxide free radical ($O_2 \bullet^-$) that rapidly reacts with itself to form hydrogen peroxide (H_2O_2). $O_2 \bullet^-$ and H_2O_2 via iron-catalysed reaction or myeloperoxidase-catalyzed oxidation, produce hydroxyl radicals (HO•) and hypochlorite (ClO^-) (Babior 1984; Dahlgren and Karlsson 1999; Thomas 2017). In addition to ROS, frustrated phagocytosis may be modulated by highly reacting nitrogen species (RNS) (Shukla et al. 2003). Active sites on the surface of the asbestos fibres also produce ROS (Turci et al. 2017). For example, O_2 reacts with Fe^{+2} exposed at the fibre surface generating H_2O_2 and HO• through Haber–Weiss/Fenton cycles (Turci et al. 2017; Gualtieri et al. 2019c). Prolonged production of ROS/RNS overcomes the antioxidant cell defence and induces alteration of the cell membrane, cell injury and DNA damage (Carbone and Yang 2012; Mossman 2018). The combined cyto/genotoxic

activity of asbestos induces chronic inflammation and leads to the growth of mutated lung cells prone to cancer development (Carbone and Yang 2017; Gualtieri 2018; Mossman 2018; Carbone et al. 2019).

The size of a fibre is also determinant in inducing MM (Donaldson et al. 2010). The small diameter of asbestos fibres makes it possible for them to reach the pleural cavity (Donaldson et al. 2010; Gualtieri et al. 2017). Short fibres (<5 μm) are easily cleared from the pleura as they pass through the stomata (cavities in the parietal side of the pleura) and end up in the lymphatic capillary system (Donaldson et al. 2010). Conversely, long fibres (>5 μm) cannot leave the cavity, because they are too long to pass through the stomata (Donaldson et al. 2010). According to Carbone and Yang (2012), the asbestos fibres retained in the pleura cause chronic inflammation (via frustrated phagocytosis and ROS/RNS generation) and induce programmed necrosis of pleural mesothelial cells (Fig. 16.5b). The proinflammatory protein HMGB1 released from necrotic cells stimulates AMs to secrete cytokines like IL-1β and TNF-α prompting the proliferation of DNA-damaged cells responsible for the onset of MM (Carbone and Yang 2017; Carbone et al. 2019).

Carcinogenesis is a complex multistep process in which genetic susceptibility plays a primary role (Carbone et al. 2007; 2019). Recent studies demonstrated that subjects with germline mutations of the *BAP1* gene are prone to develop MM after asbestos exposure (Carbone et al. 2019). *BAP1* modulates several cellular functions like DNA repair and apoptosis (i.e., programmed cell death). Mesothelial cells with germline *BAP1* mutations are unable to adequately repair DNA damage and fail apoptosis (Carbone and Yang 2012). It follows that, if exposed to asbestos fibres, the mesothelial cells mutated in *BAP1* easily undergo neoplastic processes (Carbone and Yang 2012; Carbone et al. 2019).

Although all six asbestos species revealed carcinogenic effects (International Agency for Research on Cancer 2012), a part of the scientific community questions the toxicity of chrysotile (see Sect. 16.5) due to its low biopersistence (i.e., the resistance of a particle to biochemical decomposition and mechanical clearance) with respect to amphibole (Camus 2001; Bernstein et al. 2008; 2013). However, as stressed by IARC in Monograph 100c, low biopersistence is not synonymous with low toxicity and chrysotile toxicity must be related to other chemical/physical parameters (International Agency for Research on Cancer 2012). In this context, the recent toxicity model proposed by Gualtieri et al. (2019a) suggests that chrysotile induces toxicity in the same way as nanoparticles do (Studer 2010). During phagolysosome-induced dissolution, chrysotile fibres release the metals (e.g., Fe, Mn, Cr and Ni) stored at the octahedral site (Gualtieri et al. 2018; Gualtieri et al. 2019a). These metals when released into lung tissues prompt ROS formation (Gualtieri et al. 2019c). Low biodurability of chrysotile allows a fast release of these redox-active metals and induces an acute cytotoxicity (Gualtieri et al. 2018, 2019a). Furthermore, recent in vitro tests have shown that the amorphous silica fibre produced by the dissolution of chrysotile possesses moderate cyto/genotoxicity against monocytes and mesothelial cells (Gualtieri et al. 2019b).

