Shifting towards a temporary storage of asbestos-cement combined with innovative treatment techniques within a sustainable, circular economy, following the concept of Enhanced Landfill Mining

Luk Aerts, Jana De Cuyper, Astrid De Man; Ecorem, Belgium
Sven De Mulder, Anne Adriaens; OVAM, Belgium
Luk.Aerts@abo-group.eu, Jana.DeCuyper@abo-group.eu, Astrid.DeMan@abo-group.eu, sdmulder@ovam.be, aadriaen@ovam.be

Abstract

Asbestos are naturally occurring fibrous minerals with specific features that led to its wide-spread use until medical research showed that they cause severe medical consequences. This resulted in the implementation of more strict regulations. In Flanders, it became mandatory to double-bag non-friable asbestos, label and dispose it, while friable asbestos has to be cemented before disposal. With this technique, the asbestos is treated and 'permanently' landfilled' which is neither the safest nor the most sustainable method so the necessity for research on a more innovative treatment is evident. As an intermediary step the asbestos can be landfilled in 'temporary storage facilities' so it can be treated once the necessary techniques are developed and more suitable regulations are in place. Besides temporary storage, also the asbestos already stored in mono landfills can be subject to treatment. The use of Enhanced Landfill Mining (ELFM) for asbestos materials currently is subject of research in Flanders.

Introduction

Asbestos is the generic term for a group of six naturally occurring, fibrous silicate minerals [1]. These six minerals are grouped together in two classes: the amphibole and the serpentine class. Of both types, also non-fibrous/non-asbestiform forms exist. The asbestiform of serpentine and amphibole is characterized by fibres that are defined by the US ATDSR (= Agency for Toxic Substances and Disease Registry: Agency of the US Department of Health and Human Services) and the EU directives as particles of asbestos minerals that have a length of >5µm and a length-width ratio of >3:1. The difference between the serpentine and amphibole type of asbestos is the polymeric structure of these fibres. On the one hand, for the amphibole-type asbestos, the polymeric structure is a linear double chain made up by basic silicate units (SiO_4^{-4}; Figure 1). These double chains make for long, thin and straight fibres which are the characteristic structure of this class of asbestos. Five types of asbestiform amphiboles can be distinguished: amosite, tremolite, actinolite, anthopyllite and crocidolite. Specifications of these five minerals can be found in Table 1.

Table 1: List of common synonyms and chemical formulas for the six individual asbestos minerals [1]

Asbestos Type	Synonyms	Chemical Formula
<u>Amphibole Group</u>		
Amosite	• Brown asbestos • Fibrous cummingtonite / grunerite • Mysorite	$(Fe^{2+})_2)(Fe^{2+},Mg)_5Si_8O_{22}(OH)_2$
Tremolite*	• Silicic acid • Calcium magnesium salt (8:4)	$Ca_2(Mg_5)Si_8O_{22}(OH)_2$
Actinolite*	/	$Ca_2(Mg,Fe^{2+})_5Si_8O_{22}(OH)_2$
Anthophyllite	• Ferroanthophyllite • Azbolen asbestos	$Mg_7Si_8O_{22}(OH)_2$
Crocidolite	• Blue asbestos • Riebeckite	$Na_2(Fe^{2+}, Mg)_3Fe^{3+}Si_8O_{22}(OH)_2$
<u>Serpentine Group</u>		
Chrysotile	• White asbestos	$Mg_3Si_2O_5(OH)_4$

Secondly there is the serpentine class which contains one asbestiform mineral, namely chrysotile (Table 1). For the serpentine class, the polymeric form is an extended sheet, also made up by basis silicate units (SiO_4^{-4}; Figure 1)). This extended sheet tends to wrap around itself and as such forming a tubular fibre structure. Typically, chrysotile fibres are long fibres that are often curved, in contrast with amphibole-type of asbestos minerals. Other typical differences between these two classes of asbestos minerals are:

- Amphibole-type asbestos have a greater hardness that serpentine-type asbestos
- Amphibole-type asbestos has smooth fibres
- Amphibole-type asbestos are relatively rigid
- The fibres of amphibole-type asbestos are thicker and have a more pronounced needle-structure than those of serpentine-type asbestos
- The fibres of amphibole-type asbestos are more brittle than those of serpentine-type asbestos

