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Environmental
Protection Agency

# Waste containing asbestos and other environmentally problematic substances

# Characterization, risks and management

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# Executive Summary

In Denmark, waste containing asbestos (WCA) is separately collected, handled, and landfilled. Waste contaminated with environmentally problematic substances such as PCBs, PAHs, and heavy metals is also separately collected; incineration is the adopted disposal method for some waste fractions and substances, with landfilling and recycling used only in specific situations. In some cases, besides asbestos, the waste also contains other environmentally problematic substances (e.g., PCBs, PAH, heavy metals) in concentrations exceeding the limit values for hazardous waste. When a combination of waste and other environmentally problematic substances occurs, the waste is likely to be classified as hazardous for multiple reasons. The combined presence of asbestos and other environmentally problematic substances makes managing this type of waste is challenging. While incineration of waste containing asbestos is currently not done in Denmark, the presence of organic substances and heavy metals may limit the possibilities for landfilling. Given the variety of situations (and combination of substances) no general guidelines exist, and Danish municipalities have to make specific decisions on a case-by-case basis.

The objective of this project was to identify and evaluate possibilities for handling waste containing both asbestos and other environmentally problematic substances (WCAPS) in Denmark. The focus was in particular on two potential solutions: i) Landfilling of waste containing asbestos and heavy metals; ii) Thermal treatment of waste containing asbestos and PCB/PAH.

The main objective of the project was achieved through the following specific activities:

- Review of existing literature concerning relevant information and previous assessments of suitable treatment options for asbestos-containing waste.
- Map relevant waste fractions containing asbestos in combination with either i) heavy metals or ii) organic compounds such as PCBs and PAHs, and identify the most important (i.e., largest or more frequently present) at the national level.
- Assess the potential for compliance of the above waste fractions with acceptance criteria for disposal of hazardous waste in accordance with the Landfill regulation, based on laboratory leaching experiments on waste samples containing both asbestos and heavy metals.
- Based on laboratory-scale thermal tests, assess the possible transformation of asbestos fibers and related potential emissions induced by high-temperature conditions.
- Screen the risk of asbestos leaching from landfills to the aquatic environment towards humans (via drinking water) and organisms in the receiving surface waters in Denmark.

About 200 Mton of asbestos have been produced since 1920 up to nowadays. Because of its carcinogenicity, the marketing and use of asbestos-containing products have been banned in the EU since 2006; however, about 2 Mton of asbestos are still produced globally every year. The use of asbestos is linked to a variety of products and applications, most of them related to the construction sector. It is, for example, estimated that, in the 80s, about 70% of asbestos was used in cement products and 10% in vinyl/linoleum flooring.

The generation of waste containing asbestos, originating from products used in the past, is currently in the order of 90,000 ton per year in Denmark. Precise data on the amount of asbestos contained in the waste are not available, but an overall estimate is around 10,000-30,000 ton of asbestos fibers per year. The main treatments for asbestos-containing waste in Denmark are landfilling or exporting for special treatment.

Statistical data about WCAPS are not readily available. Hence Danish municipalities and companies dealing with this type of waste – either demolition or waste handling companies - were contacted to collect information via a questionnaire; 46 municipalities and 8 companies provided a response. While confirming that information is lacking, it was estimated that few hundred ton WCAPS may be generated yearly in Denmark. The most relevant material fractions, either because of frequency or amounts, are:

- Vinyl/linoleum flooring + asbestos + heavy metals;
- Tiles + asbestos + heavy metals;
- Roofing felt + asbestos + organic pollutants.

Experimental activities were carried out to evaluate two potential scenarios for the management of waste containing both asbestos and other environmentally problematic substances:

- "Landfill scenario" focusing on waste samples containing asbestos and relatively high contents of heavy metals, to investigate the potential for compliance with the leaching criteria defined for landfilling of hazardous waste;
- "Thermal treatment scenario" focusing on waste samples containing both asbestos and relatively high contents of organic pollutants, to investigate the pontial for destruction of asbestos fibers and organic pollutants at high temperatures.

Four samples of WCAPS - as classified in the respective Environmental Mapping Report (i.e. Miljøkortlægningsrapport) - were obtained from waste management companies and analyzed for their content of asbestos, PCB, PAHs, heavy metals and hydrocarbons. Procedures for screening, mapping and classifying WCAPS were discussed; options for improving the procedures were identified. This included for example:

- the establishment of a coordinated system for recording the occurrence of waste containing both asbestos and other environmentally problematic substances;
- preparation of an official guideline describing how sampling should be done, to ensure objectivity and consistency across municipalities in screening/mapping and the subsequent hazardousness classification;
- implementation of routines so that, for materials known to be potentially inhomogeneous, additional samples are taken and analyzed for the presence of asbestos;
- improvement of material classification strategies by encouraging more sampling of waste materials also during the demolition phase, to cross-check and confirm the results of the mapping phase, and eventually re-classify the waste accordingly.

Samples of tiles and linoleum were tested for compliance with acceptance criteria at hazardous waste landfills. The release tests showed that both materials would comply with the acceptance criteria for all classes of landfills approved for hazardous waste disposal.

Samples of linoleum and roofing felt were treated at 1100 °C, to assess the efficacy of thermal treatment in destroying asbestos and organic pollutants. The results indicated that high temperatures are effective in significantly reducing or eventually almost completely destroying the organic pollutants contained in the waste. With regards to asbestos, results were only available for linoleum flooring (because of the lack of asbestos in the roofing felt samples, despite the fact that their documentation indicated presence). While conclusions beyond the specific samples cannot be made, the experiments indicated that heating of waste to 1100 °C can be effective in destroying the asbestos fibers, in agreement with existing literature on the topic.

The risk screening evaluated leaching of asbestos from landfills to the aquatic environment. The screening indicated that there is low risk towards humans (via drinking water) and organisms in the receiving surface waters. The project further identified that there is no scientific evidence regarding toxicity effects or risks from the combination of asbestos and other contaminants. These finding further support the results obtained via the compliance tests.

Based on the results, potential options for management of the waste evaluated in this project containing both asbestos and other environmentally problematic substances were identified (TABLE 1), together with key parameters to be checked during the decision-process. Regarding the risk screening more knowledge and data on source characteristics, asbestos leaching from waste, exposure and toxicity towards sensitive sub-populations (e.g. children) are required to improve the results. It should be noted that the risk screening is based solely on available data and general assumptions, and specific data collection and stakeholder involvement e.g. for site descriptions was beyond the scope of the project.

**TABLE 1.** Summary of potential management options for waste containing both asbestos and other environmentally problematic substances evaluated in this project.

| Material | Contaminants | Hazardous waste landfilling | Hazardous waste incineration |
|---|---|---|---|
| **Linoleum** | Asbestos<br>Heavy metals<br>Hydrocarbons | Yes<br>(upon compliance with acceptance criteria) | Yes |
| **Tiles** | Asbestos<br>Heavy metals<br>Hydrocarbons | Yes | Not applicable |
| **Roofing felt** | Asbestos<br>PCB<br>PAH<br>Hydrocarbons | Yes, if:<br>PCB <50 mg/kg<br>$\text{PAH}_{\text{total}}$ <4 mg/kg | Yes* |

* Assuming asbestos fibers are destroyed as effectively as for linoleum.

# Resume (dansk)

I Danmark indsamles og håndteres asbestholdigt affald separat og deponeres. Affald, der er forurenet med miljøfarlige stoffer, såsom PCB, PAH og tungmetaller, indsamles også separat. For disse affaldsfraktioner og stoffer er forbrænding ofte den foretrukne behandlingsmetode, mens deponering og genanvendelse kun anvendes i specifikke situationer. I nogle tilfælde, indeholder affaldet udover asbest også miljøfarlige stoffer (f.eks. PCB, PAH, tungmetaller) i koncentrationer, der overstiger grænseværdierne for farligt affald. Ved sådanne kombinationer af affald og miljøfarlige stoffer, klassificeres affaldet således som farligt af flere årsager. Den kombinerede tilstedeværelse af asbest og andre miljøfarlige stoffer giver udfordringer i forhold til håndteringen af denne type affald: dels forbrændes asbestholdigt affald i øjeblikket ikke i Danmark, og dels begrænser tilstedeværelsen af organiske stoffer og tungmetaller mulighederne for deponering. Set i lyset af de mange forskellige situationer (og kombinationer af stoffer) findes ikke generelle vejledninger for håndtering af affaldet; kommunerne skal derved træffe beslutninger fra sag til sag.

Formålet med dette projekt var at identificere og vurdere mulighederne for håndtering af affald indeholdende både asbest og andre miljøfarlige stoffer i Danmark. Fokus var især på to muligheder: i) Deponering af affald indeholdende asbest og tungmetaller; ii) Termisk behandling af affald indeholdende asbest og PCB / PAH.

Hovedmålet blev opnået gennem følgende specifikke aktiviteter:
- Gennemgang af eksisterende litteratur med hensyn til relevant information og tidligere vurderinger af relevante behandlingsmuligheder for asbestholdigt affald.
- Kortlægning af relevante affaldsfraktioner, der indeholder asbest i kombination med enten i) tungmetaller eller ii) organiske forbindelser såsom PCB og PAH, og identifikation af de vigtigste fraktioner (dvs. største eller hyppigst observerede) på nationalt niveau.
- Vurdering af potentialet for overholdelse af acceptkriterier for deponi af farligt affald på grundlag af laboratorieudvaskningsforsøg på udvalgte affaldsprøver indeholdende både asbest og tungmetaller.
- Vurdering af potentialet for omdannelse og nedbrydning af asbestfibre på grundlag af termiske forsøg i laboratorieskala på udvalgte affaldsprøver indeholdende asbest og PCB/PAH.
- Risikoscreening af udvaskning af asbest fra lossepladser til vandmiljøet og overfor mennesker (via drikkevand) og organismer i det modtagende overfladevand i Danmark.

Cirka 200 Mton asbest er produceret siden 1920 og frem til i dag. På grund af dets kræftfremkaldende virkning er markedsføring og anvendelse af asbestholdige produkter blevet forbudt i EU siden 2006; dog produceres der stadig ca. 2 Mton asbest globalt hvert år. Anvendelsen af asbest er knyttet til en række produkter og anvendelsesområder, hvoraf de fleste er relateret til byggesektoren. Det anslås for eksempel, at omkring 80% af asbest i 80'erne blev brugt i cementprodukter og 10% i vinyl/linoleumsgulve.

Produktionen af asbestholdigt affald, der stammer fra tidligere anvendte produkter, er i øjeblikket i størrelsesordenen 90.000 tons om året i Danmark. Præcise tal for mængden af asbest indeholdt i affaldet er ikke tilgængelig, men et groft skøn er i størrelsesordenen 10.000-30.000 tons asbestfibre om året. Asbestholdigt affald i Danmark deponeres, eller eksporteres til særlig behandling i udlandet.

Statistiske data for affald indeholdende både asbest og miljøfarlige stoffer eksisterer ikke i Danmark. Derfor blev danske kommuner og virksomheder, der beskæftiger sig med denne type affald - enten nedrivnings- eller affaldshåndteringsfirmaer - kontaktet for at indsamle oplysninger via et spørgeskema; 46 kommuner og 8 virksomheder svarede. Mens det blev bekræftet, at der er stor mangel på konkrete data, blev det bedste groft estimeret, at der årligt formentlig genereres nogle få hundrede tons affald indeholdende både asbest og miljøfremmede stoffer i Danmark. De mest relevante materialefraktioner, enten på grund af hyppighed eller mængder, er:

- Vinyl/linoleumsgulve + asbest + tungmetaller;
- Fliser + asbest + tungmetaller;
- Tagpap + asbest + organiske forurenende stoffer.

En række laboratoriebaserede forsøg blev gennemført med henblik på vurdering af to potentielle scenarier for håndtering af affald indeholdende både asbest og andre miljømæssigt problematiske stoffer:

- "Deponeringsscenarie" med fokus på affaldsprøver, der indeholder asbest og relativt højt indhold af tungmetaller, for at undersøge om udvaskningskriterier for deponering af farligt affald kan opfyldes;
- ”Termisk behandlingsscenarie” med fokus på affaldsprøver, der indeholder både asbest og relativt højt indhold af organiske stoffer, for at undersøge om asbestfibrene og de organiske stoffer nedbrydes ved høje temperaturer.

Fire affaldsprøver klassificeret via miljøkortlægningsrapporter som indeholdende både asbest og miljøfarlige stoffer, som PCB, PAH, tungmetaller og kulbrinter, blev indsamlet fra affaldshåndteringsvirksomheder. Procedurer for screening, kortlægning og klassificering af affald indeholdende både asbest og miljøfarlige stoffer blev diskuteret og en række muligheder for forbedring fremsat. Dette omfatter for eksempel:

- etablering af koordineret system til registrering af forekomsten af affald, der indeholder både asbest og andre miljøproblemer;
- udarbejdelse af nationale vejledninger, der beskriver, hvordan prøveudtagning skal udføres for at sikre objektivitet og konsistens på tværs af kommuner i screening/kortlægningsfasen såvel som den efterfølgende klassificering af farlighed;
- implementering af rutiner, så supplerende prøvetagning og analyse sikres for materialer, der i særlig grad kan være inhomogene;
- forbedring af procedurer for materialeklassificering ved tilskyndelse til mere omfattende prøveudtagning og karakterisering af affaldsmaterialer også i nedrivningsfasen for at krydstjekke og bekræfte resultaterne af kortlægningsfasen, og efter behov genklassificere affaldet i overensstemmelse de supplerende data.

Prøver på fliser og linoleum blev testet for overholdelse af acceptkriterier for deponering af farligt affald. Udvaskningsforsøgene viste, at begge materialer ville opfylde acceptkriterierne for alle deponiklasser godkendt til modtagelse af farligt affald.

Prøver af linoleum og tagpap blev behandlet ved 1100 °C for at vurdere effektiviteten af termisk behandling for destruktion af asbest og organiske stoffer. Resultaterne viste, at de høje temperaturer er effektive til væsentligt at reducere eller fuldstændigt nedbryde de organiske forurenende stoffer indeholdt i affaldet. Med hensyn til asbest var det kun muligt at opnå resultater for linoleumsgulve (på grund af manglende tilstedeværelse af asbest i tagpapprøverne, på trods af klassificering som asbestholdigt affald). Mens der ikke kan opnås konklusioner udover de konkrete affaldsprøver, indikerer forsøgene, at opvarmning af affald til 1100 °C kan medføre effektiv nedbrydning af asbestfibrene, hvilket er i overensstemmelse med den eksisterende litteratur på området.

Risikoscreeningen evaluerede frigivelse af asbest fra deponeringsanlæg til grundvand og vandmiljø via udvaskning. Screeningen viste, at der er lav risiko for mennesker (via drikkevand) og organismer i nærliggende overfladevandsrecipienter. Projektet identificerede endvidere, at der ikke er videnskabelig dokumentation for toksiske effekter eller yderligere risici forbundet med tilstedeværelsen af både asbest og andre forurenende stoffer. Disse fund understøtter yderligere de opnåede resultater via overensstemmelsestestene.

Ud fra resultaterne blev mulige behandlingsløsninger for affaldet analyseret i projektet indeholdende både asbest og andre miljøfremmede stoffer identificeret (TABEL 1), med angivelse af nøgleparametre der bør afklares i beslutningsprocessen. Med hensyn til risikoscreening er det nødvendigt at få mere viden og data om kildekarakteristika(-styrke), asbestudvaskning fra affald, eksponering og toksicitet over for udsatte befolkningsgrupper (f.eks. børn) for at forbedre resultaterne. Det skal bemærkes, at risikoscreeningen udelukkende er baseret på tilgængelige data og generelle antagelser, og specifik dataindsamling og involvering af interessenter fx for fastlæggelse af lokale forhold, ikke har været omfattet af projektet.

**TABEL 1.** Oversigt over potentielle behandlingsmuligheder for affald indeholdende både asbest og andre miljøfarlige stoffer i projektet.

| Materiale | Forurenende stoffer | Deponering af farligt affald | Forbrænding af farligt affald |
|---|---|---|---|
| **Linoleum** | Asbest<br>Tungmetaller<br>Kulbrinter | Ja<br>(ved overholdelse af modtagekriterier) | Ja |
| **Fliser** | Asbest<br>Tungmetaller<br>Kulbrinter | Ja | Ikke relevant |
| **Tagpap** | Asbest<br>PCB<br>PAH | Ja, hvis:<br>PCB <50 mg/kg<br>$PAH_{total}$ <4 mg/kg | Ja* |

* Forudsat, at asbestfibre destrueres lige så effektivt i tagpap som for linoleum.

# Preface

This report provides a basis for informed-decision regarding waste containing both asbestos and other environmentally problematic substances, such as organic compounds and heavy metals. The geographical scope of the project was Denmark.

The project was commissioned by the Danish Environmental Protection Agency (EPA). The work was carried out jointly by the Technical University of Denmark (DTU) and Aarhus University (AU), in the period April 2020 to June 2021.

This work includes literature review, analysis of statistical data and management information, survey and discussions with stakeholders, experimental activities related to material characterization, and screening of the risk related to management and disposal of waste containing asbestos and other contaminants.

The findings and recommendations in this study can serve as the basis for deciding on management of waste, as well as on adjusting screening, classification and reporting procedures regarding waste containing both asbestos and other environmentally problematic substances.

The Danish stakeholders were represented by municipalities, utility companies and waste companies involved in the management and handling waste.

The Danish Environmental Protection Agency was represented by Cecilie Østerskov Madsen and Anne Juul Jensen.

The report was prepared by Alessio Boldrin, Alberto Maresca, and Thomas Fruergaard Astrup from the Department of Environmental Engineering (DTU), and Patrik Fauser and Hans Sanderson from the Department of Environmental Science (AU).

# Abbreviations

The following are some of the key acronyms that are used throughout this report.

| Abbreviation | Definition |
|---|---|
| BBR | Bygnings- og Boligregistret (The Building and Housing register) |
| CLP | Classification, Labelling and Packaging |
| DDSC | Derivative Differential Scanning Calorimetry |
| DSC | Differential Scanning Calorimetry |
| DTA | Differential Thermal Analysis |
| DTG | Derivative Thermogravimetry |
| dw | Dry weight |
| GHS | Globally Harmonized System |
| HC | Hydrocarbons |
| HP | Hazardous property |
| IUR | Inhalation Unit Risk |
| IV | Intervention Values |
| LOEC | Lowest observed effect concentration |
| L/S | Liquid-to-solid ratio |
| MAE | Microwave assisted extraction |
| MF | Million fibers |
| MFL | Million fibers per liter |
| MOA | Mechanism of Action |
| MoE | Margin of Exposure |
| NOEC | No observed effect concentration |
| PAH | Polycyclic aromatic hydrocarbon |
| PCB | Polychlorinated biphenyl |
| PLM | Polarized light microscopy |
| POP | Persistent Organic Pollutant |
| POC | Point of Compliance |
| PVC | Polyvinyl chloride |
| RfD | Reference dose |
| RNS | Reactive nitrogen species |
| ROS | Reactive oxygen species |
| RQ | Risk Quotient |
| SSA | Source Strength Amount |
| SEM | Scanning Electron Microscopy |
| TEM | Transmission Electron Microscopy |
| TGA | Thermogravimetry Analysis |
| TOC | Total Organic Carbon |
| XRD | X-ray diffraction |
| WCA | Waste contains asbestos |
| WCAPS | Waste containing both asbestos and other environmentally problematic substance |

# 1. Introduction and objectives

## 1.1 Introduction

In Denmark, waste containing asbestos (WCA) is separately collected, handled, and landfilled. Waste contaminated with environmentally problematic substances such as PCBs, PAHs, and heavy metals is also separately collected; for some materials and substances, incineration is the adopted disposal method, with landfilling and recycling being used for fewer specific circumstances (more details provided in section 3.4).
In some cases, besides asbestos, the waste also contains other environmentally problematic substances in concentrations exceeding the limit values for hazardous waste; using a non-technical classification, it can be said that the waste hazardousness is doubled. Indeed, the combined presence of asbestos and other environmentally problematic substances makes the management of this type of waste problematic: the presence of asbestos prevents disposal via incineration, while the presence of organic substances and heavy metals significantly restricts the possibilities for landfilling. Given the variety of situations (e.g., a combination of substances) when it comes to managing this waste, Danish municipalities have to make specific decisions on a case-by-case basis.

In this context, the Danish Environmental Protection Agency wants to uncover the possibilities for determining suitable national solutions for handling waste containing both asbestos and other environmentally problematic substances in the future. This requires a mapping of quantities at the national level as well as an assessment of the environmental aspects around two potential solutions: i) Landfilling of waste containing asbestos and heavy metals; ii) Combustion of waste containing asbestos and PCB/PAH. The risk of asbestos leaching from landfills to the aquatic environment towards humans (via drinking water) and organisms in the receiving surface waters are screened to provide a further basis for decision-making.

Within the project, the following definition of asbestos fiber was used: "*a particle with a length greater 5 µm, a diameter less than 3 µm and an aspect ratio greater than 3:1*" (Paolini et al., 2019). The project focuses on white asbestos (Chrysotile), as this represents 95% of the asbestos encountered in Denmark. This also means that the term "asbestos" refers indeed to "white asbestos", unless differently specified.

## 1.2 Objectives

The specific objectives of the project are:

- Review of available literature concerning relevant information and previous assessments of treatment options for asbestos-containing waste.
- Map relevant waste fractions containing asbestos in combination with either i) heavy metals or ii) organic compounds such as PCBs and PAHs, and identify the most important (i.e., largest or more frequently present) at the national level.
- Assess the potential for compliance of the above waste fractions with acceptance criteria for disposal at hazardous waste landfills based on laboratory leaching experiments on waste samples containing both asbestos and heavy metals.
- Based on laboratory-scale thermal tests, evaluate the possible transformation of asbestos fibers and related potential emissions induced by high-temperature conditions.
- Screen the risk of asbestos leaching from landfills to the aquatic environment towards humans (via drinking water) and organisms in the receiving surface waters in Denmark.

# 2. Background

This section provides general information about asbestos fibers and describes the issues related to the simultaneous presence of asbestos and other environmentally problematic substances. The focus is on Chrysotile or white asbestos (CAS# 12001-29-5) as this is the most commonly encountered form of asbestos, accounting for approximately 95% of the asbestos in the United States and a similar proportion in other countries (e.g., Denmark) (US EPA, 2021).

The Substances in Preparations in the Nordic Countries (SPIN) database holds data on hazardous compounds and materials reported by companies into the product register in the Danish Working Environment Authority (Arbejdstilsynet) database. FIGURE 1 shows that the use of chrysotile asbestos in Denmark has been relatively constant over the past years at 76 tons/year until 2002; after this, the information has been retained as confidential. The primary industry use is in machinery, gaskets, and fillers in plastic, cement, and paints (SPIN, 2021).

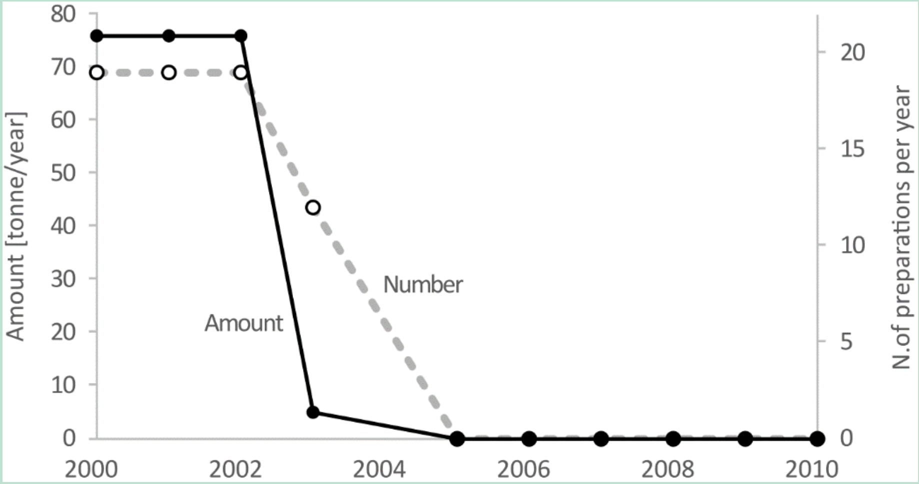

**FIGURE 1.** Overview of use of Chrysotile (white asbestos) in Denmark, by mass and number of preparations. Data retrieved from (SPIN, 2021).

## 2.1 Physicochemical properties of white asbestos

Chrysotile asbestos, or white asbestos, is a mineral belonging to the phyllosilicate, kaolinite-serpentine group. It is most commonly found as a clinochrysotile form and is distinct from other asbestiform minerals in the amphibole group. Its IUPAC name is trimagnesium-hydroxy(trioxido)silane-hydrate, and its molecular formula is $H_4Mg_3O_9Si_2$**.** The molecular weight is 277.11 g/mol. See the chemical structure in figure 2 below:

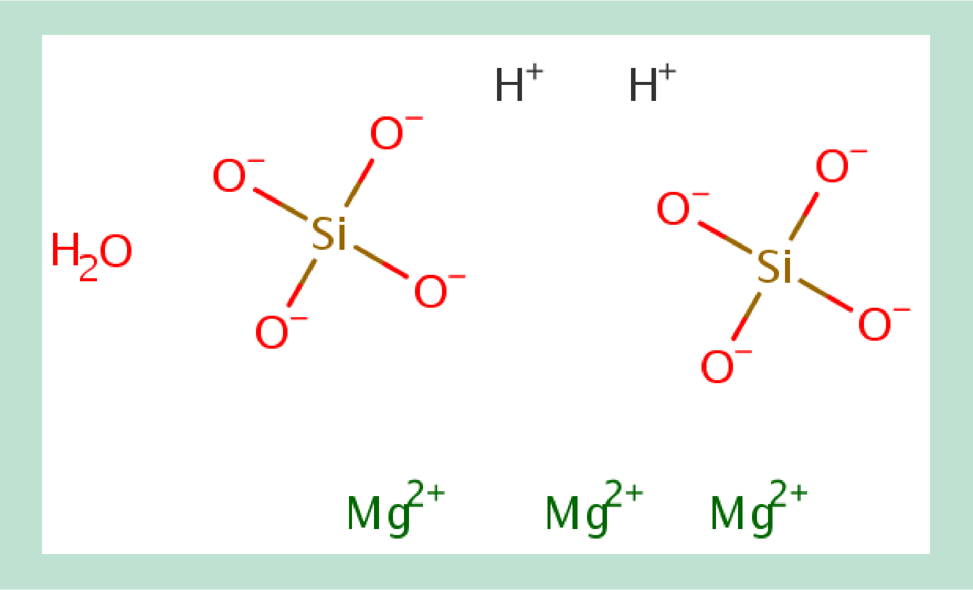

**FIGURE 2**. Chemical structure of trimagnesium-hydroxy(trioxido)silane-hydrate (Chrysotile asbestos). Image taken from US EPA (2021).

Industrially processed chrysotile asbestos fibers have a diameter of 0.1–100 µm, and the individual fibrils are even finer, i.e., 0.02–0.03 µm. Each fiber bundle contains tens or hundreds of fibrils. The median diameter of the fibers is 0.06 µm, and the median length is 0.55 µm. The surface area ranges from 13.5 to 22.4 $m^2/g$ (US EPA, 2020). It is a soft, fibrous silicate mineral that is not water-soluble and not biodegradable; it is resistant to strong bases and is stable in pore water in soil and sediment with pH above 7. When in contact with acids, the magnesium ions in the fibers are selectively dissolved, leaving a silica skeleton. The fibers are relatively resistant to heat and thermally stable up to around 550 °C, at which temperature it starts to dehydrate. Dehydration is complete at about temperatures around 850 °C, with the final products being magnesium silicate, silica, and water (PubChem, 2021; US EPA, 2021). Chrysotile asbestos fibers have a net positive surface charge and form a stable suspension in water. The zeta potential ranges from +13.6 to +54 mV (US EPA, 2020). They can embody the following impurities: Li, Be, Sc, V, Cr, Mn, Co, Ni, Cu, Zn, As, Rb, Sr, Y, Sb, Cs, Ba, La, Pb, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Th, U (PubChem, 2021).

### 2.1.1 Human toxicology

It is well-established from many authorities that there are causal associations between asbestos exposures and lung cancer and mesotheliomas. There is also a causal association between exposure to asbestos and cancer of the larynx and cancer of the ovary. Additionally, there is a well-established causal association between asbestos exposures and non-cancer health effects, including respiratory effects (e.g., asbestosis, non-malignant respiratory disease, deficits in pulmonary function, diffuse pleural thickening, and pleural plaques) as well as some evidence of immunological and lymphoreticular effects. There is also a causal association between exposure to asbestos and cancer of the larynx and cancer of the ovary, and that there is suggestive evidence of a positive association between asbestos and cancer of the pharynx, stomach, and colorectum. Moreover, all types of asbestos fibers have been reported to cause mesothelioma (US EPA, 2020).

The US EPA (2020) summarized that the chrysotile crystal structure of asbestos is made of two sheets of mineral that form a silicate layer with a slight misfit that causes curling to form concentric cylinders with the silicate layer on the inside and brucite-like layer on the outside of the cylinder. While some shorter asbestos fibers have been shown to be cleared by the pulmonary system more efficiently, evidence from *in vitro* genotoxicity studies in Chinese hamster lung cells suggests that short and intermediate chrysotile fibers may be more potent carcinogens. There is some evidence that aspect ratio and size may play differing roles in the onset and progression of lung cancer and mesothelioma. In addition to the aspect of ratio and size, the surface of asbestos fibers has a reactivity that may generate reactive oxygen species

(ROS), reactive nitrogen species (RNS). The surface reactivity of asbestos fibers, including chrysotile asbestos, also plays a role in regard to lung cancer and mesothelioma. Below is a summary of the toxicological mode of action findings the US EPA (2020) made based on their systematic review.

The US EPA (2020) concludes that: *the evidence from both in vitro and in vivo studies strongly suggests that the physicochemical properties of chrysotile asbestos fiber along with the reactive oxidants generated by these are key in the pathogenesis of asbestos-related diseases such as lung cancer and mesothelioma. However, there is currently insufficient information to determine the mechanism of action (MOA) for either chrysotile lung carcinogenicity or mesothelioma. Chrysotile asbestos mesothelioma and lung carcinogenicity may be mediated by different underlying complex mechanisms that have yet to be fully elucidated. In the absence of other information about MOA, it is recommended to take the health-protective approach of assuming a linear no-threshold risk model consistent with a mutagenic MOA*.