16.4   The Use of Asbestos in Building Materials

Several building materials contain asbestos. Asbestos can be found in both private (farms, industrial sites, houses, etc.) and public (hospitals, railway stations, schools, etc.) buildings. There are basically two different ACBMs, friable and compact, which differ in asbestos content and nature of the asbestos rich composite material (see Becklake et al. 2007; D'Orsi 2007; Gualtieri 2012). A working definition of a friable ACBM is that it can be ground or pulverized by hand when it is dry, releasing free fibre bundles of single fibres. The content of asbestos in friable ACBMs is very high (from 70 to 95 wt.%) and for this reason, friable ACBMs should be considered very hazardous. A working definition of a compact ACBM is that the asbestos fibres are strongly anchored to a matrix and not easily released unless the material is processed using mechanical tools. They are thus composite materials where the asbestos fibres are intimately adhered to a cement or polymeric matrix. The content of asbestos in compact ACBMs is generally from 1 to 20 wt.%. Because of the lower content of asbestos and the resistance to release fibres, compact ACBMs should be considered much less hazardous than friable ACBMs.

Chrysotile has been the most used form of asbestos in the past and is the only asbestos mineral used today. Ross et al. (2008) reported that about 95% of asbestos mining commercial activities regard chrysotile. Table 16.2 contains a list of the most common friable and compact ACBMs (Gualtieri 2012). The table is not meant to be comprehensive. Figure 16.6 depicts a few selected examples of ACBMs: a flat tile with about 5–10 wt.% of chrysotile (compact) (a); a gasket made of chrysotile (friable) (b); a fragment of corrugated slate with about 10 wt.% of chrysotile (compact) (c); a fragment of vinyl asbestos floor with about 2 wt.% of chrysotile (compact) (d).

The presence of asbestos in building materials prompts long term exposure of the population to this contaminant and represents a great health concern. The progressive decomposition of ACMs causes the release of airborne fibresand subsequent possible exposure to this hazardous dust (Obmiński 2020). Degradation of these building materials is chiefly due to use damage. For indoor materials, the major deterioration factors are: natural ageing and wear, anthropic action, shrinkage and thermal contraction/expansion. For outdoor materials, the major deterioration factors that lead to the decomposition of the matrix and release of the asbestos fibres are: mechanical and chemical action of atmospheric agents (e.g., acid rains, hailstorms, etc.), mosses and lichens colonization, natural ageing and wear, anthropic action, shrinkage and thermal expansion in areas subjected to high thermal excursion (Obmiński 2020).

Obviously, the nature of the ACBM (friable or compact) plays a key role although it is mainly outdoor products that suffer degradation due to weathering. The mechanism of releasing asbestos fibres from the materials is well described in Spurny (1989) and Obmiński (2020).

Table 16.2 The most common friable and compact asbestos containing building materials (ACBMs)

| Friable (loose) ACBMs	Compact ACBMs
Acoustic panels	Asphalt
Anti-vibration gaiters	Bonding cement and adhesives for floor tiles
Boilers, rope seals on boiler access room and flue	Caulk
Cavities and partitions of floors and ceilings	Ceiling tiles
Ceilings	Chimney flues and tops
Cork boards	Fire refractory bricks and cements
Coverings	Floor tiles
Ducts	Glassbestos
Expansion and compound joints	Guttering and drain pipes
Filled mastics	Insulating blocks and seals
Fire door interiors	Linoleum
Fireproofing blankets, boards and sprays	Masonry filler
Flat/flexible boards	Mastics
Floors	Mortars
Frames of windows and doors	Pipes
Gaskets	Putties
Insulating components of various nature and forms	Roof felt
Joint and patching composites	Roof planar or corrugated cement-asbestos slates
Lagging	Rubber
Panels to lift shafts	Shingles
Pipework	Sidings
Range hoods	Transit wallboards
Roof flashing	Vinyl asbestos and vinyl sheet flooring
Steam pipes	Wall boards, cladding and papers
Textured coatings and paints	Water tanks
Walls	
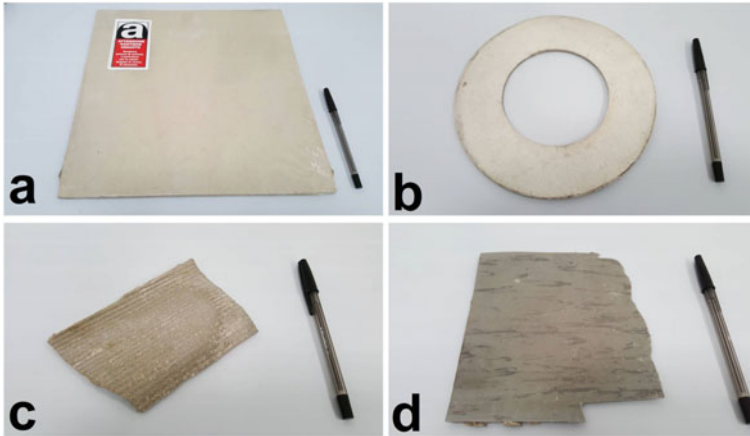
Fig. 16.6 Examples of ACBMs: **a** a flat tile; **b** gasket; **c** fragment of corrugated slate; **d** fragment of vinyl asbestos floor. Original pictures taken by A.F.G (pen included as scale marker)