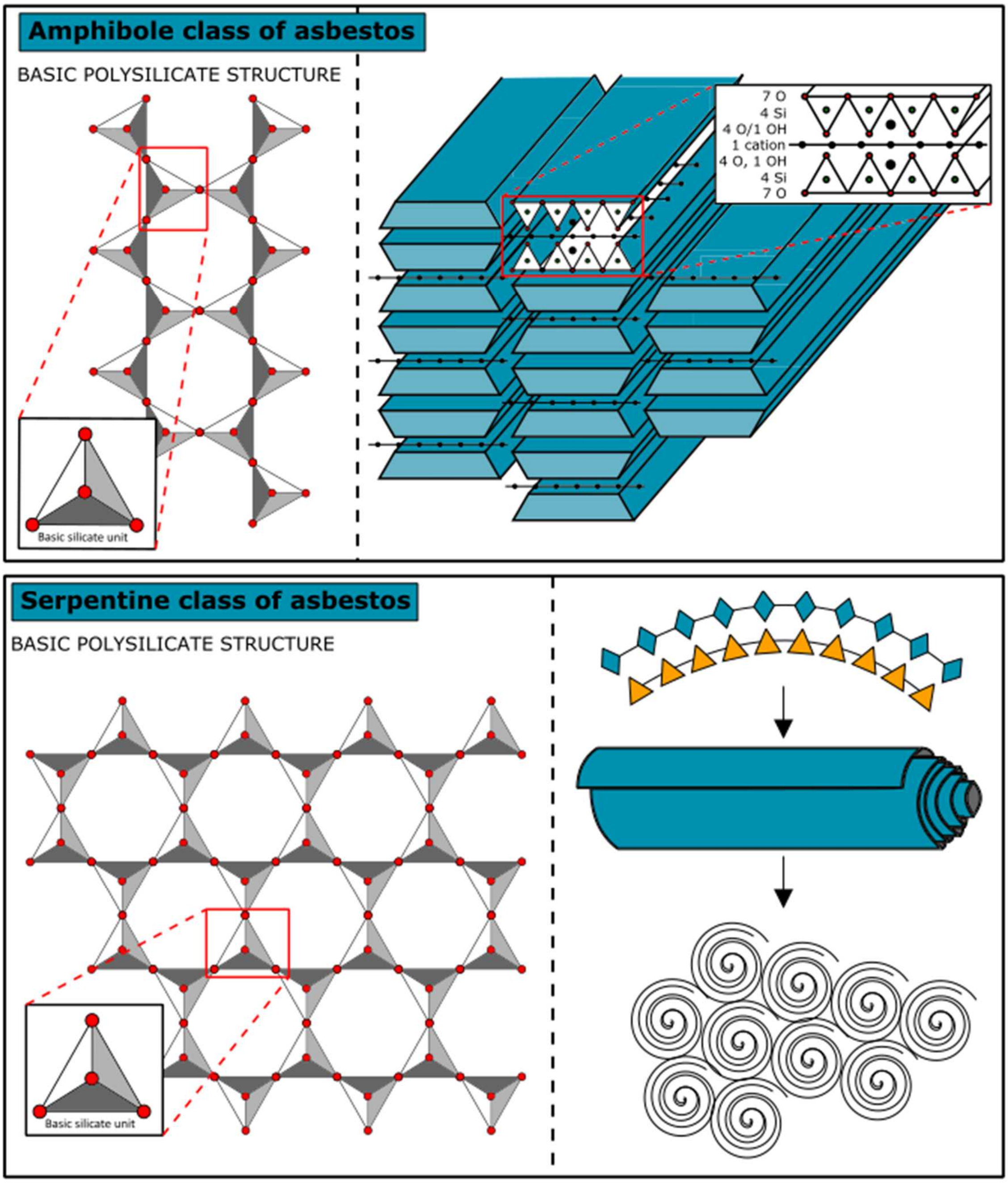

Figure 1: Structure of amphibole (top) and serpentine (bottom) class of asbestos (adapted from Hurlburt & Klein, 1977 [2])

These fibrous minerals have been widely used in various commercial products and processes in the past [3]. This commercial usage is due to the fact that this group of minerals have specific properties such as, for example, high tensile strength, flexibility, heat resistance and they are chemically inert (or nearly so), which means that they do not evaporate, dissolve, burn or undergo significant reactions with most chemicals. This made them the ideal components in many manufactured products and industrial processes. Common commercial products are e.g. plaster, roofing, fire proofing, thermal (pipe) insulation, chemical insulation, asbestos cement, etc.