In addition, we scanned the literature regarding the potential interactions between heavy metals and asbestos fibers. The scan covers both physical/chemical properties, human and environmental toxicity. The scanning of the published scientific literature was done with three different sources of information:

1) The CAS database SciFinder - as the primary chemical-specific scientific database
2) Web of Science – as a secondary and more general scientific database
3) Google Scholar – as a tertiary broad database

We used the following search terms in SciFinder; "Asbestos+heavy metals+toxicity" – resulting in 18 studies. The Web of Science was scanned with the following search terms: asbestos+chrysotile+toxicity+heavy metals – resulting in 3 studies. The last database, Google Scholar, is broader, generates many hits, and is less searchable than the scientific databases. Hence, the search terms were more detailed and specific than in the two previous assessments, including more terms: asbestos+fibers+toxicity+impact+heavy metals+health+water+fish+human+chrysolite+mixture. The search yielded 653 results sorted by relevance by the google algorithm. The first 30+ studies were indeed more relevant than the latter ones for the purpose of this analysis. See Appendix 1 for the full list of references from the scans. In addition to these screenings of the peer-reviewed literature on the topic of asbestos toxicity was assessed via the OECD E-chem portal. We did not identify any studies that addressed the topic of mixture toxicity between asbestos and heavy metals. Science today is focused on further understanding the complexity of the fibers toxicity rather than complex mixture toxicity with regards to both humans and aquatic environments.

The Danish EPA concluded in 2008, that the most important toxicological information about the fiber is the structure, size, length, and thickness of the fiber (Miljøstyrelsen, 2008). The ion charge and additional impurities such as heavy metals and other compounds inside the fibers also affect their toxicity (US EPA, 2020). There is no mentioning of mixture toxicity between the fibers and other compounds and metals in the US EPA (2020) risk analysis. Boyles et al. (2019) further elaborate on the complex nature of asbestos mechanisms of toxicity.

There are no threshold values of chrysotile asbestos in water and drinking water in Denmark (MST, 2008). The World Health Organization (WHO) concluded in 2003 that: *Although asbestos is a known human carcinogen by the inhalation route, available epidemiological studies do not support the hypothesis that increased cancer risk is associated with the ingestion of asbestos in drinking water. Moreover, in extensive feeding studies in animals, asbestos has not consistently increased the incidence of tumors of the gastrointestinal tract. There is, therefore, no consistent, convincing evidence that ingested asbestos is hazardous to health, and it is concluded that there is no need to establish a guideline for asbestos in drinking water.* The US EPA reported a safe drinking water threshold of 300.000 fibers per liter in 1985.

The main concern of asbestos is inhalation toxicity and lung cancer. Pierce et al. (2008) report in a review of 350 studies that the preponderance of the cumulative “no-effects” exposure levels for lung cancer and mesothelioma fall in a range of approximately 25–1000 fibers per cubic centimeter per year (f/cc-yr) and 15–500 f/cc-yr, respectively. The US EPA (2020) report values ranging from 0.0641 to 0.16 (f/cc-yr) as the appropriate workers IUR (Inhalation Unit Risk) value to be used in a risk evaluation.

In conclusion, the concerns regarding asbestos are primarily inhalation exposure and lung cancer. There is no threshold value or guideline value with regards to human risk due to exposure via soil. WHO has not identified a drinking water guideline value due to low toxicity via this exposure route. The US EPA identified a safe drinking water threshold of 300.000 fibers/L decades ago, which has not been updated since. There are no EU threshold values for soil or water. Hence, for the subsequent risk appraisal in this report, soil risk towards humans cannot be determined, and for the drinking water exposure, we will use the US EPA value of 300.000 fibers/L as the reference dose (RfD). In addition to the RfD of 0.3 MFL the report from the US EPA (2020) also cite a tolerable drinking water concentration of 7 MFL - which is deemed to be safe based on epidemiological studies by the ATSDR in 2001 in the risk profile of Asbestos.

### 2.1.2 Environmental toxicity

The US EPA (2020) conducted a weight-of-evidence systematic review of the published literature regarding the aquatic toxicity of chrysotile asbestos. The review resulted in four high-quality and relevant studies - all lead-authored by Dr. Scott Belanger.

The review revealed that chronic exposure to waterborne chrysotile asbestos at a concentration range of 0.0001 to 100 million fiber/L (MFL) might result in sub-lethal effects in fish and clams. Acute exposure of chrysotile asbestos to clams resulted in reduced feeding because of impaired siphoning activity at concentrations from 0.0001 to 100 million fiber/L (MFL) (US EPA, 2020). The conservative hazard value is thus 0.0001 MFL for both acute and chronic effects, while the least but still relevant hazard value is 100 MFL. This clearly covers several orders of magnitude. We asked Dr. Belanger, who led the studies, about his views of the aquatic toxic mode of action of chrysotile asbestos: *Asbestos fibers are charged very heavily at times, substantial negative zeta potentials are possible. Uptake of asbestos is a function of sheer size, and aspect ratio (larger aspect ratios (Length:width)) are more easily taken up. Mechanisms for uptake are rapid transfer across the membrane (shorter fibers with high aspects ratios) and pinocytotic. The hollow core of fiber (in the case of chrysotile) is filled with metals. Amphibole is usually geologically more layered but still fibrous. Between sheets are the metals/inorganic contaminants. These are partly what gives the fiber charge then* (Belanger, 2021). The US EPA did not report any studies concerning the mixture toxicity of chrysotile asbestos and other heavy metals or other chemicals, confirming the findings of our review.

There are no conclusive data regarding soil environmental toxicity.

## 2.2 Options for treatment of waste containing asbestos (WCA)

A literature search was conducted with the aim of collecting literature studies that: i) investigated/reviewed the options for treating asbestos minerals (with particular focus on the thermal treatment) and ii) investigated the potential leaching from materials containing asbestos (i.e., minerals, products, and waste). Details about the literature search are provided in Appendix 1. A summary of the main findings is provided in the following paragraphs. The overview has an international scope to show the existing possibilities, although not all options may be currently relevant or available in Denmark.

It is estimated that about 181 Mton of asbestos were produced globally in the period 1920-2003 (Paglietti et al., 2016). While the EU has banned the marketing and use of asbestos-containing products since 2006 (European Parliament, 2006a), and the International Labour Organization (ILO) and WHO have public asked for a phase-out of asbestos in 2006, about 2 Mton of asbestos are still produced globally every year; China, Russia, India, Kazakhstan, Brazil, Indonesia, Thailand, Vietnam, and Ukraine are the primary users, and chrysotile is the only asbestos type present in the market (Paglietti et al., 2016; Spasiano and Pirozzi, 2017). This suggests that significant amounts of waste containing asbestos are currently or will soon be generated at a global level.

Asbestos is a carcinogenic substance in Category 1A (European Parliament, 2008a), all wastes containing asbestos in concentrations ≥0.1% are classified as hazardous HP 7 (i.e., waste which induces cancer or increases its incidence) (European Parliament, 2018a, 2008b; OVAM, 2016; Paglietti et al., 2016). As the concentration of asbestos in products is most often in the range of 5-98% (Arbejdstilsynet, 2010; OVAM, 2016; Paglietti et al., 2016), almost all waste containing asbestos are classified as hazardous.

Waste containing asbestos may either be landfilled or sent to recovery facilities. Landfilling of waste containing asbestos must occur at approved facilities (European Parliament, 2018b, 2008b):

- Landfills for hazardous waste, either completely dedicated to waste containing asbestos or with separated cells/units for this type of waste;
- Landfills for non-hazardous waste (e.g., mineral, mixed waste), either completely dedicated to waste containing asbestos or with separated cells/units for this type of waste.

While the EU legislations cover all member states, their implementation at the national levels may differ substantially. For example, in France, waste containing asbestos is either disposed of in landfills for inert waste or thermally decomposed in facilities for hazardous waste disposal (DREAL, 2017; INRS, 2019; OVAM, 2016). In the Netherlands, waste containing asbestos is disposed of in landfills; however, the landfill ban declaration stipulates that if a material can be treated differently than landfilling, then this material is added to the list of materials banned from landfilling (Bureau KLB, 2018; OVAM, 2016). This means that as soon as an alternative option than landfilling is commercially demonstrated, waste containing asbestos will no longer be landfilled in the Netherlands (Bureau KLB, 2018; OVAM, 2016). In Germany, waste containing asbestos is classified as hazardous and disposed of permanently in special landfills (OVAM, 2016). In Poland, disposal of waste containing asbestos is possible in hazardous waste landfills and in separate cells of landfills for mixed or inert waste (OVAM, 2016). Despite being broadly used, landfilling of material containing asbestos cannot by default be considered the safest method (OVAM, 2016). As highlighted by the EU Parliament, when landfilling waste containing asbestos, there is a risk that acid-corrosive agents contained in the landfill leachate can partially dissolve asbestos fibers and redistribute them into the environment (Paolini et al., 2019). If safe landfilling cannot be ensured, the EU Parliament suggested that other safer methods could be subsequently considered, including stabilization to reduce the danger and inertization of the crystallochemical structure of the fibers (OVAM, 2016; Paolini et al., 2019; Spasiano and Pirozzi, 2017; Tomassetti et al., 2020). Inertization is typically reached via thermal, chemical, and mechanochemical processes, whose products can in most cases be recycled in substitution of raw materials. A detailed description of the different processes is provided in the following sections, whereas an overview of the advantages and disadvantages of individual processes is provided in the following TABLE 2.

### 2.2.1 Stabilization processes

The basic approach for handling waste containing asbestos is landfilling, where properly bagged waste is placed in landfill sites and then covered with a layer of soil or comparable material to prevent aerodispersion (Bureau KLB, 2018). Prior to landfilling, the waste can be treated via a stabilization process, which aims at reducing the hazard of waste containing asbestos by imprisoning it in a cement of resinoid matrix (OVAM, 2016; Spasiano and Pirozzi, 2017). The simplest process is the so-called “encapsulation”, where waste containing asbestos is sorted, crushed, and then mixed with cement and additives to form concrete blocks of approximately 1 $m^3$ in volume, which are then landfilled (OVAM, 2016). The cement blocks are often double-bagged in plastic bags, taped, and clearly labeled before they are landfilled

(OVAM, 2016). By doing this, the hazard of waste containing asbestos (especially the non-friable fraction) is considerably reduced by means of dilution but not completely eliminated (Spasiano and Pirozzi, 2017). The final product (i.e., the cement blocks), which is in volume significantly bigger than the initial waste, is not reusable/recyclable (OVAM, 2016; Spasiano and Pirozzi, 2017).

**TABLE 2.** Overview of advantages and disadvantages of processes for stabilization and inertization of waste containing asbestos; table based on different studies (Bureau KLB, 2018; OVAM, 2016; Paolini et al., 2019; Spasiano and Pirozzi, 2017; Tomassetti et al., 2020).

| | Process type | Advantages | Disadvantages |
|---|---|---|---|
| Stabilization | Stabilization in cement blocks | • Incorporation of large amounts of heavy metal ions which are chemically bonding inside an inorganic amorphous network;<br>• The final process product is inert towards most chemical or biological agents can be disposed of in landfills; | • Increase in volume of the waste;<br>• Not a final solution, rather a postponing of the problem;<br>• Expensive method in the long term. |
| Inertization | Thermal treatments | • Incorporation of large amounts of heavy metal ions which are chemically bonding inside an inorganic amorphous network;<br>• The final process product is inert towards most chemical or biological agents can be disposed of in landfills;<br>• Flexibility to treat wastes of various types;<br>• Consolidated technology;<br>• Reduced amount of waste.<br>• Existing full-scale facilities. | • High energy demand for heating, as most products are asbestos-cements;<br>• Need to control the feeding ate to avoid too high a ratio between asbestos and vitrifying material;<br>• Formation of atmospheric pollutants;<br>• Need to deal with extreme temperature and high corrosion. |
| | Chemical | • Low energy consumption (process at room temperature);<br>• Transportable installations;<br>• Existing full-scale facilities. | • Long treatment time;<br>• Costs of reagents;<br>• Potentially highly corrosive conditions;<br>• Intrinsic risk from working with strong acids/alkaline;<br>• Need for treatment of liquid waste. |
| | Thermochemical | • No use of chemicals;<br>• When using reducing agents, the reaction is spontaneous;<br>• Products can be recycled as secondary materials. | • Prototype scale;<br>• High operational pressure;<br>• Costs of the reducing agents (e.g. metals). |
| | Mechano-chemical | • Similar technologies largely used in the mining industry;<br>• Can be done at a small scale, in transportable units.<br>• Fast and cheap. | • Potential risk of aerodispersion. |
| | Biological | • Cheap;<br>• Low energy consumption;<br>• Can be performed in-situ.<br>• Promising for contaminated soils. | • Long treatment time<br>• Potentially incomplete destruction of fibers;<br>• Only proved for fibers, not in matrix conditions. |

### 2.2.2 Inertization processes

#### 2.2.2.1 Thermal processes

A modification of the crystal-chemical structure of the amyloidous silicates is obtained at temperatures high enough (typically >1200°C) so that fibers are no longer stable. Different asbestos minerals have different decomposition temperatures, ranging from 400 to 1040 °C (OVAM, 2016). The obtained products are significantly reduced or utterly devoid of toxicity and danger (Paolini et al., 2019; Witek and Kusiorowski, 2017). In addition to the absence of asbestos in the solid product from the thermal treatment, Tomassetti et al. (2020) additionally conclude that no production and emissions of fibers occur during the process. An overview of thermal treatment processes for inertization of waste containing asbestos is provided in TABLE 3, whereas their advantages and disadvantages are summarized in TABLE 2. Additional details can be found in Paolini et al. (2019).

**TABLE 3.** Overview of thermal treatment processes for inertization of waste containing asbestos; table based on different studies (Bureau KLB, 2018; Lázár et al., 2018; OVAM, 2016; Paolini et al., 2019; Spasiano and Pirozzi, 2017; Tomassetti et al., 2020; Witek and Kusiorowski, 2017; Znamenáčková et al., 2016).

| Process type | T range [°C] | Energy consumption [kWh/kg] | Use of final byproducts |
|---|---|---|---|
| Simple vitrification | 650-1600 | 0.63-1.0 | Inert materials used in construction industry; Railway roadbed; Forsterite for road substrate and concrete production; production of insulation materials. |
| Vitrification with controlled recrystallization | 1200-1300 | n.a. | Additive for concrete production; Inert materials used in construction industry. |
| Thermal treatment with inorganic materials (ceramitization) | 650-1200 | 0.5-1.55 | Raw material for clinkers. |
| Microwave | 1090-1200 | n.a. | Road substrate. |
| Oxyhydrogen | 1450-1550 | n.a. | n.a. |
| Pyrolysis | 1300-1600 | n.a. | n.a. |

#### 2.2.2.2 Chemical and thermochemical processes

Chemical additives are added to lower the melting temperature or enhance the mineralogical decomposition of the compounds included in the asbestos structure (Paolini et al., 2019). Chemical treatments are performed at relatively low temperatures (between the room and 100°C) but require significant amounts of chemicals and generate wastewater requiring further treatment (Paolini et al., 2019). To eliminate the problem of reagents, supercritical water (i.e., 250 MPa at 650°C) can be used in hydrothermal treatments, operating at neutral pH. An alternative thermochemical process involves the use of reducing agents (e.g., metal in its elementary state).

**TABLE 4.** Overview of the chemical and thermochemical treatment processes for inertization of waste containing asbestos; table based on different studies (Allen and Smith, 1994; Bureau KLB, 2018; Jo et al., 2017; Maletaškić et al., 2018; McCutcheon et al., 2015; OVAM, 2016; Paolini et al., 2019; Spasiano and Pirozzi, 2017; Talbi et al., 2019).

| Process type | T range [°C] | Chemicals used | Comment | Use of final byproducts |
|---|---|---|---|---|
| Strong basic | Room-200 | NaOH<br>KOH | Chemical | Flocculants |
| Strong acid | 80 | $H_3PO_4$ | Chemical | Phosphate fertilizers |

| | | | | |
|---|---|---|---|---|
| | | HCl<br>$H_2C_2O_4$<br>$H_2SO_4$<br>$HNO_3$ | | |
| Fluoride | 80 | HF | Chemical | Insulating and flame retardant material |
| Hydrothermal | 250-650 | $H_2O_2$<br>milky whey | Thermo-chemical | Inert materials used in construction industry; Silicates for ceramic industry and magnesium solution for agriculture. |
| Reducing agent | 1600 | Mg + $Fe_2O_3$ | Thermo-chemical | n.a. |

#### 2.2.2.3 Mechanochemical treatments

The treatment consists in using crushing machines – including high-energy milling or ultra-milling - to destroy the crystal lattices and the molecular bonds present in asbestos (Paolini et al., 2019). The energetic fragmentation induced by the milling results in a progressive amorphization by the release of the hydroxyl ions needed to maintain the crystalline structure (Bureau KLB, 2018; Colangelo et al., 2011; OVAM, 2016; Paolini et al., 2019; Radvanec et al., 2013; Spasiano and Pirozzi, 2017). Mechanochemical treatments build on approaches and technologies developed and employed mainly in the mining industry to obtain fine powders (Colangelo et al., 2011). The energy consumption for mechanochemical treatments can be estimated in the order of 60-70 kWh/ton (Bureau KLB, 2018), whereas the processing time is in the order of 2 hours (Colangelo et al., 2011). Products from mechanochemical treatments can be used, e.g., as a mineral powder for the production of building materials (Bureau KLB, 2018; Colangelo et al., 2011; Paolini et al., 2019; Spasiano and Pirozzi, 2017).

#### 2.2.2.4 Biological treatments

Asbestos fibers are generally harmful to both many animals and vegetal species. However, some species of fungi, lichens, and bacteria that can weather asbestos exist (Spasiano and Pirozzi, 2017). In particular, some fungi excrete siderophores and other chelating molecules, which allow extracting iron ions from asbestos fibers, thereby reducing their toxicity (Bureau KLB, 2018; Spasiano and Pirozzi, 2017). A similar ability to grow on asbestos fibers was seen for some species of lichens and bacteria (Spasiano and Pirozzi, 2017). These processes are, however, generally very slow, both because of the natural growth rate of the fungi/lichens/bacteria and the fact that most waste-containing materials have a cement-like matrix, which prevents access to asbestos fibers (Bureau KLB, 2018; Spasiano and Pirozzi, 2017). Biological processes are generally technologically immature (Bureau KLB, 2018; OVAM, 2016; Spasiano and Pirozzi, 2017).

### 2.2.3 Leaching of asbestos from waste

Available literature addresses leaching of asbestos from waste only in relation to chemical treatment of waste containing asbestos, in specific and artificial conditions with particularly high or low pH (see section 2.2.2.2 for details). Studies quantitatively addressing the leaching of asbestos from waste could not be found.

# 3. Current situation in Denmark

## 3.1 Products containing asbestos

A comprehensive overview of the (known) applications of asbestos in Denmark is provided by Arbejdstilsynet (2010), covering inter alia, the type of products, period of usage, brands selling the individual products, and concentration of asbestos. Some examples have been extrapolated for a few selected materials. Examples of materials and products containing asbestos used in Denmark are provided in TABLE 5; a more comprehensive overview can be found in Arbejdstilsynet (2010).

**TABLE 5.** Selected examples of materials and products containing asbestos used in Denmark over time. Data retrieved from Arbejdstilsynet (2010).

| | | 1920 | 1925 | 1930 | 1935 | 1940 | 1945 | 1950 | 1955 | 1960 | 1965 | 1970 | 1975 | 1980 | 1985 | 1990 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Special components | Filler in cement | X | X | X | X | X | X | X | X | X | X | X | X | X | X | |
| | Asbestos cement tiles | X | X | X | X | X | X | X | X | X | X | X | X | | | |
| Products for interior surfaces | Vinyl for floor and wall | | | X | X | X | X | X | X | X | X | X | X | X | | |
| | Floor casting | X | X | X | X | X | X | X | X | X | X | X | X | X | | |
| | Paints | | | | | | | | | X | X | X | X | X | | |
| | Tiles adhesives | X | X | X | X | X | X | X | X | X | X | X | X | X | | |
| | Sealants | X | X | X | X | X | X | X | X | X | X | X | X | X | | |
| Roofing | Eternit slate | | | X | X | X | X | X | X | X | X | X | X | X | X | X |
| | Ondulated plates | | | X | X | X | X | X | X | X | X | X | X | X | X | X |
| | Asphalt products | | | X | X | X | X | X | X | X | X | X | X | X | | |
| | Roofing membranes | X | X | X | X | X | X | X | X | X | X | X | X | X | | |
| | Roofing felt | | | | | | | | | | X | X | X | X | | |
| Facade | Eternit cladding panels | | | X | X | X | X | X | X | X | X | X | X | X | X | |
| | Eternit facade plates | | | | | | | | | X | X | X | X | X | X | X |
| | Wall covering | | | | | | | | | | X | X | X | X | X | |
| | Natursten med asbest | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| Insulation | Insulation for buildings | X | X | X | X | X | X | X | | | | | | | | |
| | Technical insulation | X | X | X | X | X | X | X | X | X | X | X | X | X | | |
| | Fire insulation for elevators | X | X | X | X | X | X | X | X | X | X | X | X | X | | |
| Perforated and non-perforated plates | Fibreboard with asbestos | X | X | X | X | X | X | X | X | X | X | X | X | X | | |
| | Asbestos plates | | | | | | | | X | X | X | X | X | | | |
| | Noise dumper | | | | | | | | X | X | X | X | X | | | |

As quantitative data are not available, an estimation of the amounts of specific materials and products that entered the Danish market over time is not possible. However, it could be expected that the distribution into applications may somehow be close to the global situation shown in TABLE 6.

## 3.2 Amount and treatment of waste containing asbestos

Waste containing asbestos originates primarily from the building/demolition sector. An overview of the amount of WCA generated in Denmark in the period 2012-2019 is provided in FIGURE 3; it is seen that WCA generation has been increasing during the last decade. Recycling hazardous waste containing asbestos is not allowed in Denmark, and incineration is not done (see section 3.5.1); hence, all waste containing asbestos is landfilled in Denmark. It should be mentioned that the Danish Waste Statistics (Miljøstyrelsen, 2021) report that minor amounts of waste containing asbestos are recycled or incinerated; however, this may be due to incorrect registration of the waste data

**TABLE 6.** World asbestos commercial applications in the 1980s. Table is taken from Paglietti et al. (2016).

| Asbestos commercial applications | % on total |
|---|---|
| Asbestos cement products | 70 |
| Vinyl asbestos flooring | 10 |
| Friction products | 7 |
| Asbestos paper and felt | 5 |
| Gaskets and packings | 3 |
| Paints, roof coatings, caulks, etc. | 2 |
| Filter media | 2 |
| Asbestos textile products | 1 |
| All other uses | < |

FIGURE 3 also provides an estimation of the amount of asbestos contained in construction and demolition waste that is landfilled. The estimate was done based on data about waste containing asbestos reported in the Danish Waste Statistics (Miljøstyrelsen, 2021) and concentrations of asbestos in different materials available in Arbejdstilsynet (2010). It should be noted that the estimation is highly uncertain, both because the data available in official statistics are highly aggregated and does not provide a detailed overview of the specific materials involved and because even within specific applications, the content of asbestos may vary significantly. In particular, statistical data do not provide information on waste containing both asbestos and other environmentally problematic substances (WCAPS).

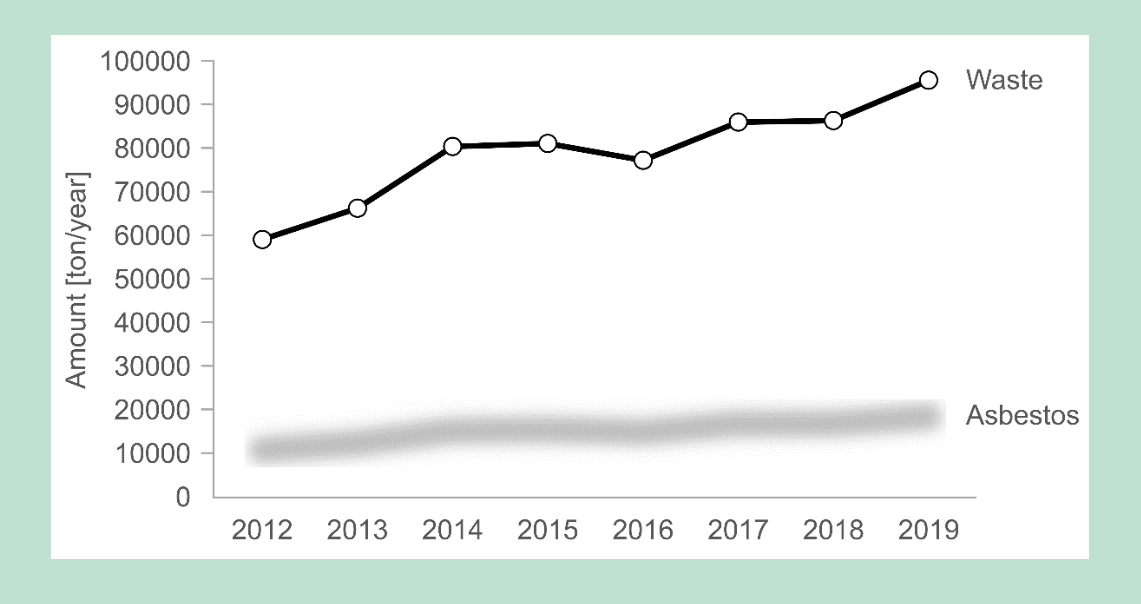

**FIGURE 3.** Yearly generation [ton/year] of waste containing asbestos in Denmark, in the period 2012-2019. The grey line estimates the amount [ton/year] of asbestos contained in the waste; the line is blurred to indicate significant uncertainty associated with the estimate. Data for 2012 are from “Affaldstatistik 2018 – Rå data”, whereas data for 2013-2019 are from “Affaldstatistik 2019 – Rå data”, retrieved from Miljøstyrelsen (2021), filtered by EAKLevel3Navn containing the word “asbest”. Content of asbestos in different materials was retrieved from Arbejdstilsynet (2010).

## 3.3 Survey of municipalities and companies

To complement and improve the publicly available data on occurrence and composition of WCAPS, a questionnaire was sent out to municipalities and companies involved in handling and managing WCAPS. The two questionnaires are provided in Appendix 3 (FIGURE 9 and FIGURE 10), and a summary of the main findings is provided in the following sections.

### 3.3.1 Municipalities

- Response rate: the questionnaire was sent to all 98 Danish municipalities; forty (40) responses were returned, representing about 46 municipalities (a few municipalities teamed up for their answer). The response rate was about 47%.
- About waste containing only asbestos (WCA):
    - Generation rates for WCA: 7–4000 ton per year
    - Use of coating before/during removal operation: no coating material; in general, they only spray water in order to reduce the release of asbestos fibers into the atmosphere.
    - Examples of materials: many examples. The largest most common fractions that have been mentioned: corrugated/slates Eternit (bøge-/skife-eternit), vinyl/linoleum flooring with adhesive (linoleum/vynil med klæb), tiles with adhesive (fliser/klinker med klæb), roofing felt (tagpap), insulating materials, etc.
    - Management option: landfill
- About waste containing both asbestos and other environmentally problematic substances (WCAPS):
    - Only ~18 questionnaires answered the second section of the questionnaire.
    - The presence of other environmentally problematic substances should be identified in connection to the preparation of the Environmental Mapping Report (i.e., “Miljøkortlægningsrapport”).
    - Not all municipalities have experienced WCAPS. The occurrence could be linked to differences in demolition projects (e.g., type and age of buildings), but also, as mentioned by one respondent, by the fact that different municipalities have different requirements for sampling and analysis of environmentally problematic substances.
    - WCAPS are sent further to licensed companies; the municipality is only involved in handling the materials when temporary storage occurs.

### 3.3.2 Companies

- Response rate: the questionnaire was sent to 15 demolition companies (ABVAC A/S, Allan Ploug A/S, Bergmann Gruppen A/S, G. Tscherning A/S, H. J. Hansen Genvindingsindustri A/S, Hvidberg A/S, JC Nedrivning A/S, Karl Popp ApS, Kingo Karlsen A/S, LH Hockerup A/S, Nedrivningsaktieselskabet J. Jensen, Odense Nedbrydning ApS, P. Olesen og Sønner A/S, Søndergaard A/S, Weisleder Nedrivning A/S) and 4 waste handling companies (Citycontainer, Deponi Syd, Sten og Grus Prøvestenen A/S, Motas I/S) that were mentioned by municipalities in their answers to questionnaires. Eight (8) answers were returned, corresponding to a response rate of ~42%.
- About waste containing only asbestos (WCA):
    - Generation rates for WCA: 3–5000 ton per year
    - Use of coating before/during removal operation: no coating material; it may be packed into plastic bags.
    - Examples of materials: many examples. The largest most common fractions that have been mentioned: (bøge-/skife-)eternit, vinyl/linoleum flooring with adhesive (vinyl/linoleum med klæb), tiles with adhesive (fliser/klinker med klæb), roofing felt (tagpap), insulating materials, etc.
    - Management option: landfill
- About waste containing both asbestos and other environmentally problematic substances (WCAPS):
    - Generation rates for WCAPS: 0–100 ton per year

- The generation of WCAPS is probably underestimated, as small renovation works (e.g., new tiles in a bathroom) that entail less than 1 ton of waste do not need to be reported to municipalities via the Environmental Mapping Report (i.e., Miljøkortlægningsrapport). The waste is then delivered by citizens at recycling stations, from where it moves to a landfill or to recycling[1]. While this is according to rules, municipalities do not have estimations of the amount of WCAPS delivered this way (i.e., not identified as WCAPS).
- One company mentioned that disposal of WCAPS is rather problematic, both in Denmark and abroad, both because of the costs and the unclear rules. It is reasonable to assume that "creative" solutions (e.g., limited sampling or restricted analyses) may be in some cases adopted to obtain a less restrictive classification of the waste (e.g., either containing asbestos or containing other environmentally problematic substances).[2]

### 3.3.3 Most relevant WCAPS materials

Based on the responses from the municipalities and the companies, the following WCAPS materials were identified as the most relevant (either because of frequency or amounts):

- Vinyl/linoleum flooring + asbestos + heavy metals;
- Tiles + asbestos + heavy metals;
- Roofing felt + asbestos + organic pollutants;

It was hence decided that these three materials would be further evaluated in the project (see section 3.5), as relevant illustrative examples.