16.5 The Actual Global Asbestos Issue

To describe the role of asbestos in the actual global market of building materials, one should start from the time when the scientific evidence of the carcinogenicity of asbestos minerals was shared among the global scientific, institutional and social communities. Since the mid-late 80's, following the compelling requests of most of the scientific community, the national associations of the asbestos victims, the health and environment protection groups, the workers' unions and many political forces, a number of countries worldwide (namely European countries) began to limit or ban asbestos in building materials.

In 1983, the European Union (EU) started to deliver issues against asbestos. The European Union Council directive 76/769/EEC (see European Council 1976) has been the framework directive to successfully limit the use of asbestos, through several amendments over the years beginning with the council directive 83/478/EEC (fifth amendment) which puts limitations to the commercialization and use of crocidolite (European Council 1983). A couple of years later, the other five asbestos fibres (i.e., chrysotile and the other four amphibole asbestos species) were banned from certain products such as toys, materials applied by spraying, paints, etc. (85/610/EEC, seventh amendment; see European Council 1985). In 1991, the total ban extended to include amphibole asbestos whereas chrysotile was only partially banned (European Council 1991). Finally, with the 1999/77/ECdirective (European Council 1999), manufacture, marketing and use of asbestos fibres and of products containing them was prohibited by 2005. Nevertheless, ACMs in use before the beginning of 2005 are allowed to remain in use if their degradation level is limited. The regulation indeed reports that "Member States may, for reasons of protection of human health, restrict, prohibit or make subject to specific conditions, the use of such articles before they

are disposed of or reach the end of their service life." In this context, the Italian law banning the extraction and use of asbestos and ACMs (Italian Ministry of Health 1994) includes a paragraph that obliges building owners to notify the local authorities (AUSL = Azienda Unità Sanitaria Locale) if friable asbestos is found on their premises. Furthermore, removal on their own expense may be required if considered necessary by authority. Today the asbestos ban is incorporated in the EC regulation 1907/2006 regarding the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), without further limitations on the use of ACMs installed before 2005 (European Parliament 2006). The United States was the most important world user of asbestos during the major part of the twentieth century (Virta 2006). In 1989, most asbestos-containing materials were banned in a document delivered by the United States Environmental Protection Agency (USEPA). Prior to this act, only some spray-applied surfacing materials and some friable asbestos-containing materials were banned beginning from 1973. However, in 1991, following a decision of the Fifth Circuit Court of Appeals of New Orleans, the 1989 regulation was amended to ban new uses of asbestos and some specific asbestos-containing products (United States Environmental Protection Agency 1994).

Today, raw bulk chrysotile is imported for the fabrication of diaphragms for use in chlorine and sodium hydroxide production, whereas a limited number of chrysotile asbestos containing products are imported for use in chemical, automotive and oil industries. These products are now facing a Toxic Substance Control Act (TSCA) risk evaluation (United States Environmental Protection Agency 2016). Following the final rule issued by USEPA in 2019, any other uses of asbestos that began prior to 1989 and therefore not prohibited by the 1989 partial ban, cannot be commercialized again without USEPA review (United States Environmental Protection Agency 2019). Asbestos-containing building materials are covered by this rule (e.g., roof coatings, cement products, millboard, roofing felt, vinyl-asbestos floor tiles and others).