However, this abundant usage of asbestos (gradually) came to an end when concerns arose based on studies involving employees that work in asbestos related industries [4], [5], [6]. These studies were focused on workers that were exposed to all six forms of asbestos minerals. These initial concerns have since then been confirmed by additional studies, which proved that there is a link between certain diseases and asbestos exposure. At present, the main known illnesses to be caused by airborne asbestos are asbestosis, mesothelioma and lung cancer. While scientists agree that these diseases are the result of the exposure to the typical fibre structure that is characteristic for the asbestiform minerals, no general consensus has been reached (as of yet) by the medical community regarding the exact mechanism(s) by which these diseases are caused.

As a result of these medical discoveries, stricter regulations concerning asbestos were being implemented, which resulted in an overall ban on the production, usage, launching and selling of asbestos of asbestos containing materials in various countries. In Belgium this ban came about gradually, starting with a restriction on the use of certain asbestos materials (e.g. sprayed asbestos) from the end of the 1970s. The Royal Decree of 1998 forbidding a very large number of asbestos applications, was eventually replaced by the Royal Decree of October 23, 2001. This Decree imposed an overall ban on asbestos, starting from 1/1/2002, with the exception of chrysotile which was allowed in certain specific applications until 1/1/2005.

When going from a society where asbestos is used in various commercial applications to one where asbestos is considered to be dangerous and where, as a result, an overall ban on the production, usage, launching and selling of asbestos and asbestos containing materials (ACM) is put in place, a lot of new challenges arise for which solutions have to be prepared. In Flanders, more strict regulations were put in place regarding the environmental protection (VLAREM), waste management (VLAREMA) and soil protection and remediation (VLAREBO) in order to comply with the new rules with respect to asbestos. In other words, asbestos and/or asbestos containing materials/wastes need to be disposed of under stricter disposal conditions. Furthermore, on the 24th of October 2014, the Flemish Government gave their consent on the implementation of an accelerated phasing-out policy in order to achieve an asbestos-safe Flanders by 2040. The study phase prior to this decision consisted of four aspects:

- Research on the exemption and dispersion of eroded asbestos-containing roofing and wall cladding.
- An inventory study of asbestos-containing materials in Flanders
- Market- and stakeholder consultation with on the one hand the policymakers, enforcers, local governments, etc. and on the other hand, sectors such as education, agriculture, private, etc.
- Exploratory feasibility study and cost-benefit analyses

The Public Waste Agency of Flanders (OVAM) got the assignment to submit, a final phasing-out strategy by 2018 in the form of a roadmap to achieve an asbestos-safe Flanders by 2040. The inventory study estimated that in Flanders, next to the ACW (ACW: Asbestos Containing Waste) that has already been landfilled, there is still 3.7 million tons of asbestos and ACMs (ACMs: Asbestos Containing Materials) present in and around buildings (~1.9 million tons) and in pipelines (~1.8 million tons).

As a result of the established goal, the remaining asbestos and asbestos containing materials will have to be removed during the following years, giving increased amounts of asbestos containing waste (ACW) that will need to be disposed of under more strict regulations mentioned above.

In Flanders, a distinction is made between friable and non-friable asbestos with regard to the manner in which they need to be disposed of. This distinction is given in Table 2.

Table 2: Differences between friable and non-friable asbestos [7]

	Definition	Examples	Manner of Disposal
Friable asbestos	Can be crumbled, pulverized or reduced to powder under hand pressure	Spray-applied insulation (on walls and ceilings), blown-in insulation, fireproofing materials, pipe insulation	1. Double-bagging, 2. Labelling 3. Landfill
Non-friable asbestos	Cannot be pulverized under hand pressure	Asbestos cement	1. Treatment to avoid distribution of fibres 2. Double-bagging 3. Labelling 4. Landfill