## 3.4 Procedure for handling waste containing asbestos (WCA) during demolition and renovation work

Handling of WCA during demolition and renovation projects is organized and monitored by individual municipalities. Some variations can hence be seen across different municipalities in Denmark. Recently, the network *Sjællandsnetværket for Bygge- og Anlægsaffald* prepared the guidelines "*Forvaltningsgrundlag for bygge- og anlægsaffald"* (in English, "Management basis for construction and demolition waste") describing the procedures for handling materials and waste during demolition projects, in an attempt to create consensus and harmonize decisions and activities (Sjællandsnetværket for Bygge- og Anlægsaffald, 2020). The general procedure is shown in FIGURE 4 and summarized in the following sections; for a complete and detailed description, the original publication including and the cited documents should be used as a reference instead.

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[1] Recycling of waste containing asbestos is not allowed. The statement is to be intended that small amounts of waste containing asbestos may be sent to recycling, because the presence of asbestos is not known. This could be for example, because the amount of waste was <1 ton, and a screening was not performed.

[2] Original text: "*Når det kommer til bortskaffelse af AHAFS, er der pt. ingen afsætnings-/bortskaffelsesmuligheder mig bekendt (deponering som farligt affald i Danmark er ikke en reel løsning grundet de uforholdsmæssigt høje omkostninger til udvaskningstest). Bortskaffelse (deponering) i udlandet er også forbundet med væsentlige både logistiske, praktiske og økonomiske udfordringer.*

*Da de private entreprenører (nedrivere mv.) og rådgivere efterhånden er blevet bekendt med problematikken, er det nærliggende at forestille sig, at der findes "kreative løsninger" – affaldet skal jo bortskaffes. Et eksempel på en kreative løsning er at undlade at tage repræsentative prøver og/eller undlade at foretage analyser af både asbest og andre stoffer (tungmetaller mv.) i forbindelse med en kortlægning. Dette kunne fx være kun at tage prøver af asbest i klæben på klinker/fliser, men undlade at analysere for bly og zink. Klinker/fliserne kan dermed bortskaffes som asbestholdigt affald på kommunens anvisning.*"

**FIGURE 4.** Overview of tasks and responsibilities for municipality and developers before, during and after demolition or renovation works. Redrawn and translated from Sjællandsnetværket for Bygge- og Anlægsaffald (2020).

### 3.4.1 Tasks before demolition and renovation work

Before the demolition, renovation, and maintenance work, the “developer” (or who else covered by the Danish term “bygherre”) has the obligation of screening, mapping and notifying the authorities about the materials contained in the building in question. The objective is to identify whether environmentally problematic substances (e.g. asbestos, PCBs, PAHs, heavy metals, chlorinated paraffins) are present, so the waste are  sorted and handled accordingly. While the construction or demolition company has the legal responsibility, this screening/mapping/reporting is often done by specialized companies and subcontractors. There is no specific legal requirements on whether a person must have specific experience, education or certification to carry out the screening; it is the municipal officer allocated to the case, who assess whether the person has an adequate profile. The municipality also assess whether the screening/mapping activities are adequate and trustable.

### 3.4.1.1 Screening

The initial screening is a key phase, as it determines to what extent a more detailed mapping of the building is needed. A screening should be carried for the entire building or plant, or the parts affected by the planned work, with respect to two types of activities: i) demolition/renovation/maintenance activities producing >1 ton of waste or  renovation; ii) replacement of double-glazed windows that may have been manufactured in the period 1950 to the end of 1977 (BEK 2159:2020, 2020). A screening should be done with respect to the environmentally problematic substances that may be present in the building/plant/waste, e.g. PCBs, chlorinated paraffin, PAHs, asbestos and heavy metals (BEK 2159:2020, 2020). A list of environmentally problematic substances most often appearing is provided in TABLE 7. A screening is also necessary when it is believed that environmentally problematic substances are present, e.g. after a visual inspection.
In practical terms, the screening is carried out by retrieving information (e.g. from the BBR-register, or the municipality's building archive) about what year the building was constructed or renovated. This will be complemented by a visual inspection of the (part of) building to be demolished/renovated.

**TABLE 7.** Overview of environmentally problematic substances to be targeted during the screening phase. Info taken from Sjællandsnetværket for Bygge- og Anlægsaffald (2020).

| Heavy metals | Environmentally problematic organic substances | Other environmentally problematic substances |
|---|---|---|
| Arsenic (As) | Brominated flame retardants | Asbestos |
| Lead (Pb) | CFCs, HCFs and HFCs | Other environmentally problematic substances that have been used or produced in the building/plant in question (typically industrial buildings) |
| Cadmium (Cd) | Chlorinated paraffins | |
| Copper (Cu) | Hydrocarbons | |
| Chromium (Cr) | PAHs | |
| Mercury – inorganic (Hg) | PCB | |
| Nichel (Ni) | | |
| Zinc (Zn) | | |

### 3.4.1.2 Mapping

When the screening indicates that environmentally problematic substances may be present, a more thorough investigation needs to be carried out for the building or plant or the specific parts of them (BEK 2159:2020, 2020). A construction work relating to several buildings or facilities, must be assessed together (BEK 2159:2020, 2020). This mapping includes analysis of material samples to determine whether and to what extent the building or parts of it are contaminated with environmentally problematic substances. Sampling and mapping activities will vary depending on the building (e.g. age, type); in some cases, sampling may occur also during the demolition/renovation process, for example when hidden materials becomes visible. While there is no predefined plan, municipalities typically require fewer samples for buildings where few different materials were used, compared to buildings where many different materials were used (and e.g. all walls are painted). In a building with uniform floors, ceilings, walls, etc. one representative sample of each material (possibly an aggregate sample of, for example, several walls) may be typically sufficient. If there are  many different types of floors, e.g. painted floors, tile floors and linoleum floors, more samples must be taken; the same applies if the walls and ceilings vary in material and treatment. The sampling is to be developed on a case-by-case basis, considering specific characteristics of the building (e.g. material composition, UV exposure, and climate) and approved by the municipality. Samples must be taken according to the principle of representative sampling, and includes both primary (i.e. originally added with contaminants) and secondary (i.e. not originally containing contaminants) sources. While a sampling plan is to be developed on a case-by-case basis, a purely illustrative example is provided in the following TABLE 8.

**TABLE 8.** Illustrative example of a sampling plan for single-houses and larger buildings. The examples is not a standard requirement, as a plan has to be designed on a case-by-case basis. The example is taken from Sjællandsnetværket for Bygge- og Anlægsaffald (2020).

| Fraction | Material | Small buildings (e.g. detached houses) | Large buildings (e.g. multifloor dwellings) |
|---|---|---|---|
| **Asbestos** | Insulation (eg bends, pipe types with insulation, built-up tag) | 1-2 samples per material | Typically 4-20 samples |
| | Tile adhesive (all types of tiles should be examined) | 1-2 samples per material | Typically 4-20 samples |
| | Roof tiles, wall panels, cover panels (assessment based on material’s age) | 1-2 samples per material (when in doubt) | Typically 2-6 samples |
| **Lead** | Glazed tiles and sanitary ware (not visually inspectable) | 1-2 samples per type of tiles | Typically 1-10 samples |
| **Lead and other heavy metals** | Painted surfaces (e.g. wood, moldings, walls, doors, metal surfaces) | 1-2 samples per aggregated paint layer or by age | Typically 3-40 samples |
| **PCB** | Elastic joints, all types | More than 1 sample per floor, at least 2 different places and more than 3 samples if over 150 m$^2$ | Typically 3-20 samples |
| | Paint (all types of painted surfaces) | 1 sample per each painted layer,<br>or 2-3 samples of large surfaces | |
| | Rubber strip / wooden frames in double glazing | A high PCB content in the rubber strip or wooden frame indicates either a PCB-containing double-glazed window and/or secondary contamination. Production date on thermal windows is to be checked.<br>Typically 2 - 10 samples | |

### 3.4.1.3 Reporting

The municipality can ask the developer (i.e.. “bygherre” in Danish) to deliver a written Environmental Mapping Report (i.e., *Miljøkortlægningsrapport)*, so that the waste can be classified and a plan for waste management is prepared accordingly, including decisions regarding the final treatment of waste. The construction or demolition company must state whether the generated waste may be considered hazardous waste and if the waste can be recycled, incinerated, or landfilled. The construction or demolition company is obliged to report waste generation for demolition or renovation work generating >1 ton of waste (combustible construction and demolition waste, construction waste for landfilling, commercial waste in the form of source-sorted construction and demolition waste). Different approaches, rules and obligations for reporting exist depending on the extent of expected contamination; further details can be found in Sjællandsnetværket for Bygge- og Anlægsaffald (2020).

## 3.4.2 Classification and treatment of construction and demolition waste

Upon receiving the notification, the municipality must i) Assess whether there is sufficient information to be able to process the case; ii) Classify the notified waste; iii) Make instructions for the waste handling in accordance with the municipality's regulations. The municipality has 14 days to respond to the notification (BEK 2159:2020, 2020; Sjællandsnetværket for Bygge- og Anlægsaffald, 2020).

**TABLE 9.** Limit values for content [mg/kg$_{DM}$] of environmentally problematic substances in construction waste (adapted and translated from Sjællandsnetværket for Bygge- og

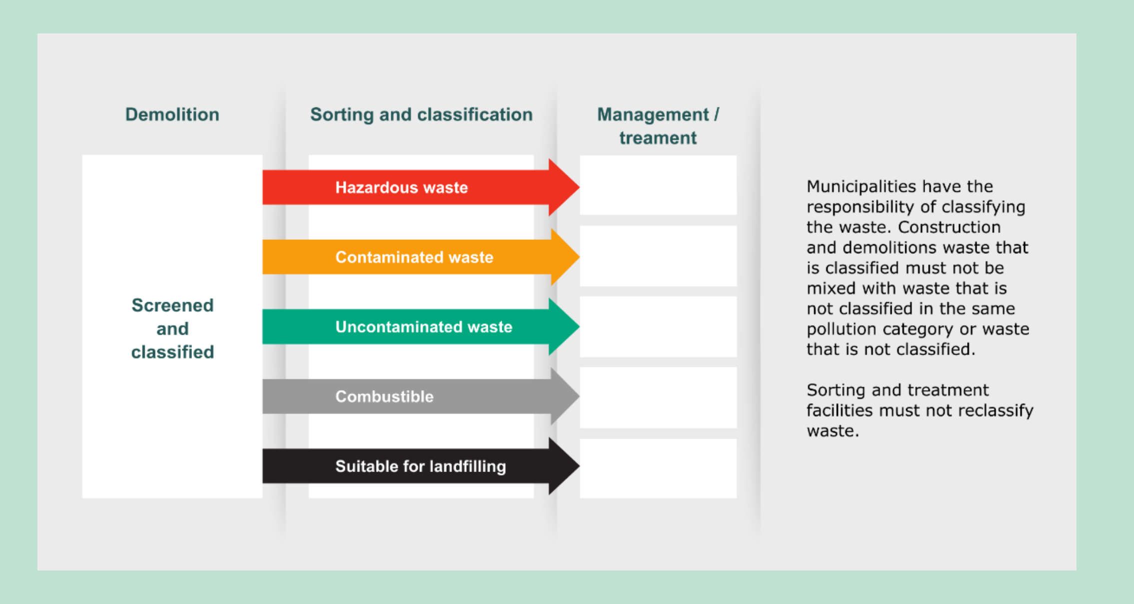
Anlægsaffald, 2020). Please note that individual municipalities may adopt modified values. The color coding for ‘Uncontaminated waste’, ‘Contaminated waste’, ‘Hazardous waste’ will be used later in the text when comparing the results of analytical activities with the limit values. For multiple elements, summation rules for HP 14 "Ecotoxic", laid out in the Council Regulation (EU) 2017/997 (European Council, 2017), applies.

| **Substance-group** | **Substance** | **Classification/limit value [mg/kg$_{DM}$]** | | |
|---|---|---|---|---|
| | | **Uncontaminated waste** | **Contaminated waste** | **Hazardous waste** |
| Asbestos | Asbestos | Not detected | Detected – Non-dusty | Detected – Dusty |
| Heavy metals | Arsenic (As) | <20 | 20-1000 | >1000 |
| | Lead (Pb) | <40 | 40-2500 | >2500 |
| | Cadmium (Cd) | <0.5 | 0.5-1000 | >1000 |
| | Copper (Cu) | <500 | 500-2500 | >2500 |
| | Chromium (Cr-total) | <500 | 500-1000[b] | >1000 |
| | Chromium (Cr-VI) | <20 | 20-1000 | >1000 |
| | Mercury (Hg, organic) | <1 | 1-2500 | >2500 |
| | Mercury (Hg, inorganic) | <1 | 1-2500 | >2500 |
| | Nikkel (Ni) | <30 | 30-1000 | >1000 |
| | Zinc (Zn) | <500 | 500-2500 | >2500 |
| PCB | PCB-total[a] | <0.1 | 0.1-50 | >50 |
| PAHs | Naftalene | | | ≥2500 |
| | Benz(a)pyrene | <0.3 | 0.3-1000 | ≥1000 |
| | Benzo(b)fluorantene | | | ≥1000 |
| | Benzo(j)fluorantene | | | ≥1000 |
| | Benzo(k)fluorantene | | | ≥1000 |
| | Dibenzo(a,h)antracene | <0.3 | 0.3-1000 | ≥1000 |
| | PAH-total | <4.0 | [c] | [c] |
| Hydrocarbons | C6-C10 | <25 | 25-1000 | ≥1000 |
| | C10-C15 | <40 | sumC10-C20 <1000 | sumC10-C20 ≥1000[d] |
| | C15-C20 | <55 | | |
| | C20-C35/40 | <100 | 100-1000 | ≥1000[d] |
| | C6-C35/40-total | <100 | 100-1000 | ≥1000[d] |

[a] In case the material recovered has a maximum content of PCBs up to 2.0 ppm (measured by the source and in the surface the place where the concentration is judged to be highest) the municipality must be notified four weeks before use (see restproduktbekendtgørelsens § 16 for details).
[b] Limit values for Chromium total and Chromium III have not yet been set according to the European Chemicals Agency (ECHA) and CLP (classification, labeling and packaging of chemicals).
[c] There is no fixed value for PAH-total as there are different values for individual PAH compounds.
[d] If the analytical results for the individual hydrocarbon intervals are below 1,000 mg/kg, the waste must be classified as non-hazardous waste. If the concentration is above 10,000 mg/kg, the waste must be classified as hazardous waste. If there are concentrations in the range 1,000-10,000 mg/kg$_{DM}$, the step-by-step procedure provided in Sjællandsnetværket for Bygge- og Anlægsaffald (2020) is used to determine whether the waste is to be classified as hazardous.

While waste is generally classified as hazardous based on a number of different criteria, the focus is hereby on the content of environmentally problematic substances. An overview of the limit values for concentration of a number of environmentally problematic substances in construction waste is provided in TABLE 9; the color code (green, yellow, red) indicates the classification of the waste as uncontaminated, contaminated or hazardous; this color code will be used later in the report when presenting the results related to the characterization of waste samples. It is not allowed to dilute contaminated with uncontaminated waste in order to change its classification and related treatment options. While typical guidelines exist, individual municipalities may adopt different threshold values for the classification. Additional details regarding the classification and the relative procedure can be found Sjællandsnetværket for Bygge- og Anlægsaffald (2020).

The municipality also decides if the waste may undergo recycling, incineration or landfilling. An appropriate treatment is identified using prioritization schemes (basically the waste hierarchy) and taking into consideration the quality of the waste. Capacity and availability of treatment facilities may play a role in the decision, as well as restrictions related to transportation (for example in relation to transboundary shipment of waste). An overview of the classifications options for construction and demolition waste is provided in FIGURE 5.



Municipalities have the responsibility of classifying the waste. Construction and demolitions waste that is classified must not be mixed with waste that is not classified in the same pollution category or waste that is not classified.

Sorting and treatment facilities must not reclassify waste.

**FIGURE 5.** Overview of the classification of construction and demolition waste by the municipalities. Redrawn and translated from Sjællandsnetværket for Bygge- og Anlægsaffald (2020).

### 3.4.3 Tasks during demolition and renovation work

During the demolition and renovation work, the construction or demolition company must separate/remove the environmentally problematic substances and hazardous waste from the building, before the actual demolition work begins, and  the recyclable materials must be sorted out. This is typically achieved by performing selective demolition, which involves demolishing the building in such a way that the materials containing environmentally problematic substances or hazardous waste are sorted out, before the building is torn down. The municipality has the duty to supervise and eventually inspect the demolition and renovation work, and check compliance with the general rules for waste management, as well as the specific plan agreed prior to the beginning of the renovation work.

Requirements for source separation of construction and demolition waste follow the proportionality principle, thereby ensuring that the efforts for source separation do not overrun the environmental and economic benefits of waste recycling. Few exemptions to source separation exist, as described in details in Sjællandsnetværket for Bygge- og Anlægsaffald (2020).
In-loco reuse of e.g. concrete and bricks is a possibility. However, documentation showing that environmentally problematic substances are not present or are present in not-harmful levels should be provided. Alternatively, a decontamination/purification treatment (e.g. for paints) for those substances may be implemented prior to reuse. Again, the principle of proportionality applies in this situation

### 3.4.4 Tasks after demolition and renovation work

It is the responsibility of the construction or demolition company (i.e. the waste producer or ”Bygherre”) that the waste is transported in a safely manner and according to the regulations for transport of waste to the designated destination. This operation can obviously be performed by registered sub-contractors. The municipality may request that the construction or demolition company submit the necessary documentation showing that waste transport and delivery was completed according to the agreed waste management plan.

Depending on the classification (see FIGURE 5), each waste type can be delivered only to treatment facilities approved for that specific waste. Mixing of waste at the reception facility may take place, but only within the same pollution category: uncontaminated, contaminated or hazardous waste. It is not legal for the reception facilities to mix waste for the purpose of diluting the pollution. Waste classified for incineration or landfill must be handled as such, meaning that the waste must be supplied to incineration plants or landfills. Different handling/treatment can only be considered if the municipality reclassifies the waste; waste treatment facilities are not allowed to reclassify waste.

Some facilities may be approved for reception of unsorted/mixed waste; the detailed composition of the mixture may typically not be described in the approval, meaning that specific restrictions may not be implemented. However, illegal mixtures are not allowed to be received. The municipality is (depending on the type of producer and handler) supervising or responsible for ensuring that the waste can be received by the waste treatment company, that it is compliant with their environmental approval, and that the treatment companies receive adequate information about the waste prior to reception.

An additional possibility is that waste is treated at facilities located abroad. Export of waste is handled by the Danish Environmental Protection Agency, who grants the export permission. Additional details on the procedure and responsibilities for export of construction and demolition waste can be found in the Waste Shipments Regulation (European Parliament, 2006b) and in the guidance documents e.g. Sjællandsnetværket for Bygge- og Anlægsaffald (2020).

## 3.5 Management of waste containing asbestos and other environmentally problematic substances (WCAPS)

Depending on the specific substance, different rules exist in Denmark regulating the treatment and disposal of waste containing environmentally problematic substances. A brief overview is provided in the following.

### 3.5.1 Waste containing asbestos

When waste contains asbestos fibers, the following general principles apply:

- Waste must be landfilled, and cannot be recycled (BEK 1792:2015, 2015; BEK 2159:2020, 2020).
- Incineration is typically not considered or listed as an option for treatment of waste containing asbestos (Sjællandsnetværket for Bygge- og Anlægsaffald, 2020).
- According to Bilag 2 of BEK 2159:2020 (2020), asbestos containing materials which are not dusty (i.e. 17 06 05) are classified as non-hazardous , whereas asbestos containing materials which are dusty (i.e. 17 06 06 Asbestholdige byggematerialer, støvende) are classified as “hazardous” (i.e. “farlig”).
- Waste can be deposited in a mineral waste landfill if certain requirements are fulfilled, among which that the waste must not contain hazardous substances other than bound asbestos and asbestos fibers bound by a binder or wrapped in plastic (BEK 1253:2019, 2019).
- Waste can be deposited in a landfill for mixed waste if certain requirements are fulfilled, among which that the waste must not contain hazardous substances other than bound asbestos and asbestos fibers bound by a binder or wrapped in plastic (BEK 1253:2019, 2019).

- Both for mineral and mixed waste landfills, waste containing asbestos must be disposed of in a separate cell or a separate disposal unit (BEK 1253:2019, 2019).
- Additional criteria for landfilling of waste containing asbestos in mineral and mixed waste landfills are listed in BEK 1253:2019 (2019).

### 3.5.2 Waste containing PCB

Rules about handling waste containing PCB are generally linked to the Stockholm Convention on Persistent Organic Pollutants (POPs) and the POP Regulation (European Parliament, 2019 and subsequent amendments) implementing the Stockholm Convention at the EU level. In general an attempt to remove PCB from the waste must be made. If this is not possible, the waste contaminated with PCB must be sorted out and disposed of using the operation in appendix V, part 1 (D9 “D9 Physico-chemical treatment” and D10 “Incineration on land”) to the POPs regulation in such a way that the PCB is destroyed (European Parliament, 2019). If PCB in the waste is <50 mg/kg the waste can be recovered or disposed of in an alternative way, however it must be in accordance with other relevant regulation and article 3 of the POPs regulation, which does not allow marketing of products containing PCB (European Parliament, 2019). In some specific cases, the waste contaminated with PCB (i.e. <50 mg/kg waste) can be landfilled in underground mines abroad. According to BEK 1253 (BEK 1253:2019, 2019), waste containing PCB (<50 mg/kg waste) can be landfilled. If the concentration of PCBs is very low (i.e. <0,1 mg/kg), some municipalities classify the construction and demolition waste as uncontaminated, meaning it can be sent for recovery/recycling. If the PCB concentration is ≥50 mg/kg, the waste must be classified as hazardous waste.

In Denmark, handling of waste containing PCB from households is decided and regulated by the individual municipalities. Information about this is typically stated in the Municipality’s waste regulation. For commercial waste (including waste originating from households but disposed of by craftsmen and contractors), the following TABLE 10 provides guidance on handling construction and demolition waste containing PCB.

**TABLE 10.** Overview of options for handling construction and demolition waste containing PCB. The table is translated, reorganized and further referenced from PCB-guiden (PCB-guiden, 2015) (specifically under https://pcb-guiden.dk/vejledning-affald-pcb).

| PCB Concentration | Classification | Guidelines |
|---|---|---|
| ≥50 mg/kg | Hazardous | Destroyed at an incineration plant with a permit for incineration of hazardous waste containing PCBs, or underground disposal (abroad). |
| <50 mg/kg | Non-hazardous (contaminated) | Destroyed at an incineration plant with a permit for incineration of hazardous waste containing PCBs.<br>In alternative, if handling of waste in incineration plants is difficult (e.g. large quantities of concrete), the waste can be landfilled, in the following manner:<br>• If the concentration is <1 mg/kg, the waste can be disposed of in landfills for inert waste. Because of the low concentration, disposal in separate cells or units is not necessary.<br>• If the concentration is in the range 1-50 mg/kg, the waste can be disposed of in landfills for mineral or mixed waste. For disposal in mineral waste landfill, the TOC must be <5%. The Danish Environmental Protection Agency recommends that this waste is disposed of in separate cells or units. |
| <0.1 mg/kg | Non-hazardous (uncontaminated) | Can be recycled as a replacement for sand, gravel and stone in accordance with the rules in the Executive Order for Residual Products, if the concentration does not exceed 2 mg PCB total/kg (measured at source) under certain conditions (BEK 1672:2016, 2016).<br>Individual municipalities have the duty and responsibility of assessing whether construction and demolition waste can be classified as uncontaminated. A concentration value for classifying waste as uncontaminated with PCB is not defined at the national level in Denmark. The Danish Environmental Protection Agency hence temporarily refers to the PCB guidelines of the City of Copenhagen (Københavns Kommune, 2015), stating that waste is uncontaminated with PCBs if the concentration is <0.1 mg/kg. |

### 3.5.3 Waste containing PAH

The following TABLE 11 provides guidance on handling construction and demolition waste containing PAH.

**TABLE 11.** Overview of options for handling construction and demolition waste containing PAH.

| PAH Concentration | Classification | Guidelines |
|---|---|---|
| >1000 mg/kg (for Benz(a)pyrene and Dibenzo(a,h)antracene) | Hazardous | Special incineration for hazardous waste (Sjællandsnetværket for Bygge- og Anlægsaffald, 2020) |
| ≥4 mg/kg (total)<br>0.3-1000 mg/kg (for Benz(a)pyrene and Dibenzo(a,h)antracene) | Non-hazardous | Final treatment depends on the specific material (Sjællandsnetværket for Bygge- og Anlægsaffald, 2020):<br>• Recycling: cement contaminated with oil, concrete into aggregate for asphalt, roofing felt<br>• Special incineration for hazardous waste: roofing felt;<br>• Landfill: paint, soot. |
| <4 mg/kg (total)<br><0.3 mg/kg (for Benz(a)pyrene and Dibenzo(a,h)antracene) | Non-hazardous (uncontaminated) | The waste can be recycled (Sjællandsnetværket for Bygge- og Anlægsaffald, 2020). Alternatively, waste can be disposed in landfill for inert waste, according to the Executive Order for Landfills (BEK 1253:2019, 2019). |

### 3.5.4 Waste containing heavy metals

Regulation for waste contaminated with heavy metals is various and relates to both the content of heavy metals in the waste as well as their potential release. When metals are collected as “clean” fractions, they are obviously not considered as contaminants, but as materials that could be sent directly to reuse/recycling, or eventually to other treatment. An overview of options for handling construction and demolition waste containing heavy metals is provided in TABLE 12.

**TABLE 12.** Overview of options for handling construction and demolition waste containing heavy metals. Summary of information from Sjællandsnetværket for Bygge- og Anlægsaffald (2020).

| Heavy metal | Waste type | Uncontaminated | Contaminated | Hazardous |
|---|---|---|---|---|
| Arsenic (As) | Wood impregnated with As | Incineration (approved plant) | Incineration (approved plant) | Hazardous waste incineration |
| Lead (Pb) | Paint on walls and alike | No restriction | Landfill | Hazardous waste incineration |
| | Paint on metals | Metal recycling | Metal recycling | Approved metal recycling |
| | Paint on wood | Incineration | Incineration | Hazardous waste incineration |
| Mercury (Hg) | Paint on walls and alike | No restrictions | Landfill | Hazardous waste incineration |
| | Paint on metals | No restrictions | Approved metal recycling | Special treatment |
| | Paint on wood | No restrictions | Incineration | Special treatment |
| Zinc (Zn) | Paint on concrete and ceramic | No restriction | Recycling (cement) | Special treatment |
| | Plasterboard | No restriction | Incineration | Special treatment |
| | Glazed tiles | No restriction | Recycling<br>Landfill | Special treatment |
| | Paint on metals | Metal recycling | Metal recycling | Approved metal recycling |
| | Paint on wood | Incineration | Incineration | Hazardous waste incineration |
| Heavy metals (generic) | Paint | No restrictions | Landfill | Hazardous waste incineration |
| | PVC flooring | | Landfill | Special treatment |
| | Tiles | Recycling<br>Landfill | Landfill | Hazardous waste incineration |
| | Glazed tile | | Landfill | Special treatment |

### 3.5.5 Waste containing multiple environmentally problematic substances

Existing regulations do not specifically address all cases where multiple environmentally problematic substances are present in waste. Hence, a risk-based precautionary approach is often taken when classifying the waste and deciding further treatment. For example, Sjællandsnetværket for Bygge- og Anlægsaffald (2020) states that if construction and demolition waste cannot be properly sorted out in different material fractions, the mixed waste must be reclassified based on the waste fraction characterized by the largest risk factor. Indicatively, the risk of asbestos contamination is assessed over the risk of PCB contamination, which is in turn assessed over the risk of heavy metal pollution (Sjællandsnetværket for Bygge- og Anlægsaffald, 2020); PAHs and hydrocarbons are not mentioned in the risk hierarchy.

**TABLE 13.** Examples of options for handling construction and demolition waste containing asbestos and other environmentally problematic substances. Information retrieved from Sjællandsnetværket for Bygge- og Anlægsaffald (2020).

| Substances | Material | Uncontaminated | Contaminated | Hazardous |
|---|---|---|---|---|
| Asbest + Heavy metals and PCB | Linoleum | - | Landfill | Special treatment[a] |
| Asbest + heavy metals | Tiles and clinker | - | Landfill | Special treatment<br>Special landfill[b] |
| Asbest + polyvinyl chloride (PVC) | Roofing felt[c] | - | - | Special treatment |

[a] Special treatment means that non-recyclable hazardous waste must be assigned to other types of facilities than conventional incineration, special incineration or national landfill; facilities for special treatment must be approved to receive the applicable type of non-recyclable hazardous waste (Sjællandsnetværket for Bygge- og Anlægsaffald, 2020).

[b] Special landfill is here interpreted as hazardous waste landfill for dusty materials.

[c] Asbestos in the adhesive

# 4. Experimental work

## 4.1 Scenarios

As defined in section 3.3.3, the following three materials were targeted for experimental work:

- Linoleum flooring containing both asbestos and heavy metals;
- Tiles containing both asbestos and heavy metals;
- Roofing felt containing both asbestos and heavy metals or organic pollutants.

The experimental activities were planned to investigate two potential scenarios. These scenarios are "potential" in the sense that they are currently not standard practice in Denmark.

- "**Landfill scenario**": disposal of waste containing both asbestos and relatively high content of pollutants (e.g., heavy metals, organic pollutants) in hazardous waste landfills is allowed if the waste complies with the acceptance criteria. However, this is generally not done because of economic reasons (e.g., costs of tests, small amounts of waste). This scenario investigates whether the selected waste samples containing both asbestos and relatively high contents of heavy metals may be fulfilling the leaching criteria defined for landfilling hazardous waste. The hypothesis is that, despite the relatively high solid contents, low releases of heavy metals occur. Laboratory experiments investigating this scenario are described in Section 4.3.
- "**Thermal treatment scenario**": in the case of waste samples containing both asbestos and relatively high contents of organic pollutants (i.e., PCBs >50 mg/kg, or PAHs >10000 mg/kg), it was hypothesized that a dedicated thermal treatment can be used to destroy (decompose) both the asbestos fibers and the organic pollutants. Laboratory experiments investigating this scenario are described in Section 4.4.

An overview of the experimental setup is provided in **Fejl! Henvisningskilde ikke fundet.**. A detailed description of the methodology is provided in the following paragraphs.