Although in the last two decades asbestos was subjected to intensive multidisciplinary studies, the causes of toxicity and pathogenicity as well as the relationship between fibres' exposure and the development of respiratory diseases are still unclear. In this scenario, two blocks have risen in the global scenario facing each other with no concession or negotiation (the global chrysotile or asbestos issue): one block considers all the regulated asbestos fibres as toxic and carcinogenic and supports their ban; the other side recognizes that only the five amphibole asbestos species are toxic and carcinogenic while chrysotile is carcinogenic but with a low to null toxicity and low potential for producing mesothelioma (see for example Bernstein et al. 2013; Camus 2001; Liddell et al. 1997; McDonald et al. 1997) if compared to amphibole asbestos. With this assumption, these countries promote the safe ("controlled"; LaDou et al. 2010) use of chrysotile. The chrysotile defence is based upon the assumption that lung diseases due to chrysotile exposure should be attributed to the fact that chrysotile can be contaminated by amphibole asbestos. This "amphibole hypothesis" (Mossman 1993; Stayner et al. 1996) is supported by the biodurability paradigm (Hogson and Darnton 2000; Berman and Crump 2008; Gualtieri et al. 2018a). Chrysotile has a low biodurability (Gualtieri et al. 2018a) and

promptly dissolves in the intracellular macrophage environment (see Sect. 16.3), during phagocytosis, whereas amphiboles are biodurable and are kept in the lungs for decades (Giacobbe et al. 2021; Gualtieri et al. 2018a; Oze and Salt 2010; Bernstein et al. 2008; Hume and Rimstidt 1992). Although the defence of chrysotile based on the "amphibole hypothesis" is rejected by most of the scientific community, there are relatively few epidemiological studies on this issue to systematically compare the effects of the different fibre types and this somehow leaves the issue open to debate (Gualtieri 2017; 2018).

The global chrysotile litigation determines a *status quo* situation with just 67 out of 196 countries (34%) in the world that have banned asbestos whereas a "controlled use" of chrysotile is permitted in the remaining (66%) countries (International Ban Asbestos Secretariat 2021a; Zen et al. 2013). Uncertain contradicting policies result in bizarre outcomes. Above all, the example of China should be addressed: although China is among the countries allowing a "controlled use" of asbestos, the building materials used to build the 2008 Olympic venues were asbestos-free because the Chinese government assumed that some foreign athletes would not participate if they had to eventually get in contact with asbestos (Frank et al. 2014).

In any case, the global situation reveals that the chrysotile asbestos market is active, although the production of asbestos worldwide is markedly decreasing. The 2019 asbestos (chrysotile) trade data (United States Geological Service 2020) shows that the top producing countries (t/year) in decreasing order are: Russian Federation (750,000), Republic of Kazakhstan (200,000), People's Republic of China (125,000), Federative Republic of Brazil (15,000) and Republic of Zimbabwe (2,500), (total world production is 1,100,000 t/year). It should be said that in Brazil there is actually only one producer which temporarily suspended its activity. In Zimbabwe, asbestos is mined from the tailings of mines closed in 2007 (United States Geological Service 2020).

The 2018 asbestos top five users (t/year) in decreasing order are (International Ban Asbestos Secretariat 2021b): Republic of India (308,000), People's Republic of China (288,000), Russian Federation (234,000), Federative Republic of Brazil (120,000), and Republic of Indonesia (114,000).

Besides the uncertainties of the current scientific models, circumventing the global chrysotile issue will not be an easy task due to the political pressure in favour of chrysotile of the world's economy leading countries like India and Russia. In those countries, chrysotile asbestos is a primary strategic raw material whose economic importance prevails over health concern. The case of India is exemplary. India has very limited asbestos mining activity but is one of the top importers of asbestos in the world for the production of building materials with low taxes for asbestos containing products and higher taxes for the corresponding products made with asbestos substitutes (Frank et al. 2014). The situation is getting even more (intentionally) confused as other countries of the leading global economy like the United States adopt contradictory behaviour. As described above, in the United States chrysotile asbestos is not actually banned and, under the mandate of President Trump, the new issues delivered by USEPA have the potential to even increase its utilization in the future and not its conclusive ban (Landrigan and Lemen 2019).

In this scenario, it is not surprising that chrysotile asbestos has not been included so far in the category of hazardous substances concerned by the Rotterdam convention. Consequently, ACBMs are freely distributed worldwide without any labelling. This situation originates enormous problems and eventually international incidents: consider for example that an ACBM produced in a country like China (where chrysotile asbestos is safely used) can be anonymously exported to a country like Italy where import, export, and use of ACBMs are banned since 1992 (Gualtieri 2012).