The treatment technique for friable ACW in Flanders is immobilisation by cementation. In short, this implies that the ACW gets crushed and mixed with cement and other additives resulting in 1m³ blocks in which the asbestos fibres are captured. Although this technique is relatively easy, it results in a considerable increase in volume and the resulting blocks still have to be landfilled. As such, the problem is not eliminated but merely postponed to future generations. This is not in line with the objectives of the asbestos policy in Flanders, in particular realizing a circular economy. With the current method of immobilisation, the asbestos is treated and 'permanently' landfilled. In other words, the need for disposal space, linked with the current method for treating ACW, is conflicting with the idea of sustainable land use. Furthermore, the European Parliament stated that the storage of asbestos is no longer considered to be the safest method to prevent the release of fibres. Hence, the necessity of the development of more innovative treatment methods is evident and this is the case in many countries who also have the ambition of being free of asbestos in the near future. As a direct result, several countries are investing in research to develop alternative treatment methods that, instead of immobilizing the fibre structure, completely destroy it and that enable the re-use as secondary materials so landfilling is no longer necessary.

In this article, an overview will be given of the current policy and treatment of asbestos containing waste in Flanders, the problems that are linked with it and possible solutions to this problems. Not only with regard to new innovative treatment methods but also regarding Enhanced Landfill Mining, aiming to find a technique that transfers the asbestos fibres to a new, safe and stable material that can be used for several applications. The asbestos that has been deposited in safe temporary storage compartments, can eventually be treated by this innovative technology.

Current policy and treatment of Asbestos Containing Waste in Flanders

Short overview of the asbestos policy in Belgium and Flanders

In Belgium, the use of certain asbestos materials became gradually restricted from the end of the 1970s. The use of sprayed asbestos for example, has been banned in Belgium since 01/01/1980. After several intermediary steps (e.g. statement of 28/08/1986: if technically possible, asbestos should be replaced by materials that are less hazardous for the human health), the Royal Decree of 03/02/1998 eventually passed, forbidding a very large number of asbestos applications. This Royal Decree was replaced by the Decree of October 23, 2001, imposing an overall ban on asbestos starting from 01/01/2002. This included the ban on the production, usage, launching and selling of asbestos of asbestos containing materials. The one exception was the use of chrysotile, which was allowed for specific industrial applications until 01/01/2005. This Decree addressing the overall ban on asbestos was quickly followed by the Royal Decree of 03/01/2006, which states that all employees must be protected against the risks associated with the exposure to asbestos. Furthermore, all employees that have become ill due to asbestos exposure have the right to claim a compensation paid by the 'Asbestfonds' (Asbestos Fund) which is part of the fund of occupational diseases. Currently, it can be concluded that the federal legislation of Belgium regarding asbestos is mainly focused on the protection of the employees and can be found in the Codex 'Welzijn op het Werk' and in ARAB ('Algemeen Reglement voor de Arbeidsbescherming'). An overview of the evolution of the asbestos policy in Belgium is given in Table 3.

Table 3: Evolution of asbestos policy in Belgium

Reference	**Regulation**
End of the 1970s: RD(*): 15/09/1978	Use of certain asbestos materials started to get banned
RD: 28/08/1986	If technically possible, asbestos should be replaced by materials less hazardous for human health

MD(**): 22/12/1993	Companies are obligated to establish an asbestos inventory containing following information: - What types of asbestos-products are present - What is the condition of these products - Which measures are taken to prevent the exposure of employees to these products
RE: 03/02/1998	Prohibition on the use of a very large number of asbestos applications
RD: 23/10/2001	Decree, replacing RD 03/02/1998: Overall ban on production, usage, launching and selling of most types of asbestos or ACMs
01/01/2005 (Extension RD 23/10/2001	Chrysotile is inserted in the Decree of 23/10/2001
RD: 03/01/2006	Protection of employees against the risks of exposure to asbestos
RD: 28/03/2007	Regulating the recognition and certification of specialized and recognized companies for asbestos removal

(*RD = Royal Decree; **MD = Ministerial Decree)

Stabilisation processes

As stated above, the current policy in Flanders since 1986, is that all the ACW is landfilled according to the conditions determined by VLAREM and that there is a different plan of action for friable and non-friable asbestos. Where non-friable asbestos in theory does not form a threat with regard to the emission of harmful asbestos-fibres and therefore does not need more treatment than double-bagging and labelling before landfilling, friable asbestos does, i.e. the process of cementation [8],[9].