## 4.2 Collection, characterization and classification of waste samples

Four (4) waste samples of about 1-4 kg of 'Linoleum' (one sample), 'Tiles' (klinker, one sample) and 'Roofing felt' (tagpap, two samples) were collected by Motas I/S from waste material received by the company and normally sent further for treatment. The three materials selected for further work represent the most common waste containing both asbestos and other environmentally problematic substances, as identified in section 3.3.3.

The samples were delivered to DTU Miljø in secured containers for further experimental and analytical work. An overview of the samples is provided in

# Experimental setup

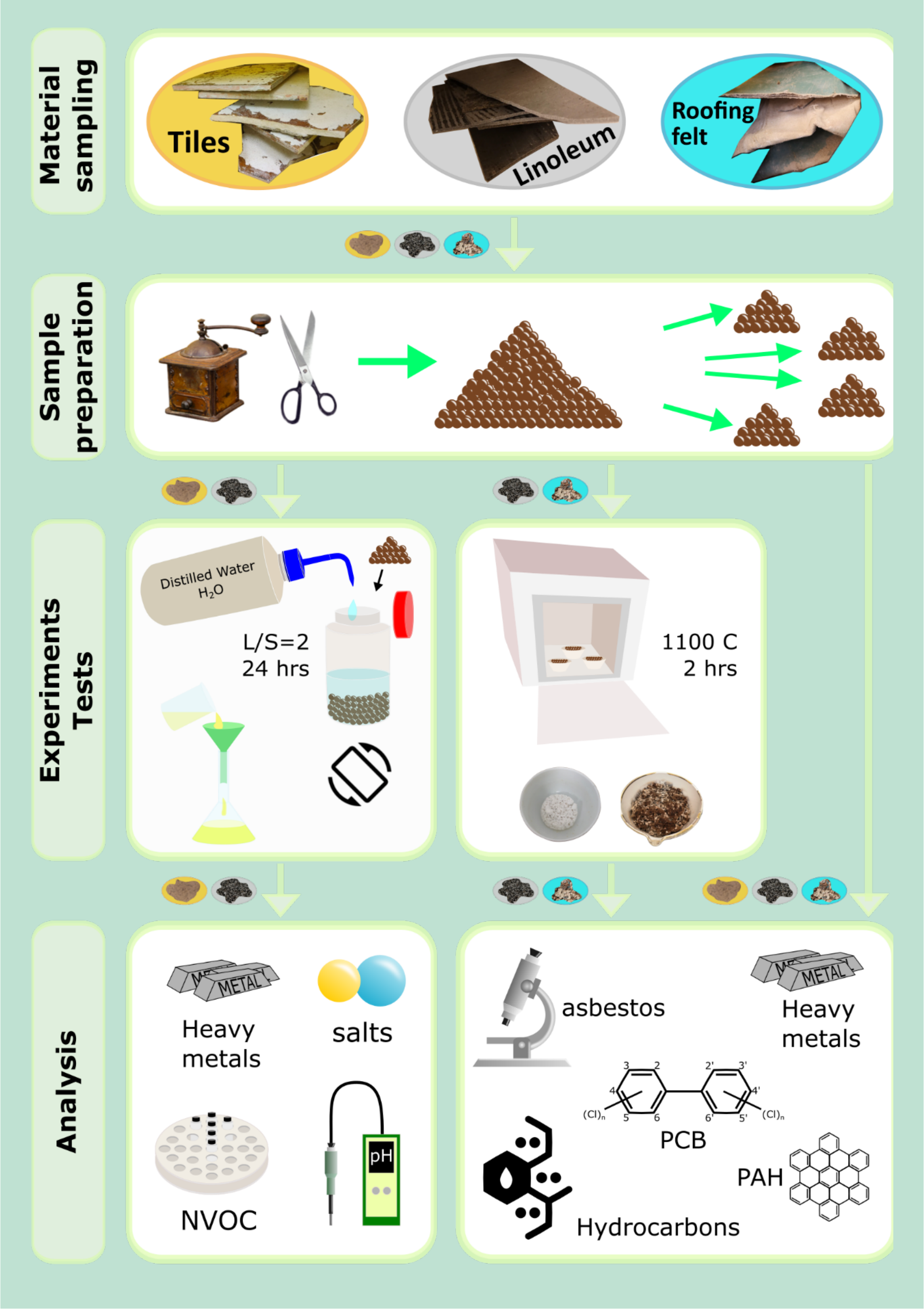


**FIGURE 6**. Overview of the setup for experimental investigation of scenarios for management of waste containing asbestos and other environmentally problematic substances.

TABLE 14, where data regarding the presence of asbestos and the concentrations of heavy metals and organic pollutants were retrieved from the Environmental Mapping Report (Miljøkortlægningsrapport) documentation provided together with the samples.

# Experimental setup

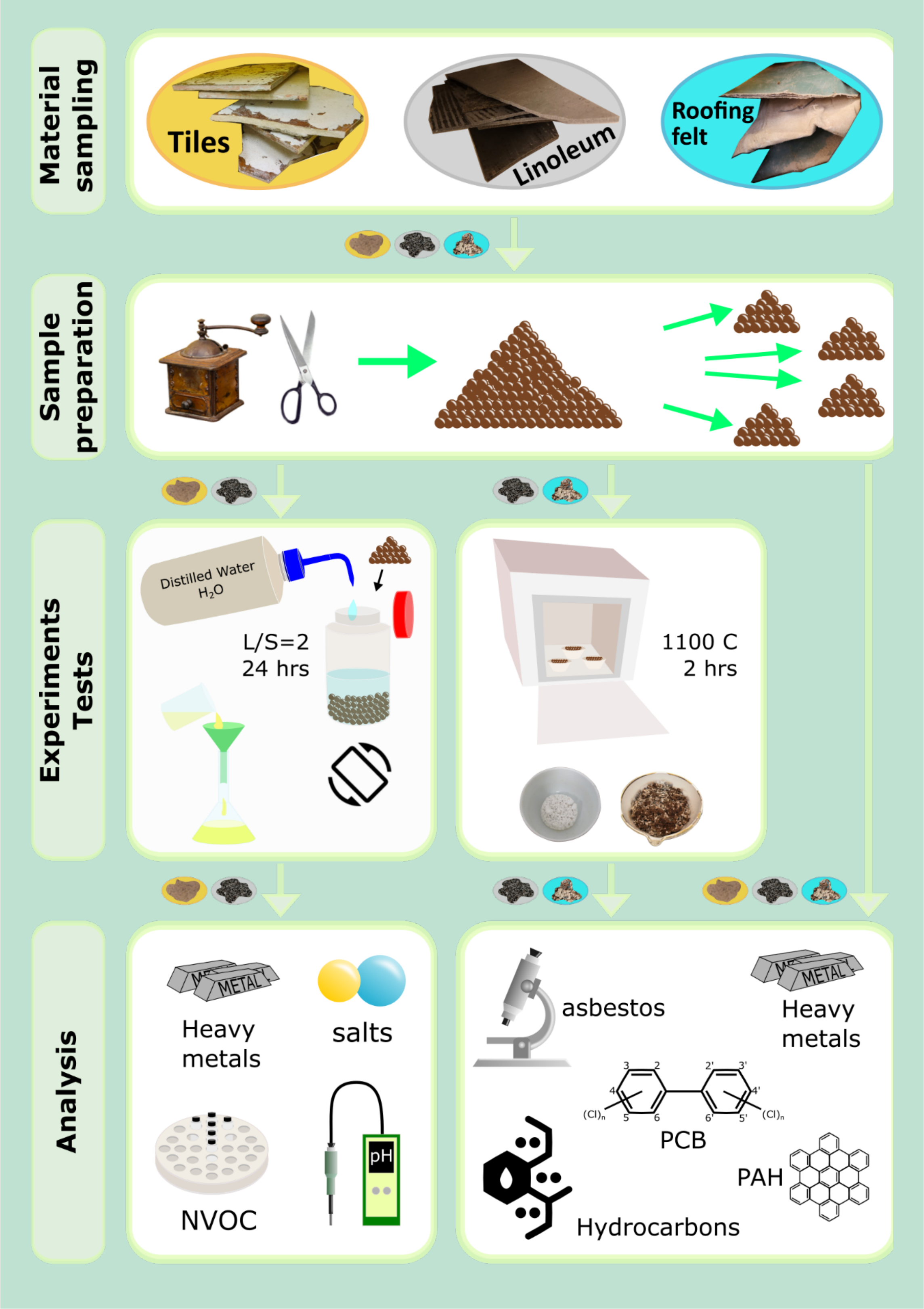


**FIGURE 6**. Overview of the setup for experimental investigation of scenarios for management of waste containing asbestos and other environmentally problematic substances.

**TABLE 14.** Overview of the waste samples containing both asbestos and other environmentally problematic substances (WCAPS) collected for analytical and experimental work. Data on asbestos, heavy metals and organic pollutants are withdrawn from environmental screening (Miljøscreening) documentation, but hereby anonymized for confidentiality reasons.  [n.m.: not mentioned; n.a.: not analyzed].

| | Amount [kg] | Sample ID | Asbestos | Heavy metals [mg/kg] | Organic pollutants [mg/kg] |
|---|---|---|---|---|---|
| **Linoleum** | 4.2 | 91697410 | Yes | Pb: 4,200 | n.m. |
| **Tiles** | 3.7 | 91705034 | Yes | Pb: 10,000 | n.a. |
| **Roofing-felt_1** | 2.0 | 91706552 | Yes | Zn: 11,000 | n.m. |
| **Roofing-felt_2** | 5.7 | 91716168 | Yes | n.a. | HC: 12,000<br>PAHs: 156 |

The samples were then delivered to Eurofins Miljø, where the materials were crushed/cut to particle size <0.4 cm. The crushed samples were then used for chemical analysis as well as all the subsequent laboratory experiments. All samples were characterized for their:

- **Presence of asbestos**: the presence was analyzed by Eurofins Miljø following the NFX 43 050:1996 standard, combined with the RC002 Eurofins' internal method. In short, a few small grains of samples were firstly analyzed using polarized light microscopy (PLM), which is able to discriminate different asbestos types (provided that the content of asbestos is >1%). In the case that no asbestos was detected, the sample underwent a new pre-treatment step in order to be analyzed using a Transmission Electron Microscopy (TEM), which has a detection limit for asbestos of about 0.0001%. Triplicate samples were used during these analyses. Three replicates of each sample were analyzed.
- **Elemental composition**: about 0.5 g of (crushed) samples were acid digested according to the US EPA Method 3052, by using 6ml $HNO_3$ 65%, 2ml HCL 30%, and 2ml HF 40% (and 12 mL of H3BO3 to react with the potentially unreacted HF), in a microwave oven, at DTU Environment. Acid digestions were performed using five replicates. The digested samples were analyzed for their elemental composition (Al, As, Ba, Ca, Cd, Co, Cr, Cu, Fe, Hg, K, Mg, Mn, Mo, Na, Ni, P, Pb, S, Sb, Se, Si, V and Zn), using Inductively Coupled Plasma (ICP) Mass Spectrometry (-MS) and Optical Emission Spectrometry (-OES).
- **Polychlorinated biphenyls (PCBs)**: Microwave-assisted extraction (MAE) was performed on a Multiwave 3000 SOLV Microwave Platform System (Anton-Paar) in Polytetrafluoroethylene (PFTE-TFM) liners and Polyether ether ketone (PEEK) pressure jackets. 2 g sample was extracted with 30 ml n-hexane at 120 °C and approx 4 bar (Power max. 1400 W) for 40 min followed by 15 min cooling. In order to obtain microwave absorption, each extraction liner contained a passive heating element as well as a magnet for stirring. After extraction, the extraction vessels was kept at 4 °C for 15 min to ensure sufficient cooling of the n-hexane extract. Five replicates of each sample were included in the analysis.
  SPE clean-up of the extract: the extract was then transferred to a 70 ml test tube and 1 ml 10 µg/l 1,2,3,4-tetrachloronaphthalene (TCN) in 2,2,4-trimethyl pentane (iso-octane) was added as internal standard and subsequently evaporated to approx. 1 ml using a gentle flow of nitrogen, filtered through a 0,22 µm filter. Clean-up was achieved on a 1 g/ 6 ml LC-Florisil SPE column (Supelco) conditioned with 2 x 6 ml n-hexane. The flow-through was collected and the column was eluted with an additional 2 x 4 ml n-hexane. A second evaporation step was performed to approx. 500 µl and the extract was then transferred to a 2 ml GC-MS vial.
  GC-MS analysis: Chromatographic separation was achieved on an Agilent 6890 gas chromatograph equipped with a 60 m x 0,25 mm i.d x 0,25 µm film thickness ZB-5ms column with a 5 m GuardZ column (Phenomenex). 1 µl sample was injected in splitless mode with the sample inlet held at 300 °C. The oven was programmed to 80 °C for 1 min, then 5

°C/min to 170 °C, then 2 °C/min to 250 °C and finally 10 °C/min to 280 °C held for 13 min. Helium was used as carrier gas with a 1 ml/min constant flow.

- **Polycyclic aromatic hydrocarbon (PAH)**: the PAHs was extracted and analyzed using the same method as for the PCBs with a few modifications. n-hexane:acetone (6:4) was used instead of n-hexane; 100 µg/l pyrene-d10 and perylene-d12 in 2,2,4-trimethyl pentane were added as internal standards; and the SPE column was eluted using n-hexane:toluene (4:1). The GC oven was programmed to 70 °C for 1 min, then 20 °C/min to 300 °C held for 13 min and finally 50 °C/min to 325 °C held for 10 min. Five replicates of each sample were included in the analysis.
- **Hydrocarbons**: 1 g sample was extracted using 50 ml n-hexane for 2 hours. The n-hexane contained 2 mg/l n-tetracontane and 1 mg/l n-decane as GC retention time markers. Anhydrous Na2SO4 was added to the extract prior to SPE clean-up. 12 ml, 2 g Florisil cartridges (LC-Florisil, Supelco), with 2 g NaSO4 on top of the Florisil, was equilibrated using 10 ml n-hexane before passing the extract through. The flow through was collected and evaporated under a gentle stream of nitrogen until approx. 1 ml. The exact volume was determined gravimetrically. The extracts were analyzed using an Trace 1300 GC-FID (ThermoScientific). Chromatographic separation was achieved on a 30m x 0,25 mm x 1 µm Zebron-5 capillary column (Phenomenex). 1 µl sample was injected in splitless mode at 280 degrees. The starting temperature was 35 degrees held for 3 minutes and increased by 20 degrees/min until 350 degrees and held for 5 min. Helium at 1 ml/min was used as carrier gas and the FID was operated at 380 degrees. Mineral oil A:B (SigmaAldrich) (1:1) was used for controls and calibrations. The hydrocarbons analysis was carried out at DTU Environment. Five replicates of each sample were included in the analysis.
- **Total organic carbon (TOC)**: the TOC analyses were carried out by Eurofins according to the EN 13137:2001 method, using a single replicate per each sample.

### 4.2.1 Results for characterization and classification of waste

Experimental results regarding the physicochemical composition of waste containing asbestos are provided in detail in Appendix 2, including:

- presence of asbestos (TABLE 23);
- elemental composition of the fresh samples (TABLE 24 respectively);
- concentration of organic pollutants (TABLE 26 and TABLE 28);
- concentration of hydrocarbons (TABLE 30);

By comparing the composition of the solid samples (i.e. the results above) with the limit values presented in section 3.4, the waste samples are classified as (see TABLE 15 for an overview):

- Linoleum: “hazardous waste” because of the observed content of Pb. Presence of asbestos was also confirmed; however, because linoleum is not a material that can result in significant dust generation, the samples would only be classified as “contaminated”.
- Tiles: “hazardous waste” because of the observed content of Pb and the presence of asbestos (anthophyllite); Cr and Cd are in the level of “contaminated” waste.
- Roofing-felt_1: “hazardous waste” because of the observed very high levels of Zn; concentrations of Pb, Cu, Hg and PAHs are in the level of “contaminated” waste.

Roofing-felt_2: “contaminated waste” because of the observed concentrations of PCBs. However, their level were still within what’s considered acceptable to be landfilled (<50 mg/kg). It should be noted that the material was not analyzed for PCB during the screening/mapping of the building prior to demolition (see

# Experimental setup

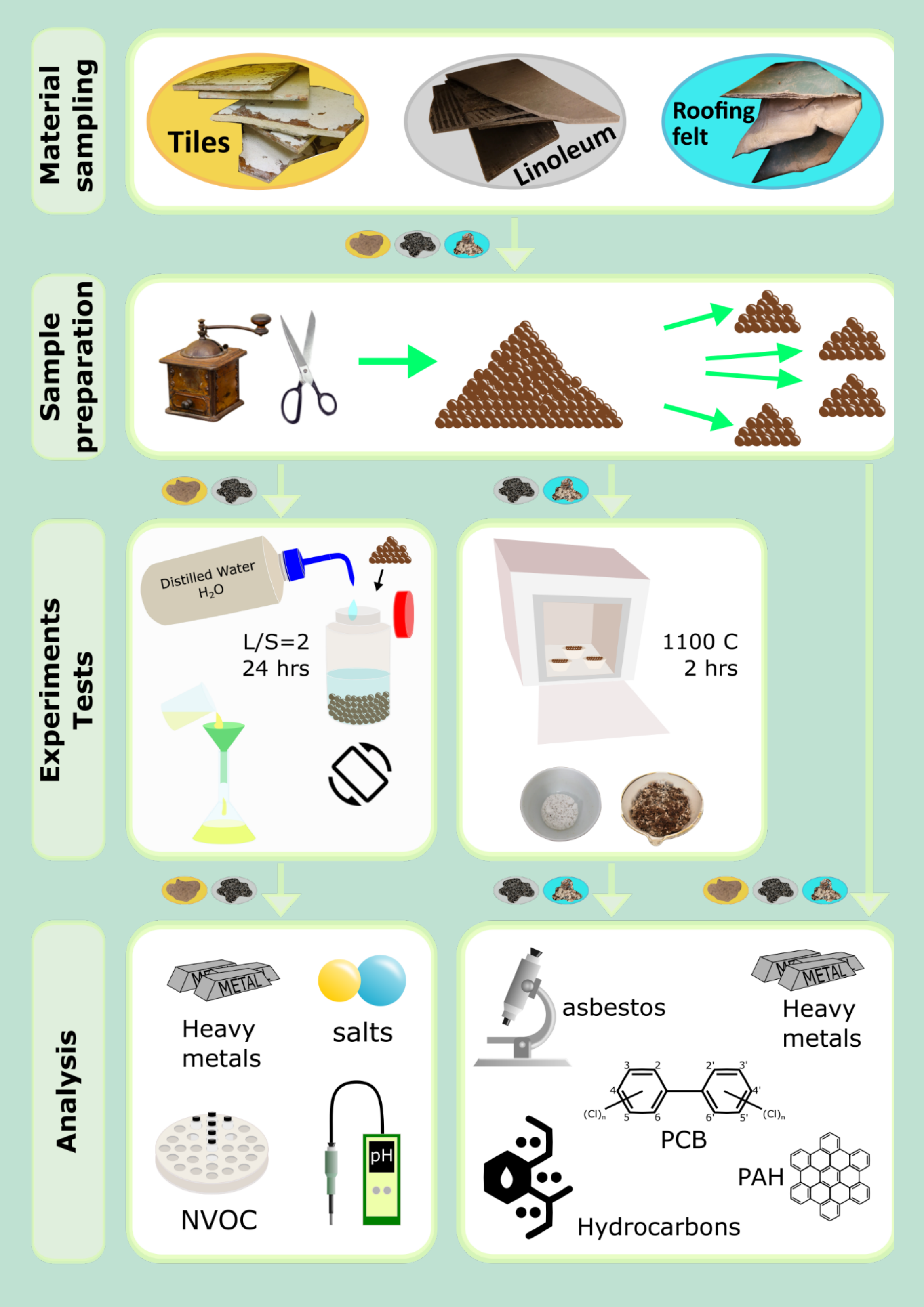


**FIGURE 6**. Overview of the setup for experimental investigation of scenarios for management of waste containing asbestos and other environmentally problematic substances.

- TABLE 14).

All samples used in this study were obtained from waste that was declared as containing asbestos in the respective Environmental Mapping Report (i.e. Miljøkortlægningsrapport). However, the results of this study showed that asbestos was found only in the linoleum and tiles samples (marked in orange and red in TABLE 15). Asbestos fibers were not detected in any of the two samples of roofing felt (marked in orange and red in TABLE 15); a precise reason for this cannot be provided. Roofing felt is in Eurofins' list for potentially inhomogeneous materials (Fynbo, 2021); hence, it can be speculated that high inhomogeneity in the asbestos distribution in roofing felt could be a reason for inconsistent results with previous investigations.

**TABLE 15.** Classification of "fresh" and "thermally treated" waste samples according to the physicochemical composition determined during the experimental activities. Color coding: green = "Uncontaminated" waste; orange = "Contaminated" waste, red = "Hazardous" waste (see section 3.4 for details).

| | Material | Asbestos | Heavy metals | PCB | PAH | Hydrocarbons |
|---|---|---|---|---|---|---|
| "Fresh" material | Linoleum | 🟧 | 🟥 | ⬜ | 🟩 | 🟧 |
| | Tiles | 🟥 | 🟥 | 🟩 | 🟩 | 🟧 |
| | Roofing-felt_1 | 🟩 | 🟥 | 🟧 | 🟧 | 🟧 |
| | Roofing-felt_2 | 🟩 | 🟩 | 🟧 | 🟩 | 🟧 |
| "Thermally treated" material | Linoleum | 🟩 | 🟩 | 🟩 | 🟩 | 🟧 |
| | Roofing-felt_1 | 🟩 | 🟥 | 🟩 | 🟩 | 🟧 |
| | Roofing-felt_2 | 🟩 | 🟩 | 🟧 | 🟩 | 🟧 |

The classification presented in TABLE 15 is, to some extent, aligned with the results reported in the Environmental Mapping Report (i.e., Miljøkortlægningsrapport). Some differences are, however, seen:

- Asbestos fibers were not found in any of the analyzed replicates of the two roofing felt samples. Because of that, the material "Roofing-felt_2" would reclassify as non-hazardous waste, and different options for its treatment would be possible, including incineration. The material "Roofing-felt_1" would still be classified as "hazardous" waste, but now based on heavy metals, meaning that incineration would be an option.
- Concentrations of hydrocarbons in "Roofing-felt_2" are found lower than what previously measured (and reported in the Environmental Mapping report); the sample could be reclassify from "hazardous" waste to "contaminated" waste. For the same sample, the concentration of PAH is significantly lower than previously assessed, but still in the range for "contaminated" waste.

## 4.3 Release tests

Linoleum and tiles were tested for their potential compliance with the Danish acceptance criteria at landfills for hazardous waste (see **TABLE 31** for an overview of the parameters and related threshold values listed among the acceptance criteria), through the use of batch leaching tests carried out at a liquid-to-solid (L/S) ratio of 2 L/kg (using 175 g dry weight of material), according to the EN 12457-1:2002 method. Leaching tests were performed in triplicates.

After a mixing time of 24 hours, pH and electrical conductivity were measured. The leachates were then filtered using a 0.45 mm polytetrafluoroethylene filter. Five (5) replicates of filtered leachate samples were analyzed by means of Ion Chromatography ($Cl^-$, $F^-$, $SO_4^{2-}$), and a carbon analyzer (NVOC). In order to determine the elemental composition of the filtered leachates (Al, As, Ba, Ca, Cd, Co, Cr, Cu, Fe, Hg, K, Mg, Mn, Mo, Na, Ni, P, Pb, S, Sb, Se, Si, V and Zn), a small portion of this was firstly acidified (using $HNO_3$ and HCl) to pH <2 and then analyzed by means of ICP-OES and ICP-MS.

### 4.3.1 Results of release tests

TABLE 31 in Appendix 2 presents the released amounts from the L/S 2 L/kg batch leaching tests. The results show that the composition and characteristics of the leachates from both linoleum and tiles samples are compliant with the acceptance criteria for all classes (FA0 to FA3) at landfills for hazardous waste.

## 4.4 Thermal tests

Based on the information contained in the Environmental Mapping report (Miljøkortlægningrapport) and on the overall results of the questionnaires, which pointed out the potential contamination from organic pollutants (besides asbestos) in the roofing felt and linoleum samples, these materials were chosen to be used during thermal tests – as this treatment has been shown to be effective with regards to the destruction of organic pollutants and decomposition of asbestos minerals.

A laboratory muffle oven was used to carry out the thermal treatment, where 65-200 g of fresh material was heated-up to 1100 °C, at the heating rate of 10 ‘C/min, for two hours. This is a similar setup as the one used by Belardi and Piga (2013).

### 4.4.1 Results of thermal tests

As a result of the thermal test, the mass of the materials was reduced. Compared to the mass of the fresh material, the final mass of the thermally treated samples was 62%, 44%, and 68% for “linoleum”, “Roofing-felt_1”, and “Roofing-felt_2” respectively. Additional experimental results regarding the physicochemical composition of treated samples are provided in details in Appendix 2, including:

- presence of asbestos (TABLE 23);
- elemental composition of the treated samples (TABLE 25);
- concentration of organic pollutants (TABLE 27 and TABLE 29);
- Concentration of hydrocarbons (TABLE 30);

By comparing the composition of the thermally treated solid samples (i.e. the results described above) with the limit values presented in section 3.4, the samples of treated waste are classified as (see TABLE 15 for an overview):

- Linoleum: “contaminated waste” because of the observed content of hydrocarbons. It should be noted that the thermal test resulted in a significant decrease in Pb concentration.
- Roofing-felt_1: “contaminated waste” because of the observed levels of Cr. During the thermal treatment, most of the Cr remained in the material, while the total mass of the sample decreased. This resulted into a higher concentration of Cr in the thermally treated materials compared with the fresh material.
- Roofing-felt_2: “contaminated waste” because of the observed levels of PCBs (although with large variations as seen by the standard deviation), which are anyhow below the levels observed in the respective fresh material. The material is considered acceptable to be landfilled (PCBs <50 mg/kg).

Fpr all three samples, the concentrations of Pb decreased during the thermal test. This was unexpected, as Pb normally tends to accumulate in bottom ash, as shown, for example, by Astrup et al. (2011). However, in situations of low combustion air stoichiometry, as it is the case for a laboratory oven, enhanced formation of a large amount of fine particles containing high concentrations of lead can occur (Yao and Naruse, 2009), with subsequent liberation of Pb with flue gas.

Asbestos was not detected in any of the samples after they were thermally treated (TABLE 23 and TABLE 15 in summary). This indicates that the asbestos fibers present in linoleum were destroyed. Conclusions could not be reached for roofing felt, as asbestos was not detected in the fresh samples. While more tests may be needed, there is an indication that high temperature (i.e. 1100 °C) thermal treatment may be effective in destroying asbestos fibers. This is in line with what reported by Belardi and Piga (2013) for different products containing asbestos (including linoleum), as well as (Bloise et al., 2016) who performed experiments on pure fibers, including Chrysotile which was completely recrystallized as forsterite. In their study, Belardi and Piga (2013) actually suggest that a pre-washing of the material with HCl would improve the asbestos decomposition process, thanks to the removal of calcite.

# 5. Risk screening

## 5.1 Purpose and scope

Based on available data and data generated in this project, and using results from simulations with the validated model GrundRisk Landfill (Miljøstyrelsen, 2019), a human and environment risk screening is performed for asbestos fibers, with focus on chrysotile (US EPA, 2020) in the groundwater (incl. drinking water), soil and recipient surface water. The risk screening approach follows the general guidelines in the Technical Guidance Document for human and environmental risk assessment (TGD, 2003). The risk screening is done for a generic site, in a semi-empiric approach, with sensitivity analysis of estimated high and low source strength values, derived from amounts of asbestos fibers in the waste, and asbestos release fractions from the waste to the underlying soil and recipient surface water. Release of asbestos fibers to the environment is an unwanted occurrence, and the risk screening performed here will evaluate the potential risks that can occur from unwanted release scenarios.

This section will include a description and quantitative assessment of the following elements, see FIGURE 7:

- Source strength of asbestos in a generic landfill;
- Transport of asbestos fibers in soil and saturated zone, incl. drinking water;
- Concentration in inflow to recipient surface water;
- Toxicities towards humans and the aquatic environment;
- Margin of Exposure and Risk quotients for human consumption of drinking water and aquatic organisms, respectively.

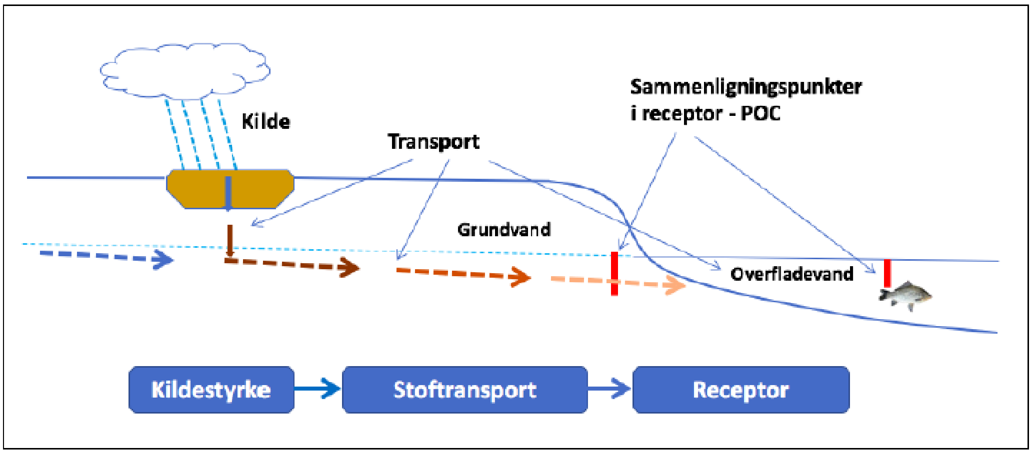


**FIGURE 7**. Elements in environmental and human risk screening. Figure taken from Miljøstyrelsen (2018).

## 5.2 Background: Asbestos characteristics, fate and risk

### 5.2.1 Asbestos in the environment

Asbestos fibers are persistent mineral parts of soils, and the behavior in soil is therefore similar to mineral particles. Asbestos fibers are associated with the finer fraction of soil minerals and vary in shape and morphology (Miljøstyrelsen, 2008; US EPA, 2020). Asbestos fibers are largely chemically inert in the environment. Fibers may undergo minor transformation with changes in length or through the leaching of minerals from the asbestos fiber surface but are generally non-volatile and insoluble in the environment (WHO, 2003). Degradation under acidic conditions, analogous to mineral weathering, can take place, however at such a slow rate that it has no short-term significance. Mechanical stress and possibly the influence of environmental factors such as temperature and moisture, can give rise to degradation of fibers. In addition to the increasing health hazard potential, smaller fibers are more susceptible to resuspension and transport in the soil (Miljøstyrelsen, 2008; WHO, 2003). In general, the asbestos fibers are insoluble in water, where they can form stable suspensions. Surface minerals may leach into solution, but the underlying silicate structure remains unchanged at neutral pH (US EPA, 2020). A continuous influence from water flow in the soil macro pores will lead to a progressing leaching and transport of colloids (0.01 – 10 µm) in the soil (Miljøstyrelsen, 2016; Naturstyrelsen, 2010). Small asbestos fibers (<1 µm) can remain suspended in water for significant periods of time, and may be transported over long distances, and eventually settle into soil and sediments. Further movement may occur via erosion, runoff or mechanical resuspension (Miljøstyrelsen, 2008; US EPA, 2020; WHO, 2003). Conclusively, the fate of asbestos fibers released into the environment is considered to be dependent on the size and shape of the fibers, but information on the fate of asbestos fibers in soil, including their binding to mineral and organic components are scarce (WHO, 2003). They may undergo minor physical and chemical changes, such as changes in fiber length or leaching of surface minerals, but do not react or dissolve in most environmental conditions (Miljøstyrelsen, 2008; WHO, 2003).