16.6 Asbestos Reclamation, Disposal and Recycling

Despite the ban of asbestos in the EU, ACBMs are still found in the living environment as current legislations do not necessarily oblige the removal of installations undertaken prior to 2005 (REACH, EC regulation 1907/2006; see European Parliament 2006). As explained in Sect. 16.4, most of those materials may be found in buildings both indoor and outdoor and represent a health concern only if the asbestos fibres become airborne, for example if damaged, friable, or located in places where they are exposed to vibration, movements or air currents. Hence, a risk assessment by certified companies is performed before deciding which actions are needed to be taken. This is done by examining the conditions of the material, environmental factors that could determine fibre release and eventually also by measuring the fibre concentration in the indoor air (Italian Ministry of Health 1994). Workers performing demolition, maintenance and refurbishing activities have the highest risk of being exposed to airborne fibres. Hence, these actions are regulated by laws assuring that necessary measures are taken to avoid exposure for both workers and the population. The 2009/148/EC directive is the roadmap for the European Union to protect workers against asbestos exposure exceeding 0.1 fibres/cm^3 on 8h long exposure time, the only activity allowed being treatment and disposal of asbestos (European Parliament 2009). Whenever workers are or may be exposed to asbestos fibres, the employer is obliged to guarantee that the exposure limit is not exceeded through risk assessment, safe work practice, protective equipment, training, etc. The employer is also required to provide a work plan to the local health/environment authority. In Italy, companies authorized to the disposal and reclamation of sites contaminated by asbestos must be listed in a national register and report their activities to the local authority "Azienda Unità Sanitaria Locale", AUSL (see Italian Law n. 257 1992).

Regulations and technical methodologies for the reclamation of ACBMs foresee the following reclamation methods (the choice of method being determined by the nature of the material, the state of preservation as well as environmental factors) (Italian Ministry of Health 1994, 1999);

Encapsulation: This method prevents the dispersion of fibres into the environment by spraying specially designed products that either isolates the material from the environment by forming a protective coating or fixes the fibres to the matrix by penetrating into the pores of the material. Although being economical and fast, this

method requires periodical controls and maintenance of the encapsulation to assure its integrity over time.

Isolation: This method is mainly used to reclaim cement-asbestos roofs in relatively good conditions and consists of placing a new lightweight metal cover over the asbestos-cement slates. Before proceeding with the new coverage, the slates are subjected to preventive encapsulation. As for encapsulation, periodical controls and maintenance are required.

Removal: This method becomes mandatory when the ACBM is very deteriorated and the risk of release of fibres into the surrounding environment is high. Prior to removal, the ACBM is encapsulated in order to limit fibre dispersion during handling. Any dust that is formed during these operations must be aspirated. Although being a final solution, the produced hazardous waste must be dealt with.

During the reclamation activity, employers are invariably obliged to provide the workers with protective clothing including gloves and shoes. Respiratory protection must also be used and the choice of device depends on the degree of air pollution (Italian Ministry of Health 1994, 1999). Suitable preparation of the working place is particularly important for indoor reclamation sites (Italian Ministry of Health 1994, 1999). Firstly, all movable items must be removed whereas those that cannot be moved should be sealed by plastic wrapping and adhesive tape including, window- and door-frames, sockets, radiators, etc. Filters in ventilation, heating and air conditioning systems must be removed and treated as asbestos-containing waste. Floors and walls must also be covered by polyethylene sheets and a temporary power supply system should be installed. An air extraction system equipped with efficient filters must be installed so that a negative pressure is kept inside the reclamation area with respect to the surroundings. This system has the dual advantage of avoiding fibre leakage and reducing the concentration of asbestos fibres inside the work area.

According to Regulation (EC) 1272/2008 (see European Parliament 2008a), asbestos is classified as a carcinogenic substance (see Sect. 16.3) with hazard statement codes H350 and H372 (i.e., may cause cancer and damage to organs, respectively). The 2008/98/EC directive, ruling the waste management in general (defining terms and basic management codes), states that a waste containing more or equal to 0.1% of a category 1A carcinogenic substance with hazard statement code H350 must be classified as carcinogenic waste with hazardous property HP7 (European Parliament 2008b). As a consequence of the waste directive, all of the asbestos-containing wastes listed in the European waste catalogue (delivered as Commission issue2000/532/EC and modified in 2014 by the 2014/955/UE issue) are classified as hazardous (European Commission 2014). Waste producers and handlers in the member states must refer to a six-digit code, the first two ones identifying the source generating the waste, when producing documentation required under waste legislations. ACMs from buildings are identified by the codes 17.01.05* (asbestos containing materials) or 17.06.01* (asbestos containing materials for insulation). It should also be mentioned that asbestos-contaminated materials produced during reclamation is identified by the code 15.02.02* (asbestos contaminated absorbents, filters, protective clothing and more). Paglietti et al. (2016) recently analysed the European laws on the management of wastes underlined the importance of correct

classification of asbestos-containing waste in order to protect workers involved in waste handling and guarantee disposal in landfills of suitable category according to current regulations (1999/31/EC; 2003/33/EC) (Paglietti et al. 2016).