Cementation is a stabilisation process. This process reduces the hazard of non-friable asbestos/ACW by imprisoning the fibres in a cement or resinoid matrix. Stabilisation by encapsulation of the asbestos in a cement matrix, as is done for the non-friable asbestos in Flanders, is a relative simple way to immobilize the unbound asbestos fibres and thus removing the direct threat.

In practice, the asbestos is delivered to the treatment facility in containers which contain bags of asbestos. These bags are opened and distributed manually on a belt conveyor. Metal and plastic parts are sorted out of the asbestos manually. A magnetic belt will remove the remaining metal. After this, the waste is transported to a first crusher. After this first crusher, the waste is transported to two other crushers to reduce the size of the waste to maximum 1 cm^3. After this, the in size reduced waste is often stored in a storage bunker. From the storage bunker, the waste is transported to a mixing unit where the asbestos is mixed with cement and other additives and distributed in volumes of 1 m^3. After a certain period of time, these volumes have dried and the end-product of the treatment are blocks of 1 m^3, which are ready to be landfilled. Additionally, it is often required that these blocks of cement with bonded asbestos are double bagged or double wrapped in plastic bags or big bags, taped and provided with a clear indication of the content of the bags before it is landfilled, which is in agreement with the treatment method used for non-friable asbestos.

Although these techniques are relatively simple, the technique of encasement in cement, as implemented at industrial scale in Flanders, does not eliminate the characteristics of the asbestos fibre since these fibres are still present, albeit in a non-breathable form. As such it merely dilutes and delays the problem. Another downside to this technique is that it does not result in a re-usable end-product. The only place the blocks of asbestos-cement can be used, is in the landfills themselves for various infrastructure-related needs. At the same time, this method increases both the volume and the mass (+150%) of the materials that need to be dumped. Furthermore, not many enterprises in Flanders have the technical know-how and the environmental licenses to carry out this treatment method.

In general, it can be concluded that although this stabilisation process eliminates the direct danger linked with friable asbestos, it does not offer a permanent solution for the asbestos problem. In addition, the technique requires a lot of space. This means that it adds to the already existing asbestos cement that is still present in Flanders and as such does not offer a solution for the increasing shortage of available space in Flanders. In other words, the need for disposal space linked with the current method for treating ACW, is conflicting with the idea of sustainable land use.

Research into new treatment methods

Several countries all over the world are doing extensive research for alternative methods for the treatment of asbestos and ACW. These countries are investing in research to develop more sustainable treatment methods that destroy the fibre structure of asbestos, enabling its re-use as a secondary material so they don't have to be landfilled anymore. This research, in some cases, has already led to small- or large scale pilot installations or even full-scale operational treatment-plants.

Next to the stabilisation processes that are described above, there are the crystallo-chemical processes. Instead of reducing the threat by immobilizing the fibres, this type of treatment methods eliminate the threat by modifying the fibrous structure of asbestos and thus transforming it into an inert substance [9], [10]. These are the processes that are the subject of the research for alternative methods since they provide a more permanent solution for the asbestos problem.

Crystallo-chemical processes

An overview of different types of crystallo-chemical methods are given in Table 4 (non-exclusive), together with the main principle behind the technique and the final destination of the end-product.

Table 4: Overview of the different crystallo-chemical processes (based on Plescia et al., 2003 [10])

Treatment	**Principle**	**Final destination**
Vitrification	Melting with plasma torch or standard furnace	Landfill, inert for buildings and roadways
Ceramitisation	Melting with standard furnace, with or without additives	Landfill, inert for buildings and roadways, tiles and other ceramic applications
Pyrolysis furnace	Melting in furnace to produce expanded clay	Building industry
Chemical attack	Dissolution in acid or bases	Landfill
Mechanochemical attack	Structural destruction by mechanical energy	Inert additives for cement, catalyst
Denaturation	Heating to 1000°C for destruction of fibre structure	Secondary material in several industries

Crystallo-chemical processes are based on mechanical, chemical or thermal principles. A combination of these principles within one method is also often used. Most investigations focus on thermal techniques. These thermal processes, together with the chemical and combination methods, are shortly described below.