### 5.2.2 Influence of metals on environmental fate

Metals can bind to the mineral-humic complexes in soil (Qu et al., 2019). Assuming a similar metal-asbestos binding, this may potentially change the surface properties of the fibers, which may alter the size, charge, sorption, and water solubility. However, no information is found in the scientific or grey literature on the influence of metals on the fate, i.e., leaching and transport, of asbestos fibers in soil and aquatic environment.

### 5.2.3 Concentrations in soil and water and exposure pathways

Based on a literature search, Miljøstyrelsen (2011, 2008) concluded that there was no information on the background levels of asbestos in the soil in Denmark, nor in urban areas with diffuse sources, such as roof tiles or industries with earlier asbestos handling and traffic (brake lining). Miljøstyrelsen (2015) stated that the methods needed to quantify the asbestos concentrations at a sufficiently low level are not available. Highly contaminated soils and materials with bound asbestos are defined as at least 10.000 mg/kg$_{dw}$, and less contaminated soils is less than 1.000 mg/kg$_{dw}$ (Miljøstyrelsen, 2008). This can be converted to a number of fibers using a conversion factor, ranging from 0.4x10$^3$ to 4.9x10$^3$ fibers per microgram, according to the working process involved (Puledda and Marconi, 1991). At historic mining, milling, and processing of vermiculite site in Montana USA, surface water samples showed concentrations of asbestos fibers from less than 0.1 to over 1,000 MFL. Groundwater concentrations of fibers >10 µm ranged from non-detected to about 65 MFL. Soil and mining waste samples had concentrations ranging from trace to 37wt-% (US EPA, 2016).

Health risks associated with asbestos fibers and asbestos-containing waste in and on soil are primarily dependent on the potential for asbestos fibers to re-suspend into the air and be inhaled (Swartjes et al., 2003). Although inhalation of airborne fibers is not a part of this study, the soil concentration of asbestos is indirectly associated with this exposure mechanism, as asbestos can be released to the air. In addition to the concentration of asbestos in soil the human exposure is dependent on a large number of factors, e.g. there is to a lesser degree resuspension from clay than from sand and increased water content of the soil has a strong inhibiting effect on the release of asbestos fibers to the air (Addison et al., 1988). Swartjes et al. (2003) investigated the relationship between asbestos in soil and the emission of asbestos fibers to the air. According to the Dutch Soil Protection Act the risk assessment of contaminated soil is based on generic Intervention Values (IV), assessed for the "average" human being in a standard situation, not on groups or individuals that work in or with soil. IV for asbestos in soil,

soil materials and debris (granular), for a site-specific assessment of contaminated soils, was in 1993 set by the National Institute for Health and Environment (RIVM) to 100 mg/kg$_{dw}$ up to 2000 mg/kg$_{dw}$, dependent on the type of asbestos. The shape and size of the asbestos fibers were not taken into account. This value represented the sum of the concentration of chrysotile asbestos (or serpentine asbestos or white asbestos) and ten times the concentration of amphibole asbestos (other asbestos types), since amphibole asbestos has an approx. ten times higher carcinogenic potency than chrysotile asbestos. In the Occupational Safety and Health legislation from 1999 (letter to the Dutch Parliament ("Tweede Kamer"), number 25 834, 6 December 1999), the residual concentration for bound asbestos was increased from 0 to 10 mg/kg$_{dw}$. Miljøstyrelsen (2011) investigated the extent of resuspension of asbestos fibers to the air and found that if the total amount of asbestos in soil is less than 100 mg/kg$_{dw}$, the amount of respirable asbestos fibers will be less than approx. 3 mg/kg$_{dw}$, which will give no unacceptable risk related to the exposure of children playing on the ground. Based on these results, a soil quality criterion of 100 mg/kg$_{dw}$ of asbestos is suggested (Miljøstyrelsen, 2015). Nathanail et al. (2014) concluded that, with the knowledge at hand, it is not feasible to derive a criterion for the asbestos content in soil, but further measurements and modelling are needed to assess the specific risks.

### 5.2.4 Risk assessments

US EPA (2020) assessed that there is minimal or no releases of chrysotile asbestos to surface water, and therefore no unreasonable risk to humans and aquatic or sediment-dwelling environmental organisms from this exposure pathway. This is based on, e.g. that 96% of ~14,000 samples from drinking water sources are below the minimum reporting level of 0.2 MFL and less than 0.2% are above the tolerable drinking water concentration of 7 MFL for humans. Furthermore, data have not shown releases of asbestos to water for the considered conditions of use. The vast majority of friable asbestos waste management was disposal to hazardous waste landfills and to non-hazardous waste landfills. It was concluded that asbestos fibers are not likely to leach out of a landfill. However, the assessment did not consider on-site releases to land that go to asbestos compliant landfills or exposures of the general population or terrestrial species from such releases. Thus, without the requirement to measure asbestos concentrations in effluent, the estimation of asbestos levels in effluent or receiving waters is challenging (US EPA, 2020).

Swartjes et al. (2003) concluded that the risks of asbestos to the ecosystem are negligible, and that risks of dispersal only occur through wind, not via the groundwater. This is agreement with (Miljøstyrelsen, 2020, 2015, 2011, 2008): asbestos fibers and asbestos containing materials, e.g. deposited waste, localized below the soil surface, do not pose an apparent health risk, as the asbestos will not dissolve in water and will therefore not affect the composition in percolate and groundwater. Nathanail et al. (2014) could not rule out that the occurrence of asbestos in soil poses a health risk, however, it is stressed that asbestos in the soil only constitutes a health risk if it can be re-suspended to the air.

## 5.3 Source strength (kildestyrke)

The generic deposit, that is modelled here, is a controlled deposit with membrane and a percolate collection system where the percolate will be collected and removed from the deposit. In FIGURE 8, the operational stages of the deposit are illustrated (Miljøstyrelsen, 2018b).

To be able to assess the risk of asbestos fibers it is necessary to estimate the leaching of fibers from the deposited waste, and subsequently the flow of fibers from the landfill to the surrounding environment, during the lifetime of the landfill. The start of leaching is set to the start of deposition, assuming that the bags containing the waste are ruptured and leaching commences instantaneously. Further, the membrane enclosing the deposit is assumed to be fractured so the leaching can occur. The fibers will disperse in the water that is in contact with the waste. This can be infiltrating rain (most predominant source) or surface water, actively supplied water or infiltrating groundwater (see FIGURE 8). The amount of water that is in contact with the waste constitutes the percolate production of the deposit. The percolate production can typically be set constant in one or more of the operational stages (filling of waste, after treatment, passive stage) of the deposit (Miljøstyrelsen, 2018a). The percolate can either be collected, leach through a fractured membrane or run over the edge of the deposit.

The percolate removal is assumed to be continuous with rate R (liter/hour) or zero, during the active stage. The filling of asbestos containing waste is assumed to take place with a constant amount each year during T years, after which the deposit is sealed and no percolate removal takes place (passive stage). Typically, the deposits are divided into hydraulically separated units where the source strengths are calculated separately (Miljøstyrelsen, 2018b). Here we assume one unit comprising the entire deposited amount of waste. Using a conservative (potential high risk) approach we assume that the groundwater level is above the lower boundary of the deposit, which will enable additional formation of percolate from groundwater intrusion, lower part of FIGURE 8.

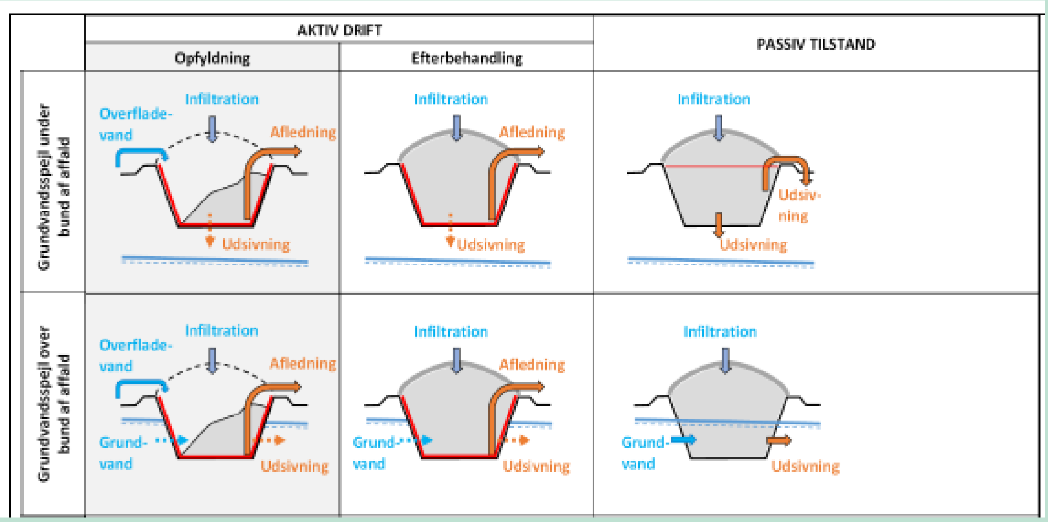


**FIGURE 8.** Operational stages in deposit with membrane. The source strength amount is the product of the percolate flow and the asbestos concentration in the percolate. Figure taken from Miljøstyrelsen (2018a).

The source strength is defined as the mass flux, or rather number (million) of fibers per year (MF/year), to the environment. The source strength is a function of time, from the moment of initial leaching from the waste, and up to a period of e.g. 500 years, which is the time horizon where the maximum concentration in the environment 100 m from the deposit is expected to have occurred (Miljøstyrelsen, 2019). For asbestos fibers that are non-soluble, the timeframe may be longer. At any given time, the source strength is thus the number of asbestos fibers that leach out of the deposit in the percolate to the surrounding environment. The source strength amount (SSA) (kildestyrkemængden) is the fraction, occasionally all, of the percolate production that leaches to the environment, and it is calculated as the product of the asbestos concentration in the percolate (C in MF/liter), and the percolate flow to the environment (P in liter/time), at any given time (Equation 1):

$$\boldsymbol{SSA(t)}[\frac{\boldsymbol{MF}}{\boldsymbol{year}}] \;=\; \boldsymbol{C(t)}\;[\frac{\boldsymbol{MF}}{\boldsymbol{liter}}] \;*\; \boldsymbol{P(t)}\;[\frac{\boldsymbol{liter}}{\boldsymbol{year}}] \qquad \text{(Equation 1)}$$

where: *P* is the sum of leachate through fractured bags and membrane, and the spill over the edge of the deposit.

The asbestos concentration in the percolate at a given time ($C_t$), depends on the amount of water that the waste has been in contact with. The asbestos concentration will peak immediately after deposition and rupture, and will thereafter follow an exponential decline, concurrently with water flowing through the waste (Equation 2):

$$C_t\left(\frac{L}{S}(t)\right) = C_0 \cdot e^{-k \cdot \frac{L}{S}(t)} \qquad \text{(Equation 2)}$$

where: $C_t$ (MF/liter) is a function of L/S; $C_0$ (MF/liter) is the percolate (max) concentration at the beginning of leaching: *L* is the accumulated percolate production (liter): *S* is the dry weight of deposited waste (kg): *k* (kg/liter) is a substance and material specific constant describing the rate with which the concentration decreases as a function of L/S. *k* can be derived from leaching experiments.

Experimentally derived *k* values are larger for initial leaching compared to longer leaching. To prevent too rapid decrease in concentration for longer leaching, when *k* is derived from short term leaching experiments, i.e. small values of L/S, a modified equation is used (Miljøstyrelsen, 2018a), as shown in Equation 3:

$$C_t\left(\frac{L}{S}(t)\right) = C_0 \cdot e^{-k \cdot \frac{L}{S}(t)} \cdot e^{-\frac{L}{S}(t)\Big/a} \qquad \text{(Equation 3)}$$

Where: *a* is the L/S value corresponding to the endpoint of the calculation period, e.g. 500 years. Default *k* values, e.g. as shown in Miljøstyrelsen (2018b), are derived from longer L/S experiments, which means that Equation 3 will give too conservative leaching. Equation 2 can be used here. When *k* is set to 0 kg/liter, both Equation 2 and Equation 3 will reveal a constant source strength with value $C_0$ in time.

At a point in time, the asbestos fiber concentration in the percolate has potentially decreased to a value that will give an acceptable (no risk) value in the environment.

The accumulated percolate production (L) increases in time with the amount of infiltrating water. The amount of waste (S) will remain constant once the deposition of waste is finished. Thus, L/S increases in time, and the asbestos fiber concentration in the percolate decreases due to leaching to the environment, according to Equation 2 and Equation 3. Waste deposited at the start leaches with the total percolate production, whereas waste deposited at the end only leaches with the subsequent percolate production. L/S at the end of the waste filling stage ($T_{\text{filling}}$) is therefore calculated as the total percolate production divided with the mean waste amount (Equation 4):

$$\frac{L}{S}\left(T_{filling}\right) = \frac{Total\ percolate\ production\left(T_{filling}\right)}{0.5 * Total\ waste\ amount\left(T_{filling}\right)} \qquad \text{(Equation 4)}$$

As an approximation L/S increases linearly during the waste filling stage. L/S in subsequent years after the filling stage will increase due to further percolate production, and is calculated as the subsequent percolate production divided with the total waste amount, in addition to L/S($T_{\text{filling}}$) in Equation 3. For example, after $T_{\text{end}}$(years), the L/S will be (Equation 5):

$$\frac{L}{S}(T_{end}) = \frac{Percolate\ production(T_{end}-T_{filling})}{Total\ waste\ amount} + \frac{L}{S}(T_{filling}) \qquad \text{(Equation 5)}$$

## 5.4 Transport and environmental concentrations

The GrundRisk Landfill model simulates the downstream contaminant transport from a contaminated site (landfill) into the underlying aquifer, and the mass flow to a Point of Compliance (POC), which here is a surface water recipient. This requires an input contaminant load, which is estimated based on reported deposited amounts of asbestos containing waste and from leachate flows, i.e. the source strength amount (SSA) (kildestyrkemængden) in Equation 1.

The GrundRisk Landfill model addresses solute vertical and horizontal contaminant transport in the groundwater aquifer, including the most relevant transport processes in time-dependent analytical solutions. GrundRisk is a risk assessment tool and as such conservative assumptions are made when treating uncertainty and selecting model structure. Similar conservative assumptions are used in the present project. Landfills with membrane and leachate collection (active controlled landfills) are covered by the GrundRisk Landfill scenarios, which is relevant for the landfills receiving asbestos contaminated waste (Miljøstyrelsen, 2019).

Results from model applications to three landfills in Denmark are used here for evaluating the asbestos flow and concentration development (Miljøstyrelsen, 2019). The model simulations are developed for chemical contaminants that can appear as dissolved in the soil water and adsorbed phases, and can undergo degradation processes. In contrast, asbestos fibers are inorganic fibers that are considered inert and will be susceptible to filtering in the soil pores, and therefore will be held back, for a shorter or longer time, in the soil. Clay particles are known as inorganic colloids and are made up of the smallest particles (<1 µm) of humus and clay in the soil. Transport of soil colloids are considered in a similar way as other types of materials in MIKE SHE's advections-dispersion module *(MIKE SHE USER MANUAL VOLUME 1: USER GUID*>, n.d.). Assuming that asbestos fibers are comparable to colloids, the model simulations can be used here.

A number of conservative assumptions and simplifications are made, from the perspective of performing a simple, fast and low demand for input parameters, suited for a regulatory risk assessment tool (Miljøstyrelsen, 2018a). Such assumptions will also be used in this project: e.g. uniform and constant groundwater velocity; uniform mass discharge from the landfill (leachate) throughout the source area; homogeneous water flow through the deposited waste. The last assumption typically indicate a higher flow rate though the soil, which produces a conservative estimate in relation to environmental risk assessments.

In modelling vertical and horizontal contaminant transport in the groundwater with GrundRisk Landfill the overall conclusions in Miljøstyrelsen (2019) was that dispersion and dilution are likely to produce limited reduction of the maximum source concentration 100 m downstream of landfills. This due to the combination of both the large areas of the landfills, limited distance downstream to POC, small groundwater velocities (i.e. few m per year). Furthermore, an assumed 10 m thick aquifer, does not provide enough water to disperse and dilute the contaminant mass from the landfill. Furthermore, variations in asbestos specific physical/chemical properties, and site-specific parameters, i.e. soil characteristics, such as macro porosity, will likely not influence the amount of asbestos leached to soil and surface water. However, they will influence the peak concentration, and the time delay of max concentration breakthrough to the recipient water.

Using these results and assumptions in this project an exposure scenario is defined that describe a high concentration of asbestos fibers in the percolate, soil and groundwater. Additionally, the inflow to recipient surface waters, 100 m downstream from the landfill, can be set equal to the input concentration, i.e. the asbestos concentration in the landfill leachate immediately below the deposit.

The output from the exposure scenario is:

i) Maximum percolate concentration.
ii) Maximum groundwater (drinking water) concentration below the deposit.
iii) Maximum input concentration to recipient surface water.

The following parameters are needed, see Equation 1 and Equation 2:

- S (t), amount of deposited asbestos containing waste.
- F (t), amount of asbestos fibers in the waste.
- $C_0$ (kg/m$^3$ or MFL), initial concentration of asbestos in percolate.
- f (g/g/year), asbestos leaching fraction from waste to percolate.
- L (m$^3$), accumulated percolate production, found from infiltrating rain amount, which is assumed constant in the period (mm/year).
- k (kg/m$^3$), material specific constant describing the rate with which the concentration in percolate decreases as a function of L/S.
- A (m$^2$), surface area of deposit.

Output concentrations will be found at the beginning of leaching, where $C_0$ (kg/m$^3$ or MFL) is the percolate max concentration, and L/S is approx. zero. Output concentrations will also be calculated after the waste filling stage is terminated and after 20 years.

Selected input parameters will be varied in a sensitivity analysis that will give the parameter values that are necessary to yield acceptable asbestos concentrations in groundwater (drinking water) and inflow to surface water recipient.

## 5.5 Input data and assumptions

To calculate the asbestos concentration in the percolate from a generic waste deposit, the following basic assumptions are made, where information and data are mainly compiled from the GrundRisk Landfill studies (Miljøstyrelsen, 2018b), and a study that more specifically consider asbestos containing waste (COWI A/S, 2017):

- A deposit with area of 25,200 m$^2$ (A) is considered, similar to the Reno Djurs area with asbestos containing waste (COWI A/S, 2017).
- The filling of waste takes place for 5 years ($T_{filling}$), after which the deposit is sealed.
- For each year in the 5 year period the deposit is filled with amounts of asbestos containing waste (S) as shown in TABLE 16.
- Percolate production comes from rain infiltration (I), which seeps to the soil, similar to the Reno Djurs deposit (COWI A/S, 2017). During the waste filling stage, this is assumed to be constant 550 mm/year, and 220 mm/year after sealing of the deposit (Miljøstyrelsen, 2018b).
- The groundwater flow is directed towards the surface water recipient, which is 100 m away.

For the amount of deposited asbestos containing waste, S (ton/year), and the amount of asbestos in the deposited waste, F (ton/year), and asbestos fraction in waste (wt-%), the figures in TABLE 16 are derived from expert judgement based on data from Miljøstyrelsen (2021) and Arbejdstilsynet (2010).

**TABLE 16.** Amount of deposited asbestos containing waste (S) [ton/year], amount of asbestos in waste (F) (average, min, max) [ton/year] and concentration of asbestos in waste (average, min, max) (wt-%) (Arbejdstilsynet, 2010). S is obtained from Miljøstyrelsen (2021), see also FIGURE 3, whereas concentrations are retrieved from Arbejdstilsynet (2010). The numbers are for total Denmark and for single deposits (n=180).

| | | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 |
|---|---|---|---|---|---|---|---|---|---|
| Asbestos containing waste to landfill, DK total (S) | ton/year | 59198 | 66382 | 80571 | 81258 | 77393 | 86162 | 86516 | 95720 |
| Asbestos containing waste to landfill, single deposit (n=180) (S) | ton/year | 329 | 369 | 448 | 451 | 430 | 479 | 481 | 532 |
| Asbestos average, DK total ($F_{average}$) | ton/year | 10909 | 12487 | 15300 | 15501 | 15067 | 16879 | 16939 | 18530 |
| Asbestos average, single deposit (n=180) ($F_{average}$) | ton/year | 61 | 69 | 85 | 86 | 84 | 94 | 94 | 103 |
| Asbestos min ($F_{min}$) | ton/year | 1480 | 1580 | 1869 | 1867 | 1675 | 1871 | 1881 | 2133 |
| Asbestos max ($F_{max}$) | ton/year | 53988 | 60361 | 73229 | 73819 | 70027 | 77893 | 78220 | 86724 |
| Asbestos average | wt-% | 18% | 19% | 19% | 19% | 19% | 20% | 20% | 19% |
| Asbestos min | wt-% | 3% | 2% | 2% | 2% | 2% | 2% | 2% | 2% |
| Asbestos max | wt-% | 91% | 91% | 91% | 91% | 90% | 90% | 90% | 91% |

Deposits in Denmark with asbestos containing waste can be estimated from Danmarks Miljøadministration (www.dma.mst.dk). A search based on BEK 2255:2020 (2020) that consider deposits (Bilag 1: punkt 5.4 og 5.6 and Bilag 2: K207, K208, K217), yields a list of approx. 180 deposits. The number of deposits with permission to have asbestos containing waste is not specified. The RenoSam (2008) report estimated that approximately half of the total amount of asbestos containing waste ended up in deposits, i.e. 11,000 t (based on 2006 figures); 338 deposits received asbestos containing waste. There can be large variations in amounts between deposits and some sites ceased to receive asbestos containing waste (RenoSam, 2008). For the present study, 180 deposits are set to receive asbestos containing waste.

No site specific data or data for asbestos containing waste, laboratory test on asbestos leaching from waste or asbestos concentrations in percolate, are available for the parameters L/S, $C_0$ and k, as needed in Equation 2 and Equation 3. Under such circumstances, Miljøstyrelsen (2018b) suggests that default values can be used. When using default values for *k*, Equation 2 must be used (Miljøstyrelsen, 2018b). For asbestos, the *k* value will probably be relatively small, e.g. $<10^{-4}$ kg/m$^3$, which is found for pentadecane that is immiscible with water (Miljøstyrelsen, 2018b). When *k* is set to zero, as suggested in Miljøstyrelsen (2018b) the C(t) will be constantly equal to $C_0$ in time regardless of the L/S value.

For k=0, $C_0$ can be estimated using an asbestos leaching fraction (assumed constant in time) from waste to percolate *f* (g asbestos in percolate/g asbestos in waste/year), asbestos amount in waste *F* (kg), and accumulated percolate production *L* (m$^3$). *f* is based on expert judgement as no data or information are available. f depends on the susceptibility of fibers to be released from the waste material and enter the percolate. It is assumed that more friable asbestos will more readily enter the percolate. The degree of rupture of the waste containing bags will also determine the size of *f*. An f = 0 indicates intact bags and/or fibers that are not released to percolate, and f = 1 indicates completely ruptured bags and all asbestos fibers can move from waste material to percolate. Potentially, the *f* value could decrease after the initial release of “free” fibers. Further degradation and mechanical stress of the waste material could cause f to increase. But, these are all assumptions and should be investigated in field and laboratory tests.

L is calculated from the rain infiltration (I = 550 mm/year (Miljøstyrelsen, 2018b)) and deposit area (A=25,200 m$^2$). During a year it becomes:

$L = 0.55\ m/year * 25{,}200\ m^2 = 13{,}860\ m^3/year$

Amount of asbestos released to the percolate per year = f * F (mg/year)

The asbestos concentration in percolate, which is constant in time (k = 0) becomes (Equation 6):

$$C_t(0) = C_0 = \frac{f*F}{L} \left({}^{mg}/_{m^3}\right) \qquad \text{(Equation 6)}$$

When k>0, the concentration in the percolate decreases as a function of L/S, according to Equation 2. It is assumed that the initial concentration $C_0$, which is the highest concentration in the percolate and for L/S = approx. 0 L/kg, is equal to $C_0$ found for k=0.

The accumulated percolate production (L) from infiltrating rain, equal to seepage to soil is:
At the end of the waste filling stage:

$L(T_{filling}) = 25{,}200\ m^2 * 5\ years * 0{,}55\ m^3/m^2 = 69{,}300\ m^3$

Hereafter for each year L increases with:

$L(yearly) = 25{,}200\ m^2 * 1\ year * 0{,}22\ m^3/m^2 = 5{,}544\ m^3$

The total for years 5 to 20 is:

$L(T_{5\text{-}20years}) = (20-5) * 5{,}544\ m^3 = 83{,}160\ m^3$

The L/S at the end of the waste filling stage ($T_{filling}$) is calculated as the total percolate production during filling divided with 0.5 times the mean waste amount (Equation 4):

$$\frac{L}{S}(T_{filling}) = \frac{\mathrm{L}(T_{filling})}{0.5 * Total\ waste\ amount(T_{filling})} = \frac{69{,}300\ m^3}{0.5\ \cdot 2{,}372\ t} = 58.4\ \frac{m^3}{kgdw}$$

Where the total waste amount is the sum of the asbestos containing waste amounts ($F_{average}$) in TABLE 16, for years 2015 to 2019.

L/S in subsequent years after the filling stage will increase due to further percolate production, and is calculated as the subsequent percolate production divided with the total waste amount, in addition to $L/S(T_{filling})$ (Equation 5):

$$\frac{L}{S}(T_{end}) = \frac{\mathrm{L}(T_{5-20\,years})}{Total\ waste\ amount(T_{filling})} + \frac{L}{S}(T_{filling}) = \frac{(83{,}160)\ m^3}{2{,}372\ t} + 58.4 = 93.5\ \frac{m^3}{kgdw}$$

The asbestos concentration in the percolate, at the end of waste filling ($T_{filling}$) and after 20 years ($T_{end}$), can be estimated from insertion in Equation 2:

$$C_t\left(\frac{L}{S}(T_{filling})\right) = C_0\ \cdot\ e^{-k\cdot\frac{L}{S}(T_{filling})}\ \left({}^{mg}/_{m^3}\right)$$

$$C_t\left(\frac{L}{S}(T_{end})\right) = C_0\ \cdot\ e^{-k\cdot\frac{L}{S}(T_{end})}\ \left({}^{mg}/_{m^3}\right)$$

Asbestos concentrations in the percolate that represent human and environmental exposure values in drinking water and inlet to surface water, are calculated for the following set of parameters:

- Time after initial release, T (years):
  - 0
  - 5 ($T_{filling}$)
  - 20 ($T_{end}$)

  - Asbestos leaching fraction from waste to percolate, assumed constant in time, f (g asbestos in percolate/g asbestos in waste/year):
    - $1*10^{-10}$ (representing no risk)
    - $2*10^{-9}$ (representing potential risk for aquatic environment)
    - $5*10^{-6}$ (representing potential risk for humans via drinking water)
  - Substance and material specific constant, k ($kg/m^3$):
    - 0 (representing no decline in percolate concentration)
    - $1*10^{-5}$ (approx. lowest default value, for pentadecane (Miljøstyrelsen, 2018b))
    - 1 (approx. highest default value, for phenol (Miljøstyrelsen, 2018b)).

Human and environmental toxicity values are:

- Humans:
  - Drinking water: Reference dose (RfD) = 300.000 fibers/L = 0.3 MFL.
  - Tolerable drinking water concentration = 7 MFL.
  - Soil: NA.

- Environment:
  - Aquatic toxicity: 0.0001 (low) to 100 MFL (high).
  - Soil: NA.

## 5.6 Risk screening results

In agreement with US EPA (2020) and the TGD (2003), the risk screening constitutes of characterization, quantification and assessment of i) asbestos containing sources, ii) releases of asbestos to the environment, iii) fate and transport of asbestos fibers in the environment, iv) exposures to environment and humans, v) risks towards environment and humans. For all stages in the risk screening the following has been performed: Evaluation, compilation and integration of available empirical (i.e., monitoring) data, modelling data and expert judgements.

The risk screening is performed to evaluate if a generic deposit for asbestos containing waste, at present or in a future scenario, constitutes an unacceptable risk to groundwater (drinking water) and surface water. An unacceptable risk means that the environmental concentrations derived from the estimated source strength exceed relevant toxicity threshold value towards the environment or humans. The risk screening considers the situation when the percolate start leaching to the surrounding environment, which potentially can happen when the plastic bags containing the waste are fractured, and the deposit plastic membrane is fractured or percolate runs over the edge of the deposit.

Input parameters have been varied to illustrate the influence of different releases, transport and exposures in scenarios that describe worst-case and probable conditions. The number of variables is kept low, as the knowledge and accuracy of data is scarce, and each parameter carries along an uncertainty that is reflected in the final estimates.

The following TABLE 17, TABLE 18, TABLE 19 provide the Margin of Exposure (MoE = RfD/C) for human risk via drinking water (dr. wat.), and risk quotients (RQ = C/TV) for aquatic environment, using low (aq. low) (most conservative) and high (aq. high) TV values as explained in section 2.1. Different values of asbestos leaching fraction f (g/g/year), time T (year), and k ($kg/m^3$) are chosen (see section 5.5). MoE<1 or RQ>1 indicate potential risk and are marked in red.