ACMs are today disposed of in controlled landfills even though viable technical solutions exist that transform the hazardous fibres into harmless compounds (Plescia et al. 2003; Paolini et al. 2019; Gualtieri, 2013). The landfill option is certainly in conflict with the EU directives (European Parliament 2008b) that lists a priority order for the waste management: (1) prevention; (2) preparing for reuse; (3) recycling; (4) different recovery plans; (5) disposal. In addition, the following statements can be found in the 2012/2065 (INI) document of the European Parliament: "delivering asbestos waste to landfills would not appear to be the safest way of definitively eliminating the release of asbestos fibres into the environment (particularly into air and groundwater) and therefore it would be far preferable to opt for asbestos inertisation plants"; "whereas creating landfills for asbestos waste is only a temporary solution to the problem, which in this way is left to be dealt with by future generations, as asbestos fibres are virtually indestructible over time" (European Parliament 2013). It is thus rather clear that the European waste management policy regarding ACMs is navigating towards recycling rather than disposal.

The 2008/98/EC directive reports the novel term "*end-of-waste*" that, under certain conditions, indicates how and when a waste ceases to be so and becomes a secondary raw material following a proper well-defined conversion process (European Parliament 2008b). However, every state of the European community may independently establish objective criteria to assess when a waste ceases to be so (article 6(4)). Since 2004, the crystal-chemical conversion process of ACMs through chemical, mechanical or thermal conversion and recycling of the product of transformation has been legalized (Italian Ministry of Environment and Protection of Land 2004).

There has been an intense research activity regarding the ACMs inertisation processes and possible recycling options of the transformation product in Europe under the last two decades. Developed processes for the total destruction of the crystal-chemical structure of asbestos can roughly be divided into three groups: thermal; chemical and mechano-chemical (Plescia et al. 2003; Paolini et al. 2019; Gualtieri 2013). Thermal treatment processes can either bring on melting of the entire system, i.e., *vitrification* or result in recrystallization of the hazardous fibres in harmless phases, i.e., *ceramization.* The lower energy consumption in ceramization processes render them economically more competitive. In some processes, vitrification is followed by a controlled recrystallization that leads to the formation of a glass–ceramic. Other ones modify the reaction path and the final properties of the product through the addition of other inorganic materials such as clay and fly ash. Chemical methods utilize chemical agents, usually strongly alkaline ones, to destroy the asbestos fibres. The various methods using mechanical action to completely convert asbestos minerals into non-hazardous material belong to mechano-chemical processes.

The by far most studied method is thermal treatment and a couple of solutions have actually been launched on an industrial scale (Gualtieri 2013; Tomassetti et al.

2020). The development of many of these processes has been coupled with research on possible recycling opportunities in the building sector, such as partial replacement of Portland cement and aluminosilicate raw materials in concretes and geopolymers, respectively; flux in ceramic tile production (Gualtieri 2013) and frits to manufacture stoneware slabs (Ligabue et al. 2020). Nevertheless, existing designs of treatment facilities have not yet been able to compete with landfill options even in a country like Italy where such solutions are allowed by current legislation.

16.7   Substitutes of Asbestos in Building Materials

With the introduction of asbestos bans in numerous countries over 30 years ago, continuous progress has been made in the development of asbestos substitutes. The most common asbestos substitute materials are basically grouped into two macro-categories: man-made and natural fibres (Table 16.3; Gualtieri 2012). Man-made fibres can be classified as organic (e.g., carbon, cellulose, polyolefins, polyester and polyvinyl) or inorganic. The latter are divided into two classes: *man-made mineral fibres* (MMMF) and *man-made vitreous fibres* (MMVF). The family of natural fibres include natural inorganic fibres (e.g., erionite, sepiolite, wollastonite), and natural organic fibres (e.g., cotton, wool, hemp). The fibrous variety of erionite is deemed to have even greater toxicological and pathogenic properties than asbestos and is known to be a potent human carcinogen causing the MM epidemics that affected some villages in Cappadocia (Turkey), where it was used as a building material (Dogan 2003; Carbone et al. 2007). Cases of MM related to erionite exposure have been reported for Mexico and the United States (Carbone et al. 2019). For this reason, fibrous erionite has recently been included in Group 1 as carcinogen for humans (International Agency for Research on Cancer 2012).