1. *Thermal processes:*

Thermal processes are processes that alter the fibre structure of asbestos by means of elevated temperatures. Two parameters that are of importance with these treatment methods are time and temperature.

The temperature range used by certain techniques depends on what the specific goal of this technique is and how is has to be achieved. Some methods for example, use the process of vitrification and need very high temperatures due to the high glass transition temperatures. Other techniques aim at altering the asbestos fibre structure rather than vitrifying it, by eliminating the OH-group which also requires high temperatures but lower than the process of vitrification. Furthermore, the range of decomposition temperature for each asbestos-type varies (no data on actinolite) [11]:

- $T_{decomposition}$(chrysotile) = 800-850°C
- $T_{decomposition}$(crocidolite) = 400-900°C
- $T_{decomposition}$(tremolite) = 1.040°C
- $T_{decomposition}$(amosite) = 600-900°C
- $T_{decomposition}$(anthophylite) = 950°C

With this in mind, some companies target specific asbestos minerals with their treatment methods to keep the temperature, and as such the cost, low, while other companies target all asbestos minerals, using the upper temperature limit to ensure total destruction of all asbestos-types.

The second, important parameter is the residence time of the asbestos. This is the time during which the asbestos has to be treated in order to ensure complete destruction of the asbestos fibres. Within the different thermal techniques, this parameter can vary from minutes to several hours or even days.

Examples of methods based on this principle of temperature and time are:

- Vitrification [12], which is a transformation of a substance into glass. When used on asbestos or asbestos containing waste, it can serve as an alternative to immobilisation in a cement matrix. During this treatment, the material is heated to extreme temperatures (~1.100-1.600°C). At these temperatures, it is possible to completely destroy the hazardous fibre structure, transforming it into an inert, vitrified end-product that can be re-used. This can be achieved in different ways, e.g. by using a plasma gun, a conventional oven or an electrical furnace. Several of the vitrification methods have been patented, leading to specific processes for different companies. In France, a full-scale installation is in operation, using the plasma-torch vitrification process.
- Denaturation, which is a process where asbestos is heated to a temperature of approximately 1.000°C, after which the hazardous fibre structure is altered in a non-hazardous structure by removal of the OH-groups. This process of denaturation is well-known and patented in at least 23 countries, e.g.in Italy, the Netherlands, etc. Just like vitrification, it can be carried out in various settings for example in a tunnel furnace or by micro-wave heating.
- Ceramitisation [13], which is a technique where the temperature of treatment is lowered by mixing the asbestos with clay. In this way, the temperatures necessary to alter the fibre-structure of asbestos ranges between 800-950°C. The firing process again leads to the complete elimination of the asbestos fibres and to the conversion of the mixture into ceramic materials whose characteristics depend on the parameters of the mixture and of the materials of the ACW.

2. *Chemical processes [14]:*

With respect to acid (e.g. NaOH) and/or base (e.g. HF) treatments, various methods have been developed which envisage the use of both organic and mineral solutions to transform ACW to obtain secondary materials that are recyclable and often reusable in the ceramics industry.

In some countries, pilot installations are/were operational for the physical-chemical treatment of ACW, turning it into an inert raw materials. However, in general, the experience is limited to pilot installations because, among others, it could not be scaled up to industrial level installations since the process needs a very high liquid-solid ratio, meaning that a lot of acid or base is needed for a full scale installation. As a result, this is considered to be unfeasible from an economic point of view, often leading to the termination of studies and/or pilot installations.

3. *Combination:*

A couple of examples of methods, using a combination of principles (thermal, chemical or mechanical) are given below.

- Thermochemical treatment [15], [16], which is generally a thermal process in which the ACW is converted into harmless mineral substances through a process of heating. The chemical component of the process consists of the mixing of the asbestos/ACW with chemical solutions which, combined with the elevated temperatures (approximately 1.200-1.250°C), results in a more rapid demineralisation of asbestos fibres. The presence of the chemical component accelerates the conversion compared to e.g. denaturation. This type of processes are, among others, patented in the U.S. and Germany.
- Mechanochemical treatment, which is a process to transform asbestos into an amorphous material with a complete modification of its fibrous morphology, rendering it harmless. This process can be compared with a cold vitrification process [10], insofar that it also results in the transformation of asbestos into amorphous and thus harmless material. In general, during this process, one creates a structural destruction by using mechanical energy. Ideally, the process follows a certain sequence: (1) plastic deformation; (2) Increase in internal stress; (3) micro plastic deformation; and (4) fracturing [17]. These four events lead to the formation of new/fresh surfaces that are unchanged by the surrounding environment and can therefore emit or receive ions. As a result, new chemical reactions and structural changes can take place.