**TABLE 17.** Margin of Exposure (MoE) and environmental risk quotients (RQ) for $f=1*10^{-10}$. MoE<1 or RQ>1 indicate potential risk and are marked in red.

| | **k = 0** | **$k = 1*10^{-5}$** | **k = 1** |
|---|---|---|---|
| T = 0 | 6.8E+04 (dr. wat.) | 6.8E+04 (dr. wat.) | 6.8E+04 (dr. wat.) |
| | 4.4E-02 (aq. low) | 4.4E-02 (aq. low) | 4.4E-02 (aq. low) |
| | 4.4E-08 (aq. high) | 4.4E-08 (aq. high) | 4.4E-08 (aq. high) |
| $T = T_{filling}$ | 6.8E+04 (dr. wat.) | 6.8E+04 (dr. wat.) | 1.6E+30 (dr. wat.) |
| | 4.4E-02 (aq. low) | 4.4E-02 (aq. low) | 1.9E-27 (aq. low) |
| | 4.4E-08 (aq. high) | 4.4E-08 (aq. high) | 1.9E-33 (aq. high) |
| T = 20 years | 6.8E+04 (dr. wat.) | 6.8E+04 (dr. wat.) | 2.7E+45 (dr. wat.) |
| | 4.4E-02 (aq. low) | 4.4E-02 (aq. low) | 1.1E-42 (aq. low) |
| | 4.4E-08 (aq. high) | 4.4E-08 (aq. high) | 1.1E-48 (aq. high) |

**TABLE 18.** Margin of Exposure (MoE) and environmental risk quotients (RQ) for $f=2*10^{-9}$. MoE<1 or RQ>1 indicate potential risk and are marked in red.

| | **k = 0** | **$k = 1*10^{-5}$** | **k = 1** |
|---|---|---|---|
| T = 0 | 3.4E+03 (dr. wat.) | 3.4E+03 (dr. wat.) | 3.4E+03 (dr. wat.) |
| | 8.8E-01 (aq. low) | 8.8E-01 (aq. low) | 8.8E-01 (aq. low) |
| | 8.8E-07 (aq. high) | 8.8E-07 (aq. high) | 8.8E-07 (aq. high) |
| $T = T_{filling}$ | 3.4E+03 (dr. wat.) | 3.4E+03 (dr. wat.) | 8.0E+28 (dr. wat.) |
| | 8.8E-01 (aq. low) | 8.8E-01 (aq. low) | 3.7E-26 (aq. low) |
| | 8.8E-07 (aq. high) | 8.8E-07 (aq. high) | 3.7E-32 (aq. high) |
| T = 20 years | 3.4E+03 (dr. wat.) | 3.4E+03 (dr. wat.) | 1.3E+44 (dr. wat.) |
| | 8.8E-01 (aq. low) | 8.8E-01 (aq. low) | 2.2E-41 (aq. low) |
| | 8.8E-07 (aq. high) | 8.8E-07 (aq. high) | 2.2E-47 (aq. high) |

**TABLE 19.** Margin of Exposure (MoE) and environmental risk quotients (RQ) for $f=5*10^{-6}$. MoE<1 or RQ>1 indicate potential risk and are marked in red.

| | **k = 0** | **$k = 1*10^{-5}$** | **k = 1** |
|---|---|---|---|
| T = 0 | 1.4E+00 (dr. wat.) | 1.4E+00 (dr. wat.) | 1.4E+00 (dr. wat.) |
| | 2.2E+03 (aq. low) | 2.2E+03 (aq. low) | 2.2E+03 (aq. low) |
| | 2.2E-03 (aq. high) | 2.2E-03 (aq. high) | 2.2E-03 (aq. high) |
| $T = T_{filling}$ | 1.4E+00 (dr. wat.) | 1.4E+00 (dr. wat.) | 3.2E+25 (dr. wat.) |
| | 2.2E+03 (aq. low) | 2.2E+03 (aq. low) | 9.4E-23 (aq. low) |
| | 2.2E-03 (aq. high) | 2.2E-03 (aq. high) | 9.4E-29 (aq. high) |
| T = 20 years | 1.4E+00 (dr. wat.) | 1.4E+00 (dr. wat.) | 5.4E+40 (dr. wat.) |
| | 2.2E+03 (aq. low) | 2.2E+03 (aq. low) | 5.6E-38 (aq. low) |
| | 2.2E-03 (aq. high) | 2.2E-03 (aq. high) | 5.6E-44 (aq. high) |

Initial asbestos concentrations ($C_0$) derived from Equation 6 vary from approx. $2*10^{-9}$ to $8*10^{-5}$ mg/L. Estimated default values of $C_0$ (based on 90%-percentiles) for controlled deposits range from $5*10^{-5}$ mg/L (fluoranthene) to 2800 mg/L (chloride, $Cl^-$) (Miljøstyrelsen, 2018b). The asbestos levels are thus in the low end of default $C_0$ values that are used in the GrundRisk Landfill model.

The concentration decrease in time is significant for k=1 (right-most columns in TABLE 17, TABLE 18, and TABLE 19. As previously mentioned a default *k* value for the water immiscible pentadecane is approx. $10^{-4}$ kg/m$^3$ and 3.4 kg/m$^3$ for phenol (Miljøstyrelsen, 2018b). Most appropriate *k* values for asbestos fibers will probably be <$10^{-4}$ kg/m$^3$ and therefore the influence of time, i.e. the accumulated amount of percolate, on the decrease of the asbestos concentration in the percolate, will probably be insignificant.

A MoE>1 for drinking water (humans) and RQ<1 for surface water (aquatic environment) is primarily dependent in the initial concentration in the percolate $C_0$. When no measurements exist, the simple relationship in Equation 6 can be used to for a steady-state situation with constant rain infiltration and constant $C_0$. The asbestos concentration in the waste (F) and the release fraction of asbestos to the percolate (f) together with the water infiltration rate from precipitation (I) will determine $C_0$. Of these parameters, f is the most uncertain and will in principle vary from zero, when the bags containing the waste are intact, and/or the deposit membrane is intact, to > zero, for any degree of rupture on the plastic bags. Furthermore, the release rate will vary depending on the waste material, i.e. how fixed the asbestos fibers are in the material and how friable the asbestos is.

The risk quotients are calculated for the immediate point of outflow to the surface water recipient. There will be a dispersion of the percolate from the soil when it enters the surface water, which reduces the concentration. Depending on the currents in the surface water body, the asbestos fibers can deposit and potentially accumulate in the sediment. This has to be measured or modelled for the specific recipient.

In conclusion, from TABLE 17, it is seen that for relatively low values of f ($1*10^{-10}$ g/g/year), the percolate concentration will not cause potential risk to humans or the environment. In TABLE 18, the low aquatic TV is exceeded for an f value of $2*10^{-9}$ g/g/year, meaning that $2*10^{-7}$ % of the asbestos in the waste is released every year. In TABLE 19, using an f value of $5*10^{-6}$ g/g/year, in addition to potential aquatic risk using the low TV, the drinking water concentration yields potential risk to humans:

Potential aquatic risk (TV=0.0001 MFL): $f>2*10^{-9}$ g/g/year.

Potential human risk (RfD=0.3 MFL): $f>5*10^{-6}$ g/g/year.

These results can be held up against findings from the US EPA (2020), who surveyed drinking water for chrysotile asbestos content and found that approx. 4% of the more than 14.000 samples analyzed exceeded 0.3 MFL - and that <0.2% exceeded 7 MLF, in the time period from 1997 to 2011. They thus concluded that there is a low risk for humans via this exposure route. The situation is generally assumed to be the same in Denmark, so these lines of evidences indicate a low human risk due to drinking water exposures. Di Ciaula (2017) discussed lack of data regarding drinking water exposures and in-depth toxicological evaluation of the fibers when ingested. Children are of specific concern due to their relatively higher water intake per mass unit, Dr Di Ciaula also notes that the majority of asbestos in drinking water is derived from cement pipes.

Moreover, the US EPA (2020) suggests in their analysis of the systematic review, that there is low or no potential for environmental risk to aquatic or sediment-dwelling receptors because water releases are expected to be negligible. It is important to note that the available high-quality aquatic toxicity studies by Belanger et al. (1990, 1986a, 1986b, 1986c, 1987) address other effect endpoints than traditionally ones such as survival, growth and reproduction – as they primarily address feeding and behavior NOECs and LOECs. They moreover report very large variations in the hazard values from 0.0001 to 100 MFL – suggesting that more research is needed to define the toxicity more precisely. The lethality of the organisms would most likely occur at concentrations higher than 100 MFL. Hence, in a more traditional risk assessment approach there is a need to include studies that address traditional endpoints. Moreover, the toxic mechanism and mode of action of chrysotile asbestos would benefit from more research to accurately assess the toxicity and thresholds.

## 5.7 Qualitative uncertainty analysis

This study has been performed using generic parameter values for asbestos that cannot be validated neither through measurements nor with models or literature values. Rather, a sensitivity analysis was performed to identify parameter values and ranges that indicate a potential risk. It is recommended to establish, via laboratory or field measurements and models, realistic values to ensure that the estimated asbestos concentrations in drinking water and surface water are within the limits of safe concentrations.

The parameters mentioned here are fundamental in the determination of the most transparent analysis, and should be prioritized in future risk assessments of asbestos in the environment.

Leaching tests for various product types and mechanical stress need to be conducted to estimate f, k and $C_0$, which are key information to estimate the source strength, both at time zero but also the progress in time. Further, measurement should be made in site specific deposit percolate to derive $C_0$ values. Furthermore, time series of interconnected values between the percolate production (L) and $C_0$ should be determined from leaching experiments. These can be used for specific deposits but also enter the model as default values.

The transport description of asbestos fibers in groundwater and soil is not optimal using GrundRisk Landfill. Soil macropore transport modelling of fibers should be made, and the model results should be verified with measurements in the percolate and in the soil and groundwater matrix. This will reveal if a macropore transport of asbestos fibers is realistic and if there is filtration and accumulation of fibers in the soil below the deposit.

The estimated amounts of asbestos vary in the different types of waste materials and products. What materials and products are present and what the asbestos concentrations are in the specific deposits are not sufficiently described. Furthermore, the state of the waste, i.e. the presence of friable asbestos is also not known. The typically occurring state of the plastic bags containing the waste must be investigated to specify if there is rupture, which is needed for asbestos to leach into percolate. These factors should be inventoried for specific deposits in connection with monitoring of percolate and groundwater concentrations.

For the aquatic environment, there is a large variation in the asbestos toxicity threshold values. Understanding the toxicity with respect to mode of action will give a more precise quantification of the toxicity threshold values for asbestos.

In addition to these parameters there are a number of factors in the modelling, e.g. in GrundRisk Landfill, that can be improved. These are further commented in e.g. Miljøstyrelsen (2018b).

# 6. Discussion and perspectives

## 6.1 General discussion of the results

The main application for asbestos in the past was in cement products. Hence, cement-matrix materials can be expected being prevalent components in waste containing asbestos which is separately collected. However, when looking at waste containing both asbestos and other environmentally problematic substances, other materials may be likely more relevant, including for example vinyl/linoleum asbestos flooring, asbestos paper and felts, and caulks.

Generation of waste containing asbestos has been increasing throughout the last decade. This could be due to several reasons, including increasing demolition/renovation of buildings that were constructed or renovated in periods when asbestos was in use, and/or more thorough screening/mapping of buildings (see section 3.4 for details) with subsequent increasing generation of waste. No official data exist for the amount of waste containing both asbestos and other environmentally problematic substances; some municipalities and companies tentatively estimate that the amounts could be up to few thousand ton per year. A coordinated system for registration of the occurrence of these waste fractions may improve this estimates, in order to support decision-making as well as share best practices and approaches.

Four samples including three materials (i.e. vinyl/linoleum flooring containing both asbestos and heavy metals; tiles containing both asbestos and heavy metals; roofing felt containing both asbestos and heavy metals or organic pollutants) were experimentally investigated. In two of the four samples, i.e. both of the roofing felt samples, asbestos was not found, this being inconsistent with the results included in the environmental screening and mapping prior to demolition. Compared with the initial declaration of the roofing felt materials one of the two samples was still classified as "hazardous" waste because of the content of heavy metals; one sample of roofing felt could be down-classified as "contaminated" waste. One sample of roofing felt was found containing PCB; the material had not been previously analyzed for PCB during the screening/mapping phases prior to demolition.

## 6.2 Procedure for classification of asbestos-containing demolition waste

Classification of waste containing both asbestos and other environmentally problematic substances is a multi-step procedure, including screening, mapping and reporting prior (and to some extent also during and after) to demolition or renovation. This process is thoroughly supervised by the municipality, who decides whether the adopted methodologies are appropriate and the provided documentation is sufficient to ensure proper management of the waste. However, as official guidelines and standards do not exist, the screening/mapping is subject to some variability across municipalities and possibly also subjectivity in approval of the waste management plan for demolition and renovation activities. Based on the project, the following critical aspects of the screening/mapping procedure were identified:

- Sampling procedures: National guidelines for sampling could improve consistency and coverage of screening/mapping efforts and subsequent hazardousness classification. Similar to sampling procedures provided by Sjællandsnetværket for Bygge- og Anlægsaffald (2020), guidelines should specify the number of samples, sampling procedures and target substances for different materials. This applies to both asbestos and other environmentally problematic substances.

- Detection of asbestos in samples: Especially for asbestos, classification seems critical, as it is based on presence rather than on quantitative thresholds. Materials are typically analyzed for asbestos using optical methods such as NIOSH 9002 (Miljøstyrelsen, 2015), which may be sensitive to inhomogeneities in material composition. This means that asbestos may or may not be detected depending on the portion of the sample that is observed (Fynbo, 2021); on the other hand, trace concentrations of asbestos (e.g. from cross-contamination) could lead to classification of waste as asbestos-containing in the unfortunate situation that fibers are found in the portion of sample being analyzed. Eurofins suggests that additional samples should be taken and analyzed for those materials considered inhomogeneous (Fynbo, 2021). Roofing felt is in Eurofins' list for potentially inhomogeneous materials (Fynbo, 2021); this may be an explanation for the inconsistent results between this project and the previous investigations done during the screening and mapping phases. Thus, the number of samples and sampling approach is critical in particular for potentially inhomogeneous materials.
- Classification strategy: Additional samples of waste materials taken also during the demolition phase could improve classification by cross-checking and confirming results from the mapping phase. If this additional sampling demonstrate that the waste does not have hazardous properties, then re-classification of the waste could be an option.

## 6.3 Management of waste containing both asbestos and environmentally problematic substances

A summary of results and treatment options is provided in the following TABLE 20, based on the hypothesis that asbestos contained in the roofing felt would be destroyed as effectively as for linoleum during thermal treatment at 1100 °C. The results of the experimental activities can be summarized as follows:

- The release tests showed that the samples of vinyl/linoleum flooring (heavy metals) and tiles (heavy metals) could comply with the acceptance criteria for all classes of landfills approved for hazardous waste disposal.
- The thermal tests indicated that high temperatures in the order of 1100 °C are effective in significantly reducing or eventually almost completely destroying the organic pollutants contained in the waste. With regards to asbestos, general conclusions could not be reached, because asbestos was detected only in one waste sample (i.e. vinyl/linoleum flooring). However, the experiments indicated that the heating of waste to 1100 °C can be effective in destroying the asbestos fibers, in agreement with the existing literature on the topic.

**TABLE 20.** Summary of potential management options for waste containing both asbestos and other environmentally problematic substances.

| Material | Contaminants | Hazardous waste landfilling | Hazardous waste incineration |
|---|---|---|---|
| **Linoleum** | Asbestos<br>Heavy metals<br>Hydrocarbons | Yes<br>(upon compliance with acceptance criteria) | Yes |
| **Tiles** | Asbestos<br>Heavy metals<br>Hydrocarbons | Yes | Not applicable |
| **Roofing felt** | Asbestos<br>PCB<br>PAH<br>Hydrocarbons | Yes, if:<br>PCB <50 mg/kg<br>$PAH_{total}$ <4 mg/kg | Yes* |

* Assuming asbestos fibers are destroyed as effectively as for linoleum.

# 7. Conclusions

This project investigated options for managing waste containing both asbestos and other environmentally problematic substances (WCAPS). The project identified the following three materials as the most frequently occurring combinations of materials, asbestos and environmentally problematic substances within demolition and renovation activities in Denmark:

- vinyl/linoleum flooring containing both asbestos and heavy metals;
- tiles containing both asbestos and heavy metals;
- roofing felt containing both asbestos and heavy metals or organic pollutants.

Four samples of these WCAPS materials (as classified according to their accompanying documentation) were obtained from waste management companies and analyzed for their content of asbestos, PCB, PAHs, heavy metals and hydrocarbons. While all samples were classified as hazardous waste, one sample of roofing felt could qualify as “contaminated waste” (“forurenet affald” in Danish). Procedures for screening, mapping and classifying waste containing both asbestos and other environmentally problematic substances were discussed and critical aspects identified.

Samples of tiles and linoleum were tested for compliance with acceptance criteria for hazardous waste landfills. The leaching of inorganic elements showed that both materials would comply with the acceptance criteria for all classes of landfills approved for hazardous waste disposal.

Samples of linoleum and roofing felt were treated at 1100 °C to assess the efficacy of thermal treatment in destroying asbestos and organic pollutants. The results indicated that high temperatures are effective in significantly reducing or potentially completely destroying the organic pollutants contained in the waste. With regards to asbestos, results were only available for linoleum flooring (asbestos were not detected in the roofing felt samples, despite the fact that their documentation indicated its presence). While conclusions beyond the specific samples cannot be made, the experiments indicate that heating of waste to 1100 °C may be effective in destroying the asbestos fibers, in agreement with the existing literature on the topic.

The risk screening evaluated leaching of asbestos from landfills to the aquatic environment. The screening indicated that there is low risk towards humans (via drinking water) and organisms in the receiving surface waters. The project further identified that there is no scientific evidence regarding toxicity effects or risks from combinations of asbestos and other contaminants.

Based on the results, potential options for management of waste containing both asbestos and other environmentally problematic substances were identified, together with key parameters to be checked during the decision-process. Regarding the risk screening more knowledge and data on source characteristics, asbestos leaching from waste, exposure and toxicity towards sensitive sub-populations (e.g. children) are required to improve the results. It should be noted that the risk screening is based solely on available data and general assumptions, and specific data collection and stakeholder involvement e.g. for site descriptions was beyond the scope of the project.

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# Appendix 1. Literature search

The aim of the literature search was to collect literature studies that i) investigated/reviewed the options for treating asbestos minerals (with particular focus on the thermal treatment) and ii) investigated the potential leaching from materials containing asbestos (i.e. minerals, products and waste). The searching results were screened based on the following criteria:

1. title of the publication and publication year;
2. abstract;
3. content, based reading the full text.

“Relevant” studies fulfilled all three criteria above, whereas “non-relevant” studies could be excluded already at the first step. It should be noted that studies focusing on insulation properties, mechanical properties and airborne releases of asbestos containing products were considered “not relevant” for this literature search and were thus excluded from the results of this search.
A preliminary literature review based on the most common databases for science research was performed, by using specific keywords. In addition to this, following searching criteria were used to complement the list of articles found during the preliminary search.

**TABLE 21.** Results of general literature search on asbestos-containing materials.

| Keywords combination | N. found | Notes |
|---|---|---|
| "asbestos" "flooring" | 399 | 197 since year 2000 |
| "asbestos" "vinyl” AND (“flooring" OR “floor”) | 53 | 7 since year 2000 |
| "asbestos" "linoleum" | 16 | |

**TABLE 22.** Results of literature review on specific aspects of asbestos-containing materials.

| Keywords combination | N. found | N. relevant | Notes |
|---|---|---|---|
| "asbestos" AND ("thermal" OR “leaching”) AND ("polyvinyl chloride" OR "PVC") | 25 | 1 | |
| "shingle" "asbestos" AND ("leaching" OR "thermal") | 2 | 0 | |
| "asbestos" "flooring" AND ("leaching" OR "thermal") | 22 | 3 | |
| "asbestos" "flooring" "treatment" | 29 | 1 | |
| "asbestos" "linoleum" AND ("leaching" OR "thermal") | 1 | 1 | |
| "asbestos" AND ("PAH" OR “PCB”) AND ("thermal" OR "leaching") | 10 | 2 | |
| "asbestos" AND ("heavy metals") AND ("thermal" OR "leaching") | 17 | 2 | |
| "asbestos" AND ("roofing" OR “roof” OR “shingle”) AND ("leaching" OR "thermal") | 90 | 7 | |
| "Asbestos cement" AND ("leaching" OR "thermal") | 100 | 2 | |
| (“asbestos corrugated sheets” OR "Asbestos cement sheet") AND ("leaching" OR "thermal") | 18 | 0 | |

| | | |
|---|---|---|
| "Asbestos cement" AND ("heavy metal" OR "PAH" OR "PCB") AND ("leaching" OR "thermal") | 3 | 2 |
| "asbestos" AND ("leaching test" OR "leaching experiment" OR "acid* solution" OR "acid* extraction" OR "batch test" OR "column test") | 42 | 6 |

## Appendix 1.1 Toxicity and risk screening

**SciFinder:**

1. **Friction material on disc brake pad [Machine Translation].**

   By Chen, Shengda

   From Faming Zhuanli Shenqing (2020), CN 111853119 A 20201030, Language: Chinese, Database: CAPLUS

   [Machine Translation of Descriptors]. The invention relates to a friction material on a disk brake pad, which comprises the following materials in parts by wt.:11-20 parts of phenolic resin, 10-17 parts of nitrile rubber, 6-14 parts of mineral fiber, 5-12 parts of calcium sulfate whisker, 2-7 parts of aramid fiber, 2-7 parts of natural graphite, 3-5 parts of brown corundum, 15-21 parts of barite powder, 2-7 parts of friction powder and 4-10 parts of chromite powder, 5-12 parts of heavy calcium carbonate, 1-5 parts of zircon sand and 7-13 parts of mica powder.The friction material prepd. from the raw materials has the effects of long service life, good braking effect and no toxic or side effect on a human body;The raw materials of the product do not contain asbestos, and dust harmful to human bodies cannot be generated during braking;The invention also does not contain heavy metal elements, thereby protecting the environment, and has the advantages of reasonable formula, high cost performance and good product quality.

   ~0 Citings

2. **A review of recycled aggregate in concrete applications (2000-2017)**

   By Tam, Vivian W. Y.; Soomro, Mahfooz; Evangelista, Ana Catarina Jorge

   From Construction and Building Materials (2018), 172, 272-292. Language: English, Database: CAPLUS, DOI:10.1016/j.conbuildmat.2018.03.240

   Solid waste has been an inevitable byproduct of the operations of industrialised societies. One result of economic growth is an increase in generation of solid waste which normally was dumped in landfills and caused contamination of soil, water and air from toxic substances such as polychlorinated bi-phenyls (PCB's), asbestos, construction chems., heavy metals, but the scarcity of land-filling areas, industrial growth as well as strict environmental regulations in developed and developing economies has led to the global re-assessment of the methods employed to recycle and utilize construction and demolition (C&D) waste as recycled aggregate for civil engineering projects i.e. construction and infrastructure development. Depending on their quality, recycled aggregate produced from C&D waste can be employed in various civil engineering works, which can help in a long way the eco-nomic and environmental sustainability of resp. countries. With further research and development into overcoming tech. as well as market barriers, considerable increase in recovery rates can be achieved with the existing technologies in developed economies. The main aim of this study is to review the literature on the prodn. and utilization of recycled aggregate in concrete, concrete pavements, roadway construction, and other civil engineering works and some discussion on the savings on CO2 emissions have been included. The globally published data on recycled aggregate stds. (normative documents) of various countries have been systematically analyzed and evaluated, and some barriers mentioned. This review may help to alleviate the concerns of con-sumers and encourage and further promote the use of recycled aggregate on a larger scale in civil engineering projects.

   ~95 Citings

3. **Current status of air toxics management and its strategies for controlling emissions in Taiwan**

   By Tsai, Wen-Tien

   From Toxics (2016), 4(2), 8/1-8/7. Language: English, Database: CAPLUS, DOI:10.3390/toxics4020008

   Since the 1970s, hazardous air pollutants (HAPs), so-called air toxics, have been of great concern because they can cause serious human health effects and have adverse effects on the environment. More noticeably, some of them are known to be human carcinogens. The objective of this paper is to investigate the regulatory systems and human health effects of air toxics which have been designated by the Taiwan government under the Air Pollution Control Act. These toxic air pollutants include acutely toxic gas (i.e., ammonia, chlorine, fluorides, hydrochloric acid, hydrogen cyanide, hydrogen sulfide, nitric acid, phosphoric acid and sulfuric acid), gas contg. heavy metals, and carcinogenic chems. (including formaldehyde, vinyl chloride, asbestos and matter contg. asbestos, dioxins and furans, volatile org. compds., polycyclic arom. hydrocarbons, and polychlorinated biphenyls). In line with international concern about the carcinogenic risk and environmental persistence of polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans

(PCDDs/PCDFs) and heavy metals in recent years, the current status in monitoring and reducing the emissions of PCDDs/PCDFs from stationary sources was analyzed as a case study in the present study. Furthermore, the control strategies for reducing emissions of air toxics from stationary sources in Taiwan were also addressed.

~2 Citings

4. **Environmental toxins and ecotoxicology**

   By Sahu, Kaushilya; Patel, Hemkumari

   From Indian Journal of Scientific Research (2017), 13(2Spec.Iss.), 158-160. Language: English, Database: CAPLUS

   Environmental toxicol. is a multidisciplinary field of science which deals with the study of harmful effects of toxic chems., biol. and phys. agents on various organisms. Ecotoxicol. is a sub discipline of environmental toxicol. concerned with effects of these toxic chems. particularly on the community and at ecosystem level. Saving our environment is the foremost concern of the human being because our existence on this earth depends on our effort to keep our environment safe for the living organisms. Because of the polluted ecosystem many species have become the talk of the past and many other are on the verge of extinction like bald eagle, ospreys and peregrine falcons etc. Ecotoxicol. can inform us the best possible measures to restore our contaminated ecosystem. This paper attempts to analyze the effect of these harmful chems. on individuals and community and to suggest the possible ways of preventions. The common environmental toxicants are pesticides, phthalates, volatile org. compds. such as formaldehyde, asbestos, heavy metals, and chlorine etc. Since we are all connected to the ecosystem through food chain plants absorb these toxins through their roots and leaves, when animals consume these contaminated plants these toxins transfer through the food chain into other animals and finally transmit to human beings which is called as secondary poisoning. So ecotoxicol. is an ongoing battle that can affect everything and everyone in an ecosystem. Hence preventive measures to check the flow of toxicants are the dire needs to maintain a healthy and well balanced ecosystem.

   ~0 Citings

5. **Is phytoremediation of asbestos contaminated sites feasible?**

   By Gonneau, Cedric; Mohanty, Sanjay; Willenbring, Jane; Casper, Brenda

   From Abstracts of Papers, 252nd ACS National Meeting & Exposition, Philadelphia, PA, United States, August 21-25, 2016 (2016), ENVR-462. Language: English, Database: CAPLUS

   Asbestos is a colloquial term encompassing several fibrous silicates. Inhalation of the fibers can cause mesothelioma and cancer of the lung. In the US, there are 1312 asbestos contaminated sites including Superfund, Brownfield and naturally occurring asbestos sites. Currently, the EPA protocol for treatment of asbestos contaminated sites is to move it and/or cap it. However, capped piles contg. fibers can pose threats to nearby human populations. Indeed, new remediation strategies, such as remediation, should be explored. Three locations with different asbestiform minerals were studied: BoRit, a superfund site with two areas: sediments and stream banks. Nottingham Park, a serpentine site with several mines such as a chromite mine. To det. feasibility of phytoremediaton of asbestos contaminated soils, we evaluated: 1. fertility using Fertility Capability Classification (Texture and 12 modifiers) and detd. soils properties (pH, CEC, Phosphorus, total and bioavailable concns. of heavy metal). 2. toxicity by an ecotoxicol. test. We detd. percentage of inhibition of seed germination and root growth on three species (one Poaceae, two Brassicaceae). All locations tested differed significantly in the various soil parameters. Among 12 modifiers and 23 soils parameters, limiting factors of fertility were: percentage of gravel, pH, P, K, total concns. of Ni and Cr. Ni and Cr bioavailability was low. In the ecotoxicol. test, all three asbestiform sites had reduced seed germinatioin (5-30% of control). Root growth was reduced 2-50% of control with greatest redn. for Poaceae. Our results showed that it is important to take into account all soil-limiting parameters and not only pollutants. Moreover, utilization of compost will decrease pH and increase soil fertility but could also increase bioavailability of trace elements (Ni or Cr). Indeed, serpentinophytes seem to be a possible method for phytoremediation on asbestiform. Our research proposes and validates a novel approach to the remediation of asbestos-polluted soil.

   ~0 Citings

6. **Health effects of World Trade Center (WTC) Dust: An unprecedented disaster's inadequate risk management**

   By Lippmann, Morton; Cohen, Mitchell D.; Chen, Lung-Chi

   From Critical Reviews in Toxicology (2015), 45(6), 492-530. Language: English, Database: CAPLUS, DOI:10.3109/10408444.2015.1044601

   The World Trade Center (WTC) twin towers in New York City collapsed on 9/11/2001, converting much of the buildings' huge masses into dense dust clouds of particles that settled on the streets and within buildings throughout Lower Manhattan. About 80-90% of the settled WTC Dust, ranging in particle size from ~2.5 µm upward, was a highly alk. mixt. of crushed concrete, gypsum, and synthetic vitreous fibers (SVFs) that was readily resuspendable by phys. disturbance and low-velocity air currents. High concns. of coarse and supercoarse WTC Dust were inhaled and deposited in the conductive airways in the head and lungs, and subsequently swallowed, causing both phys. and chem. irritation to the respiratory and gastroesophageal epithelia. There were both acute and chronic adverse health effects in rescue/recovery workers; cleanup workers; residents; and office workers, esp. in those lacking effective personal respiratory protective equipment. The numerous health effects in these people were not those assocd. with the monitored PM2.5 toxicants, which were present at low concns., i.e., asbestos fibers, transition and heavy metals, polyarom. hydrocarbons or PAHs, and dioxins. Attention was never directed at the very high concns. of the larger-sized and highly alk. WTC Dust particles that, in retrospect, contained the more likely causal toxicants. Unfortunately, the initial focus of the air quality monitoring and guidance on exposure prevention programs on low-concn. components was never revised. Public agencies need to be better prepd. to provide reliable guidance to the public on more appropriate means of exposure assessment, risk assessment, and preventive measures.