Man-made organic fibres are industrially produced by high-temperature processing of monomeric organic compounds, such as polyalkylene, polyester, polyamides, cellulose, and carbon (Singh and Wagner 2011). These materials are widely utilized as a substitute for asbestos to improve various technological properties like mechanical strength to the bulk materials (Gualtieri 2012).

Nowadays, MMVF are the most common asbestos substitutes in the global market (Gualtieri 2012). MMVF include amorphous silicate-based glass fibres, refractory ceramic fibres (RCF), rock-wool and many more (Table 16.3). These materials are composed of SiO_2, CaO, Na_2O, K_2O, MgO and Al_2O_3 (Singh and Wagner 2011). Glass wool is manufactured starting from sand, soda-ash, limestone and recycled glass; rock wool is produced by melting a mixture of various slags and basaltic rocks; slag wool is obtained from iron or copper production waste derived from the metallurgical industry; RCF is produced by melting a mixture of kaolin clay, alumina and silica (International Agency for Research on Cancer 2002). The European 67/548/EEC directive classifies MMVFs on the basis of their chemical composition. The main uses of MMVFs are in commercial and residential thermal and acoustic insulation, e.g., wall, roof, floor and pipe insulation (Gualtieri et al. 2009),

Table 16.3 General classification of asbestos substitute materials (adapted from Gualtieri 2012; Park 2018)

Fibres type	IARC classification
MAN-MADE FIBRES	
Organic	
Carbon fibres	–
Cellulose fibres	–
p-aramid	Group 3
Polyalkylene fibres	–
Polyester	–
Polyvinyl alcohol (PVA)	Group 3
Polyvinyl chloride (PVC)	Group 3
Inorganic	
Man-made mineral fibres (MMMF)	
PCW	Group 2B
SiC whiskers	Group 2A
SiN whiskers	–
Man-made vitreous fibres (MMVF)	
Glass wool	Group 2B
Refractory ceramic fibres	Group 2B
Rock wool	Group 2B
Slag wool	Group 2B
NATURAL FIBRES	
Inorganic (Minerals)	
Attapulgite, fibre length >5 μm	Group 2B
Attapulgite, fibre length <5 μm	Group 3
Erionite	Group 1
Sepiolite	Group 3
Wollastonite	Group 3
Organic (Vegetable, Animal)	
Cotton	–
Flax	–
Jute	–
Hemp	–
Sisal	–
Silky	–
Tendinous	–
Wool	–

but also as reinforcing material of vehicles and appliances (International Agency for Research on Cancer 2002).

The MMMF category includes several polycrystalline fibres such as PCW (poly-crystalline wools), SiC (silicon carbide) whiskers and SiN (silicon nitride) whiskers (Table 16.3). They mainly consist of silicates and mineral oxides manufactured from molten material by spinning/blowing or by sol–gel mediated synthesis (Harrison et al. 2015). Due to their excellent heat resistance, these fibres are extensively used in high-temperature applications (e.g., fire protection, furnace coatings) (Harrison et al. 2015). For example, PCW and SiC whiskers resist temperatures up to 1300 °C and 2000 °C, respectively. Moreover, SiC whiskers have mechanical strengths useful for the aerospace industry (Usukawa 2018), while PCW can be used in chemically aggressive industrial processes (Brown and Harrison 2014).