Reusable end-product

Crystallo-chemical treatment methods, either based on thermal, chemical, thermochemical, mechanic-chemical… principle, have the advantage over stabilisation by cementation that most of the methods result in the destruction, removal or permanent immobilisation of the asbestos fibres. This results in an inert end-product that can be re-used. Although denaturation seems to be a prosper solution, it is not clear for the time being if the same results can be reached hence a full 100% denaturation can be realized when applying denaturation on industrial scale. Reuse stands or falls with the assurance the product contains no free asbestos more

Table 4 gives an indication of the possibilities of industries in which the end-products of different treatment methods can be used.

Temporary storage

The above described research in the development of more sustainable treatment methods that destroy the fibre structure of asbestos (i.e. crystallo-chemical processes) rather than immobilizing them by cementation a positive evolution with regard to the asbestos problem and the transition towards a circular economy.

However, this research is often not yet advanced enough for large-scale application. Additionally the regulations in Flanders are still focused on landfilling whether or not preceded by immobilisation by cementation. In order to implement an alternative, more sustainable treatment method in Flanders, these two topics have to be addressed. Sufficient research should be done to obtain the best suitable treatment method for asbestos in Flanders and furthermore, the new policy concerning asbestos should support this technological research and should aim at the possibility to implement the obtained technique.

Next to these actions, other measures can be taken as well, directly linked to the concept of Enhanced Landfill Mining (ELFM). By landfilling the asbestos/ACW in 'temporary storage facilities', it is ensured that this waste stream can be treated once the necessary treatment techniques are developed. Furthermore, by dividing these temporary storage facilities in compartments, where every compartment is filled with a different waste stream, the asbestos/ACW can be stored separately. When in the future this waste stream can be treated, it is easily accessible. This application of ELFM fits perfectly in the idea of a circular economy which leads to material cycles with no option for landfilling.

Conclusion

In Flanders the current policy for non-friable asbestos is double-bagging, labelling and landfilling, while friable asbestos has to be cemented before disposal. . Although this technique for friable asbestos stabilizes the material by encapsulating the asbestos fibres with cement, leading to the removal of the direct danger, it does not offer a permanent solution to the asbestos problem. In both non-friable asbestos waste and the cemented friable asbestos, the harmful asbestos fibres are still present and can still become airborne again when the cement weathers, breaks … As such, the problem by landfilling all asbestos waste is not eliminated but merely postponed to future generations. Furthermore, the technique requires a lot of space, which means it does not offer a solution for the increasing shortage of available space in Flanders. In other words, the need for disposal space linked with the current policy for treating ACW in Flanders, is conflicting with the idea of sustainable land use and recycling and closing material cycles. As such, the necessity of the development of alternative, more innovative and sustainable treatment techniques is evident. In the meantime, technologies for mining of the deposited ACW in the monolandfills can be developed.

Several countries are investing in research to develop more sustainable treatment methods that destroy the fibre structure of asbestos by using either mechanical, thermal or chemical principles or even a combination of these principles. By destroying the fibre structure, the material becomes inert, enabling its re-use as secondary materials so they do not have to be landfilled. However, in Flanders, this research is not yet advanced enough for large-scale installations.

Measures that can be taken at this moment are directly linked with the concept of Enhanced Landfill Mining (ELFM). The landfilled asbestos/ACW in 'temporary storage facilities' can be retrieved once the necessary techniques are fully developed and available to treat this waste stream. These temporary storage facilities can be organized as such so that this specific waste stream can be retrieved without been mixed with other waste streams. In other words, by dividing a landfill site in compartments, asbestos/ACW can be stored separately, making it easily accessible in the future so ELFM can be applied.

The implementation of ELFM for asbestos materials currently is subject of research in Flanders. This research of opportunities and constraints for asbestos processing focusses on technical, legal, administrative and financial topics in order to be able to launch appropriate and innovative processes for a final asbestos processing.

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