~22 Citings

7. **Assessment of potentially toxic heavy metal contamination in agricultural fields, sediment, and water from an abandoned chromite-asbestos mine waste of Roro hill, Chaibasa, India**

By Kumar, Adarsh; Maiti, Subodh Kumar

From Environmental Earth Sciences (2015), 74(3), 2617-2633. Language: English, Database: CAPLUS, DOI:10.1007/s12665-015-4282-1

The major aim of the present study is to assess (1) depth-wise physico-chem. characteristics and pseudo-total metal concns. in the abandoned chromite-asbestos mine waste, contaminated agricultural soil, and control agriculture soil; (2) degree of soil contamination and metal geoaccumulation index in agricultural soil; and (3) concns. of metal in the sediment and water samples of river, tributary, and different water bodies located in the vicinity of an abandoned chromite-asbestos mine of Roro hill. Nutrient content and phys. properties of the mine waste were found low and poor. Pseudo-total metal concns. in the mine waste were found in the order of Cr > Ni > Mn > Cu > Pb > Co > Zn > Cd. High concns. of Cr (1148 mg kg-1) and Ni (1120 mg kg-1) were found in the contaminated agricultural soils which far exceed the soil threshold limits. The contamination factor and geoaccumulation index in the agricultural soils were found high and decreased with increase in depth for Cr and Ni, indicating strong contamination. Concns. of Zn, Mn, Co, Cu, Pb, and Cd were found low and within toxicity limit. Further, metal grouping and site grouping cluster anal. also revealed that Cr and Ni are closely linked with each other and chromite-asbestos mine waste was the major source of contamination. Sediment samples were found high in metal content and decreased with increase in distance and mine waste influence. Water flowing from the mine adit was found high in Cr and Ni concn. (above crit. drinking water total concn.). Further research is required to study the pollution factors for sediment and water samples and metal accumulation pattern in naturally growing plants and locally practised crops to access its impact on human and livestock.

~29 Citings

8. **An evaluation of landfill disposal of asbestos-containing waste and geothermal residues within a risk-assessment framework**

By Promentilla, Michael Angelo B.; Peralta, Genandrialine L.

From Journal of Material Cycles and Waste Management (2003), 5(1), 13-21. Language: English, Database: CAPLUS, DOI:10.1007/s101630300003

The public perception of risks related to waste disposal facilities appears to reflect general societal anxieties and fears, which may not have a reasonable basis. A 3-tier risk assessment study evaluated landfill disposal of asbestos-contg. waste (ACW) and geothermal residues. From the tier-1 anal., the dominant asbestiform phase was identified as chrysotile, tightly bound in a calcite matrix, while As, Cd, Cr, and Pb were identified as chems. of potential concern assocd. with geothermal residues. From the tier-2 anal., none of the possible exposure pathways assocd. with landfill disposal of ACW was potentially significant. There were potentially significant pathways assocd. with landfill disposal of geothermal residues due to the considerable potential pollution impact of leachate on soil and groundwater quality. From the tier-3 anal., health risks assocd. with landfill disposal of geothermal residues was time-dependent, since risk contributions from water-dependent and water-independent pathways occur at different times, as indicated by RESRAD-Chem simulations. Component pathway analyses identified crit. exposure pathways. Model sensitivity anal. results identified input parameters which have the most effect on the time of peak risk and the cancer risk assocd. with water-dependent and water-independent pathways.

~2 Citings

9. **Rapid screening of possible cytotoxic effects of particulate air pollutants by measurement of changes in cytoplasmic free calcium, cytosolic pH, and plasma membrane potential in alveolar macrophages by flow cytometry**

By Tarnok, Attila; Dorger, Martina; Berg, Ingeborg; Gercken, Gunther; Schluter, Thomas

From Cytometry (2001), 43(3), 204-210. Language: English, Database: CAPLUS

Inhalable particulate dusts are involved in the genesis of several lung diseases. Besides the well-known toxic dusts, i.e., asbestos and quartz, heavy metal-contg. pollutants are considered as possible harmful substances. In the present study, we compared the effect of silica chem. coated with certain metal oxides and dusts from industrial productions on cell physiol. parameters of bovine alveolar macrophages (BAM). The cytosolic free calcium concn., [Ca2+]i, the intracellular pH (pHi), and the plasma membrane potential (MP) of BAM were measured by flow cytometry. The dust-induced secretion of reactive oxygen species (ROS) was measured enzymically. Compared with control incubations with pure silica, the dust-induced secretion of ROS by BAM was not affected when the particles were coated with Cr2O3, NiO, and Fe3O4, whereas VO2-coated dust induced a marked increase in ROS release. This effect was not correlated to changes in [Ca2+]i, pHi, or MP. On the other hand, Cr2O3-coated silica caused alterations in all of the three latter parameters. The same pattern of changes has been reported previously for quartz dusts (A. Tarnok et al., 1997). We conclude that cell physiol. measurements by flow cytometry could extend the palette of tools to evaluate possible toxic effects of environmental dust samples.

~10 Citings

10. Rapid discrimination of silica and heavy metal oxide-coated dust by induction of changes in [Ca2+]i, pHi, and plasma membrane potential in alveolar macrophages using flow cytometry

    By Schluter, Thomas; Dorger, Martina; Berg, Ingeborg; Gercken, Gunther; Tarnok, Atilla

    From Proceedings of SPIE-The International Society for Optical Engineering (1999), 3604(Optical Diagnostics of Living Cells II), 177-187. Language: English, Database: CAPLUS, DOI:10.1117/12.349199

    Inhalable particulate dusts are involved in the genesis of several lung diseases. Besides the well-known toxic dusts, i.e. asbestos and quartz, heavy metal-contg. pollutants are considered as possible harmful substances. The effect of silica chem. coated with certain metal oxides on several cell physiol. parameters of bovine alveolar macrophages (BAM) was compared. The cytosolic free Ca concn. [(Ca2+]i), the intracellular pH (pHi), and the plasma membrane potential (MP) of BAM were measured by flow cytometry whereas the dust-induced secretion of reactive O species (ROS) was measured enzymically. Compared to control incubations with pure silica the dust-induced secretion of ROS by BAM was not affected when the particles were coated with Cr2O3, NiO, and Fe3O4, whereas VO2-coated dust induced a marked increase in ROS release. This effect was not correlated to changes in [Ca2+]i, pHi, or MP. On the other hand Cr2O3-coated silica caused alterations in all of the 3 latter parameters. The same pattern of changes was reported previously for quartz dusts. Cell physiol. measurements by flow cytometry could extend the pallet of tools to evaluate possible toxic effects of environmental dust samples.

    ~0 Citings

11. **Multimedia chemical exposure screening with a toxicity-activated biosensor**

    By Case, George D.; Bekowies, Paul J.; Russell, Geoffrey A.; Crivello, Joseph F.

    From Field Analytical Methods for Hazardous Wastes and Toxic Chemicals, Proceedings of a Specialty Conference, Las Vegas, Nev., Jan. 29-31, 1997 (1997), 875-886. Language: English, Database: CAPLUS

    A cytochrome P 450 (CYP)-based screening device is described that uses a simple color development process to detect exposure to a no. of hazardous chems. In general, the device detects oxidized intermediates that are believed to be common in initial carcinogenesis or endocrine disruption effects. Chem. agents which have been detected include heavy metals such as Cd(II), Hg(II), Cr(VI), Nio, and Ni(II); polychlorinated biphenyls (PCB); polycyclic arom. hydrocarbons (PAH) and benzene; phenolics; aldehydes and epoxides; vinyl/acrylic monomers; asbestos and other toxic mineral dusts; halogenated pesticides and herbicides, etc., at sensitivities generally appropriate to their toxicities. This study presents results of lab. and field tests of prototype units to multimedia chem. exposures. Controlled vapor exposures to 10 org. compds. of varying toxicities demonstrate reciprocity in exposure response - higher concns. trigger color development at shorter times than do lower vapor concns. of the same substance. Liq. soln. exposure tests to the same compds. reveal similar toxicity and sensitivity correlations. Particulate dusts and aerosols elicit locally enhanced color development similar to a measles pattern which often spread during archiving. Results of biosensor prototype tests are reported for lab. decontamination of hazardous chem. agents and field studies at residential sites in connection with aerial pesticide spraying and municipal waste management activities.

    ~0 Citings

12. **In vitro toxicity of respirable-size particles of diatomaceous earth and crystalline silica compared with asbestos and titanium dioxide**

    By Hart, Georgia A.; Hesterberg, Thomas W.

    From Journal of Occupational and Environmental Medicine (1998), 40(1), 29-42. Language: English, Database: CAPLUS, DOI:10.1097/00043764-199801000-00008

    The relationship between particle characteristics and in vitro toxicity was investigated using Chinese hamster ovary cells. Test dusts included respirable natural (Nat) and flux-calcined (FC) diatomaceous earth (DE), quartz, cristobalite, TiO2, and chrysotile and crocidolite asbestos. All dusts elicited a qual. similar, concn.-dependent response: particle uptake, induction of micro- and polynuclei, and redn. in cell proliferation. However, similar mass concns. of the dusts yielded a 35-fold range of toxicity: chrysotile > crocidolite> Nat DE> FC DE> quartz> Cristobalite> TiO2. In vitro toxicity did not correlate with cryst. silica content, surface area, compn., vol., particles/cm2, or fibrous geometry. Toxicity was closely assocd. with the no. of particles/cm2 culture surface that had at least one dimension > 7.5 µm. Thus particle size but not shape could be a determinant of in vitro toxicity. Particle size might also impact in vivo pathogenesis.

    ~54 Citings

13. **Save disposal of hazardous wastes by vitrification**

By Lendvay, Lajos

From Epitoanyag (1992), 44(6), 230-1. Language: Hungarian, Database: CAPLUS

The disposal of hazardous wastes, i.e., heavy metals, toxic org. substances, asbestos, by vitrification as an environmentally friendly method is discussed. The most expedient vitrification method is direct elec. heating.

~0 Citings

14. **Vitrification of contaminated soils**

By McNeill, K. R.; Waring, S.

Edited By:Rees, John F

From Contam. Land Treat. Technol., [Pap. Int. Conf.] (1992), 143-59. Language: English, Database: CAPLUS

The principles and application of the VERT vitrification process in the ex situ remediation of polluted soils in the UK are presented. Results of full scale process trials and a description of the tech. to be used in the first UK com. soil vitrification plant are also given.

~2 Citings

15. **The toxicity of cadmium air pollution: a reappraisal**

By Stewart-Pinkham, Sandra M.

From Trace Substances in Environmental Health (1990), 23, 345-69. Language: English, Database: CAPLUS

By re-examg. existing assumptions in the light of known cellular actions of cadmium, one can recognize that exposure by air is far more potent and affects all life forms around the globe. Cadmium, which concs. in tobacco leaves and dust, induces stress and enhances stress responses producing injuries in genetically susceptible cells, tissues, organs, or organisms in variety of ways. Other heavy metals, radon, asbestos, magnetic fields, toxic orgs. and microbials, which are known to react synergistically with cadmium, have similar effects.

~0 Citings

16. **On the measurement of toxic and carcinogenic aerosols in ambient air**

By Marfels, H.; Spurny, K. R.; Iburg, J.; Wenzel, A.; Fritsche, U.; Koenig, J.; Balfanz, E.

From Journal of Aerosol Science (1988), 19(7), 1299-302. Language: English, Database: CAPLUS, DOI:10.1016/0021-8502(88)90159-0

A complex sampling and anal. system measures toxic and carcinogenic aerosols. Ambient aerosols are sampled on 3 different types of filters and evaluated by electron microscopy, ion chromatog., gas chromatog., mass spectrometry, at. absorption spectrometry and PIXE. A 2-yr study in Germany showed that asbestos fibers, PCBs, polycyclic arom. hydrocarbons, heavy metals, sulfates, nitrates, acidic aerosols, etc., are the most important toxic and carcinogenic substances in the polluted air.

~0 Citings

17. **Health effects of World Trade Center (WTC) Dust: An unprecedented disaster's inadequate risk management**

By Lippmann Morton; Cohen Mitchell D; Chen Lung-Chi

From Critical reviews in toxicology (2015), 45(6), 492-530, Language: English, Database: MEDLINE

The World Trade Center (WTC) twin towers in New York City collapsed on 9/11/2001, converting much of the buildings' huge masses into dense dust clouds of particles that settled on the streets and within buildings throughout Lower Manhattan. About 80-90% of the settled WTC Dust, ranging in particle size from ~2.5 µm upward, was a highly alkaline mixture of crushed concrete, gypsum, and synthetic vitreous fibers (SVFs) that was readily resuspendable by physical disturbance and low-velocity air currents. High concentrations of coarse and supercoarse WTC Dust were inhaled and deposited in the conductive airways in the head and lungs, and subsequently swallowed, causing both physical and chemical irritation to the respiratory and gastroesophageal epithelia. There were both acute and chronic adverse health effects in rescue/recovery workers; cleanup workers; residents; and office workers, especially in those lacking effective personal respiratory protective equipment. The numerous health effects in these people were not those associated with the monitored PM2.5 toxicants, which were present at low concentrations, that is, asbestos fibers, transition and heavy metals, polyaromatic hydrocarbons or PAHs, and dioxins. Attention was never directed at the very high concentrations of the larger-sized and highly alkaline WTC Dust particles that, in retrospect, contained the more likely causal toxicants. Unfortunately, the initial focus of the air quality monitoring and guidance on exposure prevention programs on low-concentration components was never revised. Public agencies need to be better prepared to provide reliable guidance to the public on more appropriate means of exposure assessment, risk assessment, and preventive measures.

~24 Citings

18. **Rapid screening of possible cytotoxic effects of particulate air pollutants by measurement of changes in cytoplasmic free calcium, cytosolic pH, and plasma membrane potential in alveolar macrophages by flow cytometry**

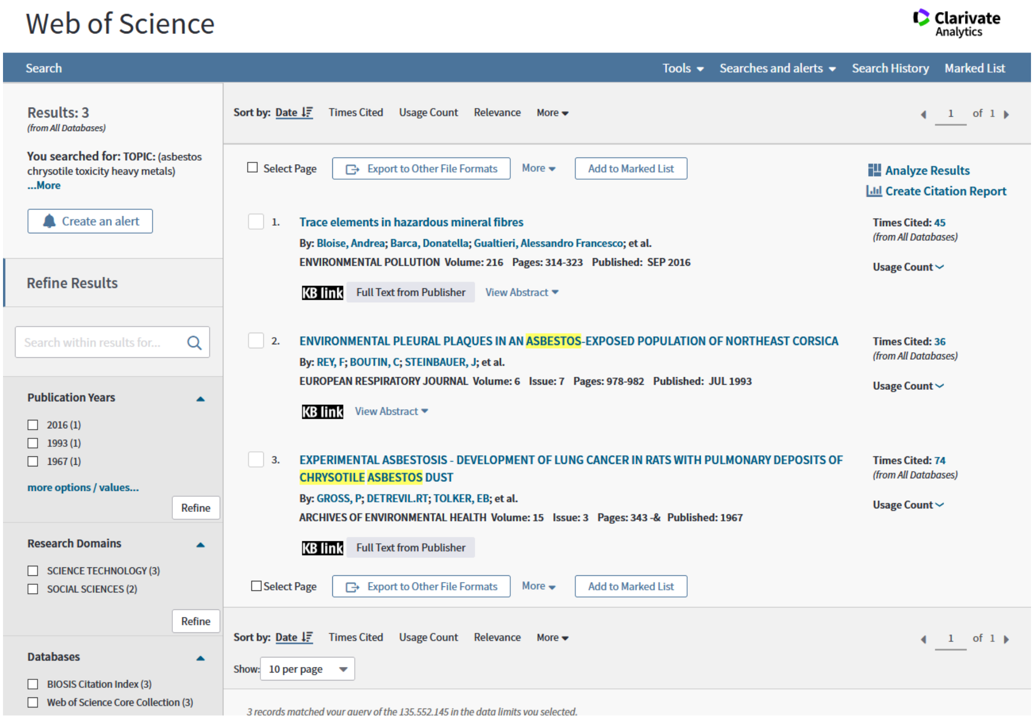
    By Tarnok A; Dorger M; Berg I; Gercken G; Schluter T

    From Cytometry (2001), 43(3), 204-10, Language: English, Database: MEDLINE

    BACKGROUND: Inhalable particulate dusts are involved in the genesis of several lung diseases. Besides the well-known toxic dusts, i.e., asbestos and quartz, heavy metal-containing pollutants are considered as possible harmful substances. In the present study, we compared the effect of silica chemically coated with certain metal oxides and dusts from industrial productions on cell physiological parameters of bovine alveolar macrophages (BAM). METHODS: The cytosolic free calcium concentration, [Ca2+](i), the intracellular pH (pH(i)), and the plasma membrane potential (MP) of BAM were measured by flow cytometry. The dust-induced secretion of reactive oxygen species (ROS) was measured enzymatically. RESULTS: Compared with control incubations with pure silica, the dust-induced secretion of ROS by BAM was not affected when the particles were coated with Cr(2)O(3), NiO, and Fe(3)O(4), whereas VO(2)-coated dust induced a marked increase in ROS release. This effect was not correlated to changes in [Ca2+](i), pH(i), or MP. On the other hand, Cr(2)O(3)-coated silica caused alterations in all of the three latter parameters. The same pattern of changes has been reported previously for quartz dusts (Tarnok et al.: Anal Cell Pathol 15:61-72, 1997). CONCLUSIONS: We conclude that cell physiological measurements by flow cytometry could extend the palette of tools to evaluate possible toxic effects of environmental dust samples.

    ~2 Citings

**Web of Science:**



Results: 3
*(from All Databases)*

**You searched for:** TOPIC: (asbestos chrysotile toxicity heavy metals) ...More

Publication Years
☐ 2016 (1)
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☐ 1967 (1)
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Research Domains
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☐ SOCIAL SCIENCES (2)

Databases
☐ BIOSIS Citation Index (3)
☐ Web of Science Core Collection (3)

1. Trace elements in hazardous mineral fibres
   By: Bloise, Andrea; Barca, Donatella; Gualtieri, Alessandro Francesco; et al.
   ENVIRONMENTAL POLLUTION Volume: 216 Pages: 314-323 Published: SEP 2016
   Times Cited: 45 *(from All Databases)*

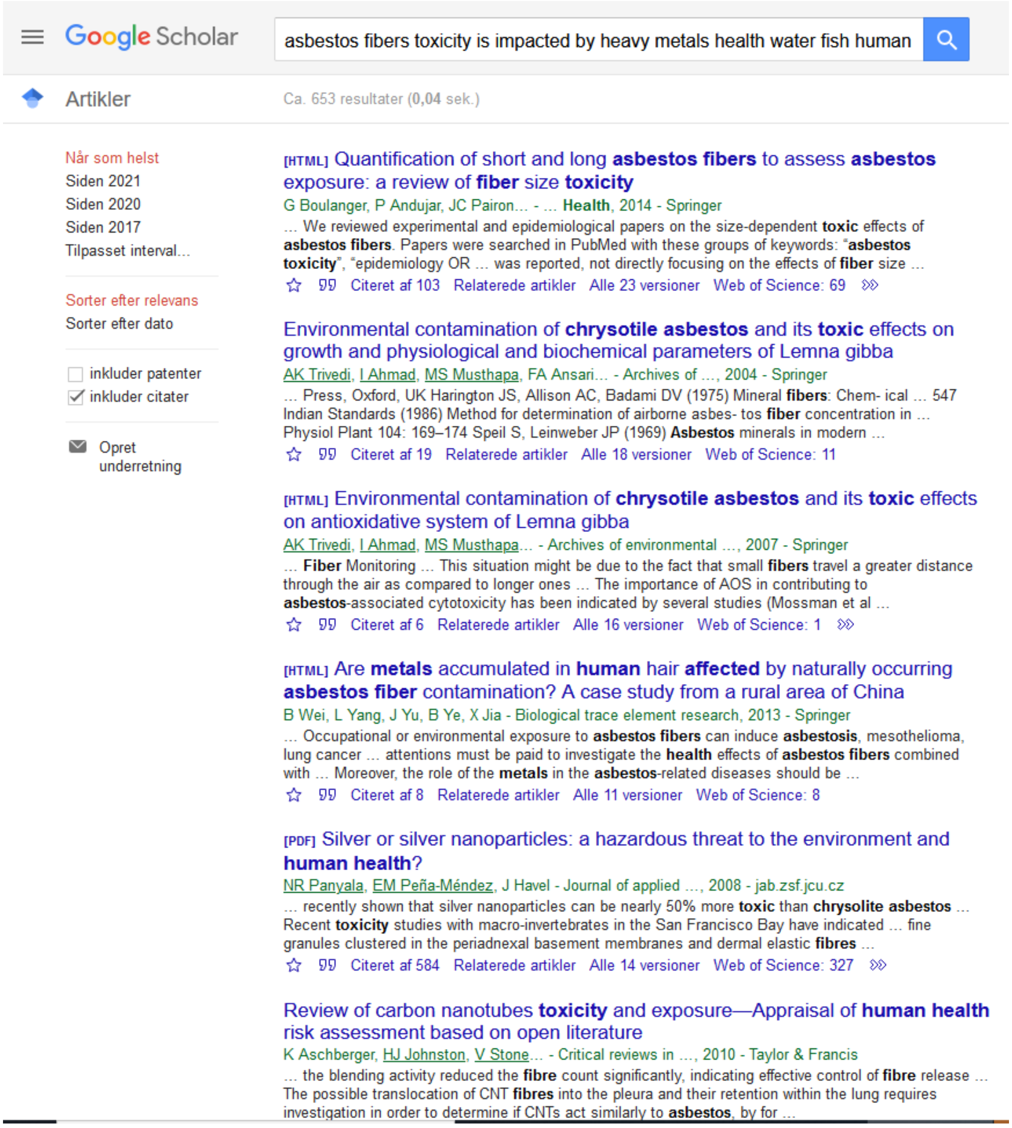
2. ENVIRONMENTAL PLEURAL PLAQUES IN AN ASBESTOS-EXPOSED POPULATION OF NORTHEAST CORSICA
   By: REY, F; BOUTIN, C; STEINBAUER, J; et al.
   EUROPEAN RESPIRATORY JOURNAL Volume: 6 Issue: 7 Pages: 978-982 Published: JUL 1993
   Times Cited: 36 *(from All Databases)*

3. EXPERIMENTAL ASBESTOSIS - DEVELOPMENT OF LUNG CANCER IN RATS WITH PULMONARY DEPOSITS OF CHRYSOTILE ASBESTOS DUST
   By: GROSS, P; DETREVIL.RT; TOLKER, EB; et al.
   ARCHIVES OF ENVIRONMENTAL HEALTH Volume: 15 Issue: 3 Pages: 343 -& Published: 1967
   Times Cited: 74 *(from All Databases)*

*3 records matched your query of the 135.552.145 in the data limits you selected.*

**Google Scholar:**

Below is just the first six of 653 hits identified by Google Scholar. The first 30 hits sorted by relevance were more relevant than the hundreds others.



asbestos fibers toxicity is impacted by heavy metals health water fish human

Ca. 653 resultater (**0,04** sek.)

[HTML] Quantification of short and long **asbestos fibers** to assess **asbestos** exposure: a review of **fiber** size **toxicity**

G Boulanger, P Andujar, JC Pairon... - ... **Health**, 2014 - Springer

... We reviewed experimental and epidemiological papers on the size-dependent **toxic** effects of **asbestos fibers**. Papers were searched in PubMed with these groups of keywords: "**asbestos toxicity**", "epidemiology OR ... was reported, not directly focusing on the effects of **fiber** size ...

☆ 99 Citeret af 103 Relaterede artikler Alle 23 versioner Web of Science: 69 »

Environmental contamination of **chrysotile asbestos** and its **toxic** effects on growth and physiological and biochemical parameters of Lemna gibba

AK Trivedi, I Ahmad, MS Musthapa, FA Ansari... - Archives of ..., 2004 - Springer

... Press, Oxford, UK Harington JS, Allison AC, Badami DV (1975) Mineral **fibers**: Chem- ical ... 547 Indian Standards (1986) Method for determination of airborne asbes- tos **fiber** concentration in ... Physiol Plant 104: 169–174 Speil S, Leinweber JP (1969) **Asbestos** minerals in modern ...

☆ 99 Citeret af 19 Relaterede artikler Alle 18 versioner Web of Science: 11

[HTML] Environmental contamination of **chrysotile asbestos** and its **toxic** effects on antioxidative system of Lemna gibba

AK Trivedi, I Ahmad, MS Musthapa... - Archives of environmental ..., 2007 - Springer

... **Fiber** Monitoring ... This situation might be due to the fact that small **fibers** travel a greater distance through the air as compared to longer ones ... The importance of AOS in contributing to **asbestos**-associated cytotoxicity has been indicated by several studies (Mossman et al ...

☆ 99 Citeret af 6 Relaterede artikler Alle 16 versioner Web of Science: 1 »

[HTML] Are **metals** accumulated in **human** hair **affected** by naturally occurring **asbestos fiber** contamination? A case study from a rural area of China

B Wei, L Yang, J Yu, B Ye, X Jia - Biological trace element research, 2013 - Springer

... Occupational or environmental exposure to **asbestos fibers** can induce **asbestosis**, mesothelioma, lung cancer ... attentions must be paid to investigate the **health** effects of **asbestos fibers** combined with ... Moreover, the role of the **metals** in the **asbestos**-related diseases should be ...

☆ 99 Citeret af 8 Relaterede artikler Alle 11 versioner Web of Science: 8

[PDF] Silver or silver nanoparticles: a hazardous threat to the environment and **human health**?

NR Panyala, EM Peña-Méndez, J Havel - Journal of applied ..., 2008 - jab.zsf.jcu.cz

... recently shown that silver nanoparticles can be nearly 50% more **toxic** than **chrysolite asbestos** ... Recent **toxicity** studies with macro-invertebrates in the San Francisco Bay have indicated ... fine granules clustered in the periadnexal basement membranes and dermal elastic **fibres** ...

☆ 99 Citeret af 584 Relaterede artikler Alle 14 versioner Web of Science: 327 »

Review of carbon nanotubes **toxicity** and exposure—Appraisal of **human health** risk assessment based on open literature

K Aschberger, HJ Johnston, V Stone... - Critical reviews in ..., 2010 - Taylor & Francis

... the blending activity reduced the **fibre** count significantly, indicating effective control of **fibre** release ... The possible translocation of CNT **fibres** into the pleura and their retention within the lung requires investigation in order to determine if CNTs act similarly to **asbestos**, by for ...