The IARC has evaluated several asbestos substitutes (Park, 2018; Table 16.3): Attapulgite fibres >5 μm are included in Group 2B (i.e., possibly carcinogenic to humans) whereas shorter attapulgite fibres (<5 μm) are classified as Group 3 (not classified as far as carcinogenicity in humans is concerned) together with sepiolite and wollastonite (International Agency for Research on Cancer 1997). Furthermore, also organic man-made fibres, such as carbon, cellulose, polyester, rayon, polyvinyl alcohol (PVA) and *p*-aramid, have raised concern about their safety for human health (International Agency for Research on Cancer 1997; Cullen et al. 2002; Inthavong et al. 2013; Singh and Bhalla 2017). According to IARC, PVA and *p*-aramid fibres are less respirable than chrysotile but more biopersistent (Gualtieri, 2012). Despite the fact that p-aramid fibres are classified in Group 3 (International Agency for Research on Cancer 1997), studies conducted by Friendmann et al. (1990) show that these fibres cause adverse pulmonary effects (Gualtieri 2012). As regards the MMVF category, RCF and glass/rock/slag wool are included in Group 2B (Park 2018). Although the evidence of carcinogenicity of RCF is limited, in vivo tests have shown that exposure to these fibres is linked to the onset of lung cancer and MM (Park 2018). Consequently, RCF is classified into Group 2B (IARC 2002). Literature data demonstrated the carcinogenicity of MMMF using in vivo animal models (Singh and Wagner 2011). In particular, PCW are classified as ceramic fibres and hence possible human carcinogens (Group 2B) by IARC in (1988) (Cannizzaro et al. 2019). According to IARC, SiC whiskers induce bio-chemical adverse effects similar to those observed for asbestos wherefore they are included in Group 2A as probably carcinogenic to humans (International Agency for Research on Cancer 2014).

Health risks can also arise from exposure to asbestos-contaminated natural raw materials utilized in building materials (International Agency for Research on Cancer 2012). Noteworthy in this regard are the health problems experienced by the employees of the vermiculite plant in Libby, Montana, United States, where about 5.8 Mt of raw vermiculite containing fibrous amphiboles were extracted and processed between 1924 and 1990 (Horton et al. 2008; Larson et al. 2010). A cohort study of workers exposed to Libby's vermiculite revealed excess lung cancer and asbestosis morbidity compared to the mean mortality in Montana and the United States (Larson et al. 2010). Since then, asbestos fibres have been identified in several raw materials

considered as non-hazardous such as talc (Dyer 2019; Tran et al. 2019) and feldspar (Gualtieri et al. 2018b). In this context, the first case of a commercial product of brucite contaminated with chrysotile asbestos was recently documented by our group. This particular sample was imported to Italy from China in 2018 and destined for the glass and ceramic industries. Thanks to an established analytical protocol (Gualtieri et al. 2018b), a significant amount of respirable chrysotile fibres was detected. The results imply that commercial raw brucite currently marketed should be checked for the presence of asbestos to avoid situations similar to those of commercial talc and feldspar. The case of asbestos-contaminated brucite from China is one example of problems created by different asbestos regulations in trading partner countries (see Sect. 16.5).

16.8   Conclusions

In this chapter the following topics were presented:

- classification and definitions of asbestos minerals;
- application of commercial asbestos in building materials;
- toxicity and pathogenicity mechanisms of asbestos with a view on the global asbestos issue;
- past and current uses of asbestos in building materials;
- potential exposure to asbestos during, e.g., restoration and remediation of old buildings;
- current regulations regarding restoration and remediation of buildings containing asbestos, including waste management and recycling;
- substitutes of asbestos in building materials.

The classification and, sometimes conflicting, definitions of asbestos minerals have been revised and updated with respect to the existing literature. The issues raised by the absence of an universally shared definition of asbestos have been highlighted.

Regarding the applications of asbestos in building materials, it was evidenced that the extensive use of asbestos at an industrial scale started in the twentieth century, and prompted the manufacture of more than 3000 different asbestos-containing materials. The largest economic impact has been, and continues to be in some part of the world, the fibre-reinforced cement industry. Nevertheless, a clear decreasing trend is observed in the global use of asbestos even in countries like China and Brazil where the production and consumption of these fibres are among the highest in the world. Considering the development of asbestos policies in countries like Italy where, e.g., chrysotile was mined, processed and consumed, the global decreasing trend is expected to be decisive for future bans. Unfortunately, the ceased use of these toxic materials will not put an immediate end on human exposure.

Potential occupational and non-occupational exposure to asbestos has been illustrated. If looking at the European countries where the extraction and use of asbestos

fibres are banned since a couple of decades, ACBM are still found in the living environment mainly due to their long service-life and the lack of firm legislation that forces building owners to remediate contaminated sites.

The chapter also revised the current regulations regarding the restoration and remediation of old buildings containing asbestos with a special attention to the problem of waste management and recycling that should be universally followed. An immediate solution to the asbestos-problem would include more restrictive legislations on remediation coupled with the adoption of existing technologies capable of transforming ACBM into non-hazardous compounds that may eventually be re-entered in the construction sector as secondary raw material.

The classification of synthetic fibres, in particular for use in building materials made of fibre-reinforced cement has been revised. It is clear that the availability of asbestos-substitutes is decisive for the decreased reliance of asbestos.

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