# Appendix 2. Characterization

## Appendix 2.1 Results of physicochemical characterization

**TABLE 23.** Results on the presence of asbestos in material samples (three replicates for each sample). Color coding:  green = “clean” waste; orange = “Contaminated” waste, red = “Hazardous” waste.

| | Material | Repl.#1 | Repl.#2 | Repl.#3 | Classification |
|---|---|---|---|---|---|
| “Fresh” material | Linoleum | not-detected | detected | detected | Detected – Non-dusty material |
| | Tiles | detected | detected | detected | Detected – Dusty material |
| | Roofing-felt_1 | not-detected | not-detected | not-detected | Not detected |
| | Roofing-felt_2 | not-detected | not-detected | not-detected | Not detected |
| “Treated” material | Linoleum | not-detected | not-detected | not-detected | Not detected |
| | Roofing-felt_1 | not-detected | not-detected | not-detected | Not detected |
| | Roofing-felt_2 | not-detected | not-detected | not-detected | Not detected |

**TABLE 24.** Elemental composition of the “fresh” samples (as collected), in comparison with the limit values for “clean” (green), “contaminated” (yellow) and “hazardous” (red) waste. Note: μ = mean; CV = coefficient of variation (n=5).

| ‘Fresh’ | Linoleum | | Tiles | | Roofing-felt_1 | | Roofing-felt_2 | | Waste classification limits | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | μ [mg/kg] | CV [%] | μ [mg/kg] | CV [%] | μ [mg/kg] | CV [%] | μ [mg/kg] | CV [%] | Uncontaminated[1] | Contaminated[2] | Hazardous[3] |
| As | 0.331 | 4% | 6.2 | 7.0% | 0.707 | 40% | 0.349 | 42% | <20 | 20-1000 | >1000 |
| Cd | 0.251 | 25% | 12.5 | 24% | 8.32 | 51% | <0.05 | | <0.5 | 0.5-1000 | >1000 |
| Cr-tot | 3.77 | 7% | 28.1 | 6.2% | 397 | 43% | 2.38 | 42% | <500 | 500-1000 | >1000 |
| Cu | 0.958 | 33% | 11.9 | 7.5% | 22.3 | 25% | 4.06 | 2% | <500 | 500-2500 | >2500 |
| Hg | <0.025 | | <0.025 | | 2.31 | 110% | 0.276 | 14% | <1 | 1-2500 | >2500 |
| Ni | 1.03 | 22% | 6.15 | 7.9% | 7.17 | 39% | 1.88 | 75% | <30 | 30-1000 | >1000 |
| Pb | 6220 | 7% | 21700 | 24% | 1180 | 48% | 8.86 | 74% | <40 | 40-2500 | >2500 |
| Zn | 132 | 5% | 1170 | 25% | 16500 | 51% | 174 | 191% | <500 | 500-2500 | >2500 |
| Al | 2950 | 3% | 48200 | 8.4% | 19000 | 29% | 329 | 5% | | | |
| Ba | 51.6 | 3% | 149 | 6.3% | 5300 | 38% | 67.5 | 173% | | | |
| Ca | 53500 | 9% | 27400 | 4.6% | 71300 | 40% | 197000 | 6% | | | |
| Co | 0.145 | 17% | 1.48 | 6.1% | 15 | 50% | 0.315 | 66% | | | |
| Fe | 782 | 5% | 4810 | 10% | 11100 | 44% | 168 | 16% | | | |
| K | 3350 | 3% | 5870 | 6.6% | 3090 | 24% | 356 | 6% | | | |
| Mg | 340 | 13% | 828 | 8.1% | 7300 | 17% | 1300 | 12% | | | |
| Mn | 29.7 | 30% | 46.5 | 4.0% | 9850 | 51% | 12.7 | 14% | | | |
| Mo | 0.212 | 9% | 0.668 | 15% | 0.601 | 23% | 0.146 | 9% | | | |
| Na | <100 | | 2250 | 12% | 1670 | 31% | 625 | 30% | | | |
| P | 333 | 6% | 192 | 7.7% | 387 | 35% | <50 | | | | |
| S | 272 | 12% | <250 | | 4950 | 26% | 169000 | 2% | | | |
| Sb | 2.46 | 3% | 0.901 | 14% | 3.36 | 105% | 0.125 | 8% | | | |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Se | < 1 | | < 1 | | < 1 | | < 1 | | |
| Si | 144000 | 3% | 213000 | 18% | 59500 | 41% | 2920 | 14% | |
| V | 2.95 | 10% | 27.7 | 7.3% | 124 | 51% | 5.6 | 5% | |
| In Danish: [1] = ’Uforurenet’; [2] = ‘Forurenet’; [3] = ’Farligt’ | | | | | | | | | |

**TABLE 25.** Elemental composition of the thermally treated samples, in comparison with the limit values for “clean” (green), “contaminated” (yellow) and “hazardous” (red) waste. Note: μ = mean; CV = coefficient of variation (n=5).

| **‘Thermally treated’** | **Linoleum** | | **Roofing-felt_1** | | **Roofing-felt_2** | | **Waste classification limits** | | |
|---|---|---|---|---|---|---|---|---|---|
| | μ [mg/kg] | CV [%] | μ [mg/kg] | CV [%] | μ [mg/kg] | CV [%] | Unconta-minated[1] [mg/kg] | Contamina-ted[2] [mg/kg] | Hazar-dous[3] [mg/kg] |
| As | 0.403 | 9% | 1.73 | 15% | 0.351 | 12% | <20 | 20-1000 | >1000 |
| Cd | 0.0951 | 15% | 0.448 | 28% | <0.05 | | <0.5 | 0.5-1000 | >1000 |
| Cr-tot | 6.02 | 5% | 847 | 5% | 2.57 | 12% | <500 | 500-1000 | >1000 |
| Cu | 18 | 4% | 85.5 | 9% | 21.9 | 15% | <500 | 500-2500 | >2500 |
| Hg | <0.025 | | <0.025 | | <0.025 | | <1 | 1-1000 | >1000 |
| Ni | 2.09 | 17% | 16.8 | 27% | 1.86 | 6% | <30 | 30-1000 | >1000 |
| Pb | 4.17 | 41% | 5.39 | 19% | 1.8 | 10% | <40 | 40-2500 | >2500 |
| Zn | <0.5 | | 2580 | 28% | 28.6 | 4% | <500 | 500-2500 | >2500 |
| Al | 4980 | 5% | 43800 | 2% | 473 | 7% | | | |
| Ba | 77.8 | 4% | 9510 | 29% | 18.8 | 9% | | | |
| Ca | 101000 | 5% | 156000 | 5% | 253000 | 7% | | | |
| Co | 0.167 | 47% | 24.4 | 35% | 0.24 | 21% | | | |
| Fe | 156 | 8% | 25700 | 5% | 226 | 8% | | | |
| K | 4910 | 8% | 3580 | 11% | 309 | 7% | | | |
| Mg | 639 | 6% | 15800 | 6% | 1840 | 6% | | | |
| Mn | 28.8 | 4% | 22600 | 9% | 14.2 | 9% | | | |
| Mo | 0.3 | 9% | 1.03 | 17% | 0.194 | 35% | | | |
| Na | 522 | 5% | 2640 | 15% | <100 | | | | |
| P | 557 | 10% | 845 | 3% | < 50 | | | | |
| S | <250 | | 6700 | 21% | 223000 | 7% | | | |
| Sb | 2.36 | 18% | 4.31 | 21% | 0.183 | 9% | | | |
| Se | <1 | | <1 | | <1 | | | | |
| Si | 227000 | 12% | 127000 | 5% | 4000 | 6% | | | |
| V | 4.24 | 5% | 288 | 7% | 7.43 | 4% | | | |

**TABLE 26.** Content of PCBs in the fresh waste samples. ∑PCBs are calculated considering the <0.02 mg/kg values as equal to 0.01 mg/kg (i.e. half of the analytical limit of quantification). Uncertainty is reported as standard deviation (n=5).

| **‘Fresh’** | **Linoleum** | **Tiles** | **Roofing-felt_1** | **Roofing-felt_2** | **Waste classification limits** | | |
|---|---|---|---|---|---|---|---|
| | [mg/kg] | [mg/kg] | [mg/kg] | [mg/kg] | Unconta-minated[1] [mg/kg] | Contami-nated[2] [mg/kg] | Hazar-dous[3] [mg/kg] |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| PCB 28 | <0.02 | <0.02 | 0.06 ± 0.02 | <0.02 | | | |
| PCB 52 | <0.02 | <0.02 | 0.07 ± 0.02 | <0.02 | | | |
| PCB 101 | 0.03 ± 0.01 | <0.02 | 0.38 ± 0.24 | 0.05 ± 0.02 | | | |
| PCB 118 | <0.02 | <0.02 | 0.11 ± 0.09 | <0.02 | | | |
| PCB 138 | <0.02 | <0.02 | 1.78 ± 0.31 | 0.19 ± 0.09 | | | |
| PCB 153 | 0.04 ± 0.02 | <0.02 | 2.89 ± 0.55 | 0.24 ± 0.11 | | | |
| PCB 180 | <0.02 | <0.02 | 2.07 ± 0.45 | 0.24 ± 0.15 | | | |
| ∑ PCBs | 0.11 ± 0.02 | 0.07 ± 0.0 | 7.36 ± 1.31 | 0.74 ± 0.37 | <0.1 | 0.1 - 50 | >50 |

**TABLE 27.** Content of PCBs in the thermally treated waste samples. ∑PCBs are calculated considering the <0.02 mg/kg values as equal to 0.01 mg/kg (i.e. half of the analytical limit of quantification). Uncertainty is reported as standard deviation (n=5).

| 'Thermally treated' | Linoleum | Roofing-felt_1 | Roofing-felt_2 | Waste classification limits | | |
|---|---|---|---|---|---|---|
| | [mg/kg] | [mg/kg] | [mg/kg] | Uncontaminated[1] [mg/kg] | Contaminated[2] [mg/kg] | Hazardous[3] [mg/kg] |
| PCB 28 | <0.02 | <0.02 | <0.02 | | | |
| PCB 52 | <0.02 | <0.02 | <0.02 | | | |
| PCB 101 | <0.02 | <0.02 | <0.02 | | | |
| PCB 118 | <0.02 | <0.02 | <0.02 | | | |
| PCB 138 | <0.02 | <0.02 | <0.02 | | | |
| PCB 153 | <0.02 | <0.02 | 0.07 ± 0.09 | | | |
| PCB 180 | <0.02 | <0.02 | 0.12 ± 0.15 | | | |
| ∑ PCBs | 0.07 ± 0.0 | 0.07 ± 0.01 | 0.25 ± 0.24 | <0.1 | 0.1 - 50 | >50 |

**TABLE 28.** Content of PAHs in the fresh waste samples. ∑PAHs are calculated considering the <0.02 mg/kg values as equal to 0.01 mg/kg (i.e. half of the analytical limit of quantification). Uncertainty is reported as standard deviation (n=5).

| 'Fresh' | Linoleum | Tiles | Roofing-felt_1 | Roofing-felt_2 | Waste classification limits | | |
|---|---|---|---|---|---|---|---|
| | [mg/kg] | [mg/kg] | [mg/kg] | [mg/kg] | Uncontaminated[1] [mg/kg] | Contaminated[2] [mg/kg] | Hazardous[3] [mg/kg] |
| Naphthalene | 0.4±0.03 | <0.02 | 1.2±2.21 | 0.02±0.01 | | | |
| Acenaphthene | <0.02 | <0.02 | 1.1±2.14 | <0.02 | | | |
| Acenaphthylene | 0.3±0.1 | <0.02 | 0.33±0.29 | <0.02 | | | |
| Fluorene | 0.17±0.02 | 0.02±0.01 | 1.17±1.99 | <0.02 | | | |
| Phenantrene | 2±0.14 | <0.02 | 3.04±1.76 | 0.25±0.09 | | | |
| Antracene | <0.02 | <0.02 | 0.53±1.04 | <0.02 | | | |
| Fluoranthene | 0.47±0.07 | <0.02 | 0.82±0.34 | 0.13±0.04 | | | |
| Pyrene | 0.37±0.05 | <0.02 | 1.27±1.45 | 0.06±0.02 | | | |
| Benz(a)antrecene | <0.02 | <0.02 | 0.23±0.42 | <0.02 | | | |
| Chrysene | <0.02 | <0.02 | 0.29±0.43 | 0.02±0.01 | | | |
| Benz(b,k)fluoranthene | 0.06±0.02 | <0.02 | 0.15±0.27 | <0.02 | | | |
| Benz(a)pyrene | <0.02 | <0.02 | 0.21±0.44 | <0.02 | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Benz(ghi)perylene | <0.02 | <0.02 | <0.02 | <0.02 | | | |
| Dibenz(ah)anthracene | <0.02 | <0.02 | <0.02 | <0.02 | | | |
| Indeno(1,2,3-cd)pyrene | <0.02 | <0.02 | <0.02 | <0.02 | | | |
| ∑ PAHs | 3.84±0.29 | 0.17±0.02 | 10.37±12.47 | 0.58±0.17 | <4 | 4 - 1000 | >1000 |

**TABLE 29.** Content of PAHs in the thermally treated waste samples. ∑PAHs are calculated considering the <0.02 mg/kg values as equal to 0.01 mg/kg (i.e. half of the analytical limit of quantification). Uncertainty is reported as standard deviation (n=5).

| 'Thermally treated' | Linoleum | Roofing-felt_1 | Roofing-felt_2 | Waste classification limits | | |
|---|---|---|---|---|---|---|
| | [mg/kg] | [mg/kg] | [mg/kg] | Uncontaminated[1] [mg/kg] | Contaminated[2] [mg/kg] | Hazardous[3] [mg/kg] |
| Naphthalene | 2.05±2.62 | 0.15±0.13 | 0.05±0.06 | | | |
| Acenaphthene | <0.02 | <0.02 | <0.02 | | | |
| Acenaphthylene | <0.02 | 0.05±0.06 | <0.02 | | | |
| Fluorene | <0.02 | 0.05±0.03 | <0.02 | | | |
| Phenantrene | 0.02±0.01 | 0.29±0.33 | 0.07±0.04 | | | |
| Antracene | <0.02 | <0.02 | <0.02 | | | |
| Fluoranthene | <0.02 | 0.05±0.07 | <0.02 | | | |
| Pyrene | <0.02 | 0.04±0.05 | <0.02 | | | |
| Benz(a)antrecene | <0.02 | <0.02 | <0.02 | | | |
| Chrysene | <0.02 | <0.02 | <0.02 | | | |
| Benz(b,k)fluoranthene | <0.02 | <0.02 | <0.02 | | | |
| Benz(a)pyrene | <0.02 | <0.02 | <0.02 | | | |
| Benz(ghi)perylene | <0.02 | <0.02 | <0.02 | | | |
| Dibenz(ah)anthracene | <0.02 | <0.02 | <0.02 | | | |
| Indeno(1,2,3-cd)pyrene | <0.02 | <0.02 | <0.02 | | | |
| ∑ PAHs | 2.21±2.62 | 0.73±0.67 | 0.26±0.07 | <4 | 4-1000 | >1000 |

**TABLE 30.** Content of hydrocarbons in the 'fresh' and thermally 'treated' samples (n=5). Averages are calculated considering the <80 mg/kg values as equal to 40 mg/kg (i.e. half of the analytical limit of quantification).

| | Substance | C10-C20 [$\text{mg/kg}_{\text{DM}}$] | C20-C40 [$\text{mg/kg}_{\text{DM}}$] | C10-C40 [$\text{mg/kg}_{\text{DM}}$] |
|---|---|---|---|---|
| | LOD | 80 | 80 | 80 |
| 'Fresh' material | Linoleum | 197 ± 51 | 774 ± 236 | 971 ± 279 |
| | Tiles | 103 ± 61 | 227 ± 149 | 341 ± 195 |
| | Roofing-felt_1 | 105 ± 46 | 441 ± 182 | 552 ± 216 |
| | Roofing-felt_2 | 193 ± 113 | 527 ± 437 | 719 ± 551 |
| 'Treated' material | Linoleum | 133 ± 83 | 300 ± 196 | 441 ± 257 |
| | Roofing-felt_1 | 94 ± 55 | 152 ± 60 | 259 ± 96 |
| | Roofing-felt_2 | 171 ± 88 | 356 ± 242 | 527 ± 329 |
| | Uncontaminated | <55[a] | <100 | <100 |
| | Contaminated | 100-1000 | 100-1000 | 100-1000 |
| | Hazardous | >1000 | >1000 | >1000 |

LOD=limit of detection; [a] conservatively assumed as for C15-C20 (see TABLE 9 for details).

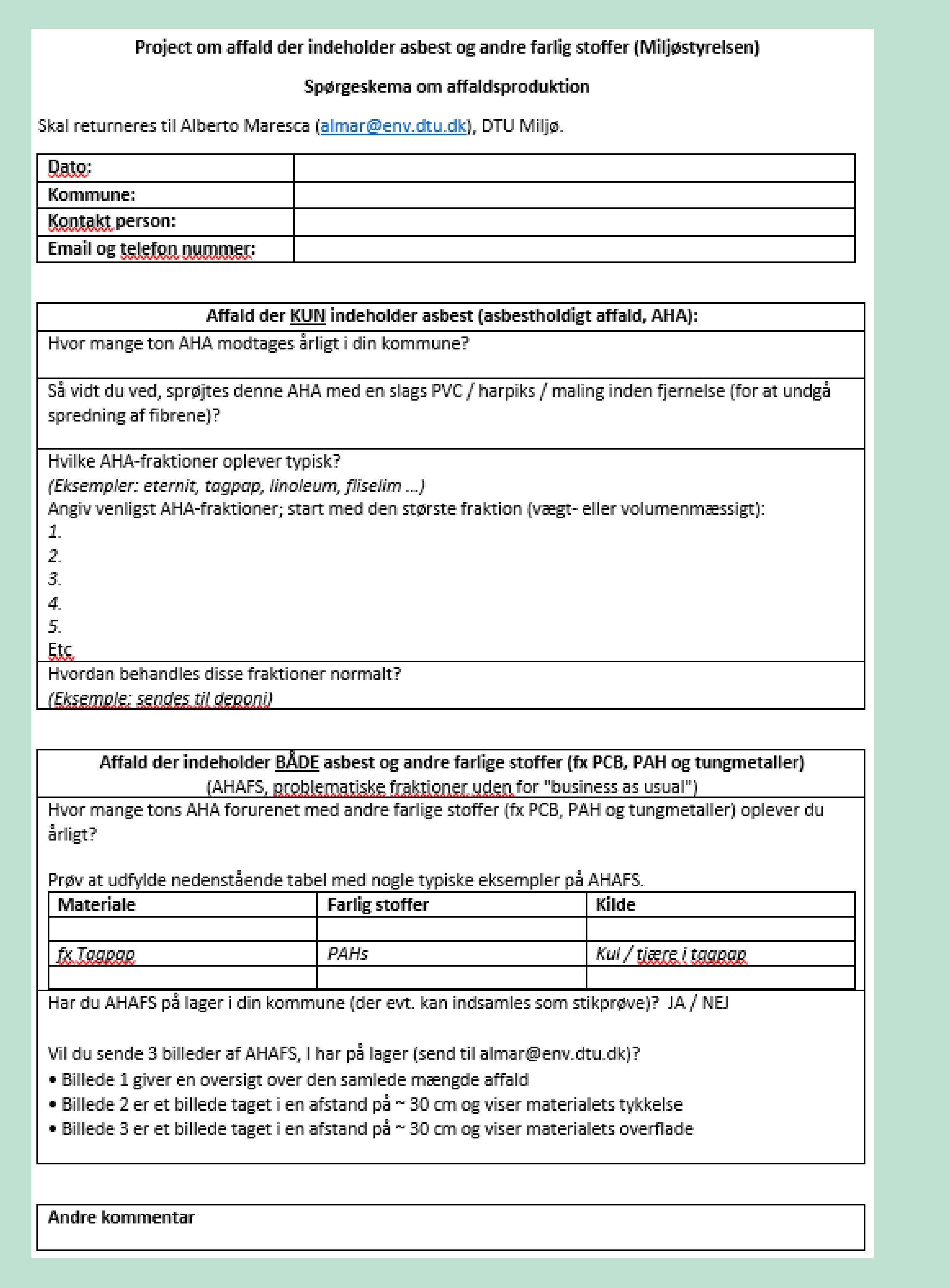
## Appendix 2.2 Results of the release tests

**TABLE 31.** Results of batch leaching tests, carried out at the Liquid-to-Solid ratio of 2 L/kg (n=5). The analytical results are compared with the acceptance criteria defined for landfills of "mineral" (class MA1) and "hazardous" waste (range of classes FA0-FA3), as defined in BEK 1253:2019 (2019). *=limit values for DOC.

| | | Linoleum | | Tiles | | Landfill acceptance criteria | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | μ | CV | μ | CV | Mineral | Hazardous | | | |
| | | | | | | MA1 | FA0 | FA1 | FA2 | FA3 |
| **Trace elements and metals** | | | | | | | | | | |
| Al | mg/kg | < 0.1 | | 0.1466 | 23% | | | | | |
| Ca | mg/kg | 23.0000 | 6% | 79.2000 | 6% | | | | | |
| K | mg/kg | 7.2200 | 7% | 19.6400 | 3% | | | | | |
| Mg | mg/kg | 1.2260 | 12% | 2.3600 | 2% | | | | | |
| Na | mg/kg | 9.0800 | 8% | 24.0000 | 5% | | | | | |
| P | mg/kg | 5.8800 | 13% | < 2 | | | | | | |
| S | mg/kg | 5.3200 | 7% | 69.8000 | 9% | | | | | |
| Si | mg/kg | 1.2800 | 1% | 46.8000 | 9% | | | | | |
| As | mg/kg | 0.0004 | 9% | 0.0063 | 10% | 0.4 | 0.08 | 6.0 | 6.0 | 6.0 |
| Ba | mg/kg | 0.0042 | 7% | 0.0148 | 2% | 30 | 10 | 100 | 100 | 25 |
| Cd | mg/kg | < 0.0002 | | < 0.0002 | | 0.6 | 0.09 | 3.0 | 3.0 | 3.0 |
| Cr | mg/kg | 0.0014 | 38% | 0.0020 | 21% | 4 | 0.39 | 25 | 12 | 3.5 |
| Co | mg/kg | 0.0013 | 3% | 0.0011 | 3% | | | | | |
| Cu | mg/kg | 0.0190 | 3% | 0.0076 | 2% | 25 | 6.8 | 0.50 | 0.50 | 25 |
| Fe | mg/kg | 0.0314 | 9% | 0.0326 | 9% | | | | | |
| Hg | mg/kg | < 0.0001 | | < 0.0001 | | 0.05 | 0.012 | 0.50 | 0.50 | 0.50 |
| Mo | mg/kg | 0.0003 | 9% | 0.0372 | 3% | 5 | 0.52 | 20 | 20 | 20 |
| Mn | mg/kg | 0.0191 | 6% | 0.0017 | 3% | | | | | |
| Ni | mg/kg | 0.0294 | 2% | 0.0070 | 6% | 5 | 0.25 | 20 | 20 | 20 |
| Pb | mg/kg | 0.2200 | 7% | 0.0103 | 10% | 5 | 0.32 | 25 | 25 | 25 |
| Sb | mg/kg | 0.0006 | 3% | 0.0008 | 3% | 0.2 | 0.025 | 2.0 | 2.0 | 1.0 |
| Se | mg/kg | < 0.004 | | < 0.004 | | 0.3 | 0.21 | 4.0 | 4.0 | 4.0 |
| V | mg/kg | 0.0057 | 11% | 1.2400 | 4% | | | | | |
| Zn | mg/kg | 0.4660 | 6% | < 0.002 | | 25 | 2.4 | 90 | 90 | 90 |
| **Salts, NVOC and pH** | | | | | | | | | | |
| Floride | mg/kg | <1 | | <1 | | 60 | 15 | 200 | 200 | 200 |
| Chloride | mg/kg | 14.9 | 4% | 16.8 | 4% | 10000 | 2300 | 17000 | 17000 | 17000 |
| Sulfate | mg/kg | 8.4 | 6% | 205.2 | 10% | 10000 | 3100 | 25000 | 25000 | 25000 |
| NVOC | mg/kg | 125.5 | 4% | 73.1 | 4% | 380* | 100* | 480* | 480* | 480* |
| pH | - | 7.0 | 1% | 9.4 | 0% | >6 | | | | |
| electr. Cond | mS/m | 10.4 | 3% | 31.6 | 5% | | | | | |

# Appendix 3. Questionnaires

## Appendix 3.1 Questionnaire to municipalities



**Project om affald der indeholder asbest og andre farlig stoffer (Miljøstyrelsen)**

**Spørgeskema om affaldsproduktion**

Skal returneres til Alberto Maresca (almar@env.dtu.dk), DTU Miljø.

| | |
|---|---|
| **Dato:** | |
| **Kommune:** | |
| **Kontakt person:** | |
| **Email og telefon nummer:** | |

**Affald der KUN indeholder asbest (asbestholdigt affald, AHA):**

Hvor mange ton AHA modtages årligt i din kommune?

Så vidt du ved, sprøjtes denne AHA med en slags PVC / harpiks / maling inden fjernelse (for at undgå spredning af fibrene)?

Hvilke AHA-fraktioner oplever typisk?
*(Eksempler: eternit, tagpap, linoleum, fliselim ...)*
Angiv venligst AHA-fraktioner; start med den største fraktion (vægt- eller volumenmæssigt):
*1.*
*2.*
*3.*
*4.*
*5.*
Etc

Hvordan behandles disse fraktioner normalt?
*(Eksemple: sendes til deponi)*

**Affald der indeholder BÅDE asbest og andre farlige stoffer (fx PCB, PAH og tungmetaller)**
(AHAFS, problematiske fraktioner uden for "business as usual")

Hvor mange tons AHA forurenet med andre farlige stoffer (fx PCB, PAH og tungmetaller) oplever du årligt?

Prøv at udfylde nedenstående tabel med nogle typiske eksempler på AHAFS.

| Materiale | Farlig stoffer | Kilde |
|---|---|---|
| | | |
| *fx Tagpap* | *PAHs* | *Kul / tjære i tagpap* |
| | | |

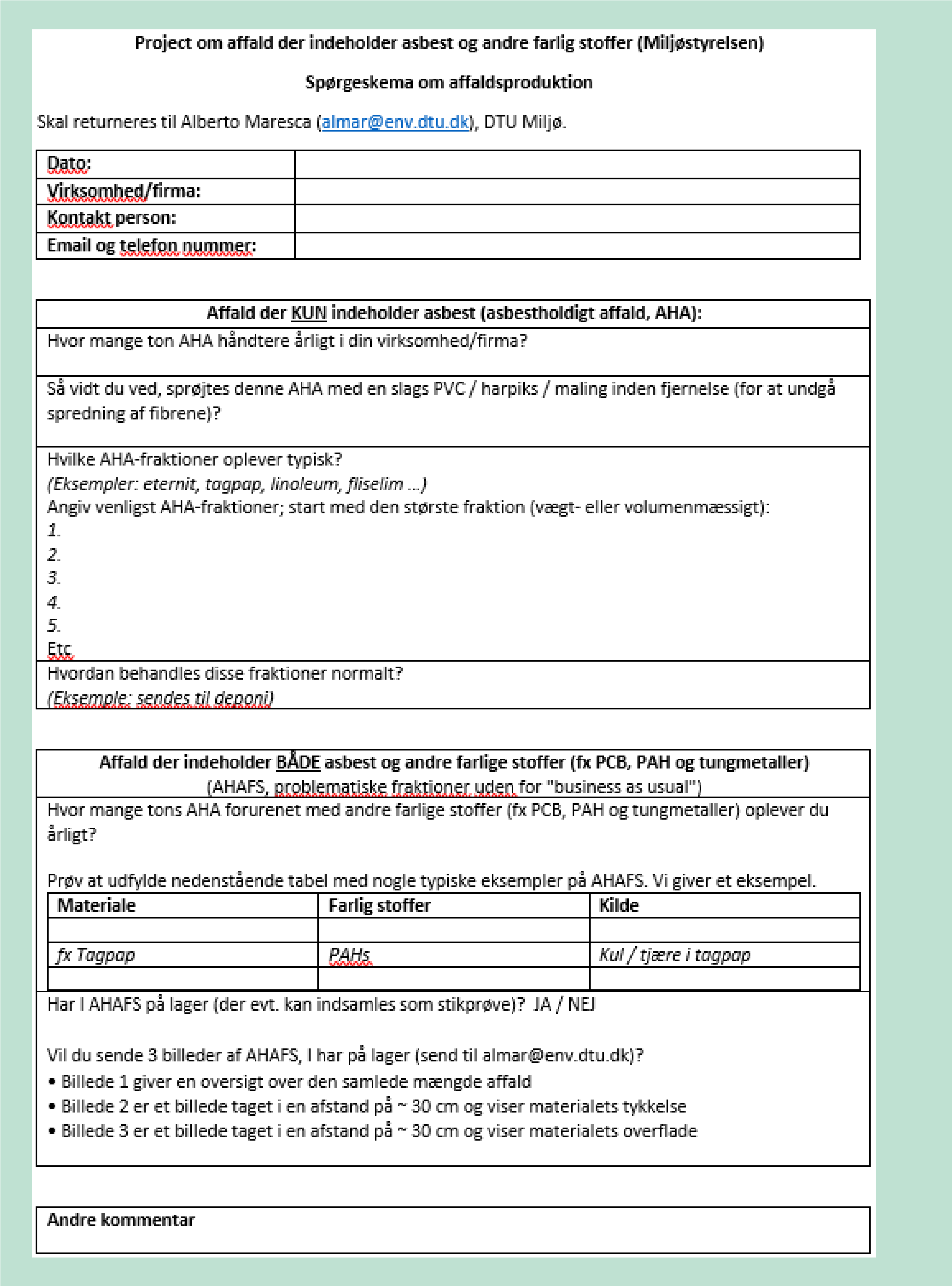
Har du AHAFS på lager i din kommune (der evt. kan indsamles som stikprøve)? JA / NEJ

Vil du sende 3 billeder af AHAFS, I har på lager (send til almar@env.dtu.dk)?
- Billede 1 giver en oversigt over den samlede mængde affald
- Billede 2 er et billede taget i en afstand på ~ 30 cm og viser materialets tykkelse
- Billede 3 er et billede taget i en afstand på ~ 30 cm og viser materialets overflade

**Andre kommentar**

**FIGURE 9.** Questionnaire sent to 96 municipalities in Denmark about waste containing asbestos and other environmentally problematic substances.

## Appendix 3.2 Questionnaire to municipalities



**Project om affald der indeholder asbest og andre farlig stoffer (Miljøstyrelsen)**

**Spørgeskema om affaldsproduktion**

Skal returneres til Alberto Maresca (almar@env.dtu.dk), DTU Miljø.

| | |
|---|---|
| **Dato:** | |
| **Virksomhed/firma:** | |
| **Kontakt person:** | |
| **Email og telefon nummer:** | |

**Affald der KUN indeholder asbest (asbestholdigt affald, AHA):**

Hvor mange ton AHA håndtere årligt i din virksomhed/firma?

Så vidt du ved, sprøjtes denne AHA med en slags PVC / harpiks / maling inden fjernelse (for at undgå spredning af fibrene)?

Hvilke AHA-fraktioner oplever typisk?
*(Eksempler: eternit, tagpap, linoleum, fliselim ...)*
Angiv venligst AHA-fraktioner; start med den største fraktion (vægt- eller volumenmæssigt):
*1.*
*2.*
*3.*
*4.*
*5.*
Etc

Hvordan behandles disse fraktioner normalt?
*(Eksemple: sendes til deponi)*

**Affald der indeholder BÅDE asbest og andre farlige stoffer (fx PCB, PAH og tungmetaller)**
(AHAFS, problematiske fraktioner uden for "business as usual")

Hvor mange tons AHA forurenet med andre farlige stoffer (fx PCB, PAH og tungmetaller) oplever du årligt?

Prøv at udfylde nedenstående tabel med nogle typiske eksempler på AHAFS. Vi giver et eksempel.

| **Materiale** | **Farlig stoffer** | **Kilde** |
|---|---|---|
| | | |
| *fx Tagpap* | *PAHs* | *Kul / tjære i tagpap* |
| | | |

Har I AHAFS på lager (der evt. kan indsamles som stikprøve)? JA / NEJ

Vil du sende 3 billeder af AHAFS, I har på lager (send til almar@env.dtu.dk)?

- Billede 1 giver en oversigt over den samlede mængde affald
- Billede 2 er et billede taget i en afstand på ~ 30 cm og viser materialets tykkelse
- Billede 3 er et billede taget i en afstand på ~ 30 cm og viser materialets overflade

**Andre kommentar**

**FIGURE 10.** Questionnaire sent to 15 demolition companies and 4 waste handling companies in Denmark about waste containing asbestos and other environmentally problematic substances.

**Waste containing asbestos and other environmentally problematic substances**
The Danish Environmental Protection Agency has, in collaboration with the Technical University of Denmark and Aarhus University, completed a project investigating options for managing waste containing both asbestos and other environmentally problematic substances (WCAPS). The combination makes the management of this waste problematic within the current legislation: the presence of asbestos prevents disposal via incineration, while the presence of organic substances and heavy metals restricts significantly the possibilities for landfilling.
The project identified vinyl/linoleum flooring, tiles and roofing felt as the WCAPS materials that have most frequently been collected during demolition and renovation activities. Four samples of these materials were obtained from waste management companies and analyzed for their content of asbestos, PCB, PAHs, heavy metals and hydrocarbons. Samples of tiles and linoleum were tested for compliance with acceptance criteria at hazardous waste landfills. Samples of linoleum and roofing felt were treated at 1100 °C, to assess the efficacy of thermal treatment in destroying asbestos and organic pollutants. Risk screening of asbestos leaching from landfills to the aquatic environment indicates there is low risk towards humans (via drinking water) and organisms in the receiving surface waters. It was identified that there is no scientific evidence regarding toxicity mixture effects or risks of asbestos and other contaminants. The results provided a basis for recommendations on how these materials can be treated, and what are the key parameters to be checked in the decision-process.

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