A brief introduction to chemical hazards in the life cycle of building products with floor coverings as a case study

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Introduction

Buildings play an essential role in the social and economic advancement of human societies. However, modern buildings contain numerous synthetic, chemically processed and or treated materials, most of which have never been tested to determine the health hazard status (Liddell et al, 2008; AQS, 2010). Given the inordinate materials demand of the building sector, the production, use and disposal of modern building products has come to play a central role in the creation of human and environmental health hazard.

The types and quantities of building products are constantly on the increase. The exposure to potentially hazardous chemicals is therefore likely to increase in the absence of an intervention aimed at replacing toxic with benign building products. At the beginning of the 20^{th} Century, about 50 materials were used in buildings (Liddell et al, 2008). Now, more than 55 000 building products are available, and over half are man-made.

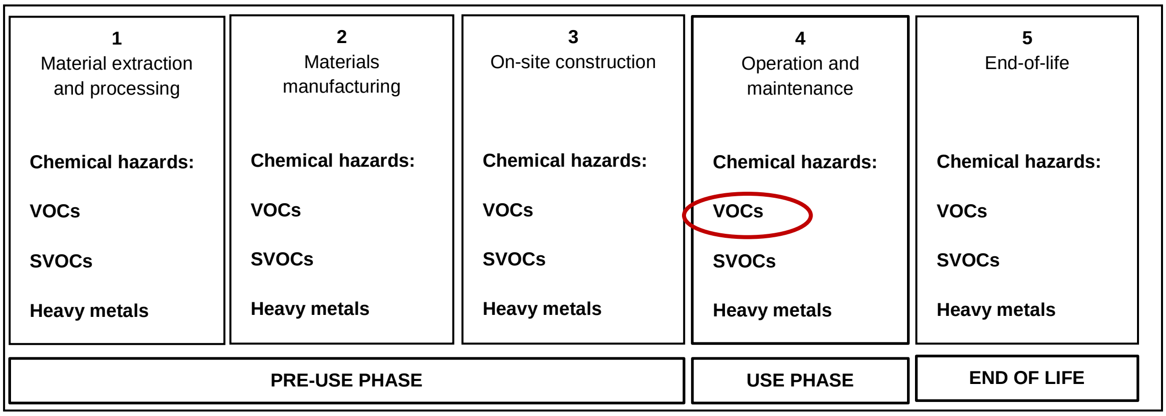

Figure 1: chemical hazard can manifest in any form at any stage of the building product life cycle however, improvement efforts focus mainly on VOC emissions in the Use Phase

The efforts aimed at addressing the environmental impact of buildings have prioritised energy and to some extent, materials. Extensive guidance is now available on how to achieve building whole life cycle energy and materials efficiency. In principle, the key building sector stakeholders have recognised the management of chemical toxicity in buildings as good practice. However, in practice, the focus of the voluntary building rating systems, such as Green Star South Africa, is to limit building occupant exposure to volatile organic compounds (VOCs). This approach however overlooks building occupant exposure to non-VOC toxics. Furthermore, it cannot address the human and environmental health hazards in the other building life cycle stages. The limitation of the current approach to chemical hazard management is depicted in Figure 1. The rationale for replacing the current approach with a new approach includes:

- Environmental regulation is likely to become more stringent – for example, the European Union and Japan have already adopted mandatory, building and construction-specific frameworks which ban, restrict and/or limit chemical hazards in the building product life cycle
- Building activity is likely to continue worldwide into the foreseeable future. Replacing toxic with benign building products will therefore limit exposure
- In order to protect future generations, the current material resource strategies of recycle and reuse would need to return benign – not toxic – materials back into the building life cycle.

In the absence of local mandatory provisions addressing chemical hazards in building products, the duty surely falls on the key building sector stakeholders - material manufacturers, contractors, built environment professionals – to inform themselves about the extent of the problem in order to avoid or minimise the human and ecosystem health risks.

This chapter aims to establish the chemical hazard in building products as a whole life cycle concern for the key actors in the building product supply chain and thereby create an enabling environment for the reduction of the chemical loads on humans and the environment. Section 1 sets out the purpose; and describes the methodology and the scope of the chapter. Section 2 identifies and describes globally accepted health hazard criteria; and the major classes of chemical hazards associated with the building product life cycle. Section 3 uses the health hazard criteria to identify, analyse and categorise chemical hazards in selected building products. Section 4 summarises the findings and also presents an outline of future chapters which will add to and complete the research work presented here. The scope of this chapter is limited to three major South African floor covering materials – ceramic tile, carpet (stretch and tile) and poly vinyl chloride (sheet and tile). The findings for ceramic and PVC products are valid for wall/floor coverings.

Building materials and chemical hazards

What is a chemical hazard?

The use of chemicals to enhance and improve life is a widespread practice worldwide. The chemical industry converts raw materials such as oil, natural gas, metals and minerals into thousands of products many of which are destined for use in buildings. The global production of chemicals has increased from one million tonnes in 1930 to several hundreds of millions of tonnes today – the exact number of chemicals on the market is however unknown as new ones are being introduced each year. However, chemicals are a blessing and a curse (ECHA, 2015a). Many chemicals used to produce every day products may constitute a health hazard to humans and ecosystems at any stage of the product life cycle, from cradle-to-grave.

A chemical constitutes a human or environmental health hazard when there is statistically significant evidence based on at least one scientific study that adverse health effects may occur if humans, wildlife or flora and fauna are exposed to the chemical[1]. For all living species, including humans, the health endpoint of greatest concern is exposure to persistent and bio-accumulation toxicants (PBTs). The human-specific health endpoints of concern range from toxicity – arising from exposure to carcinogenic, mutagenic and reproductive (CMR) chemicals, to sensitization – arising from exposure to chemicals of equivalent level of concern (ELoC). The eco-system specific health endpoints of concern include aquatic eco-toxicity and terrestrial eco-toxicity. These human and environmental health categories are elaborated in the sections which follow.

[1] Author definition extrapolated from American OSHA definition

Health hazard categories

Persistent and bio-accumulative toxicants (PBTs)

Manmade substances that are difficult to breakdown (persist), accumulate in living organisms (bio-accumulate) and are toxic, are generally known as persistent and bio-accumulative toxicants (PBTs) (ECHA, 2015b). PBTs accumulate in plants and animals as they travel up the food chain hence the largest quantities of these substances are usually found in humans. Protection of the environment from PBTs is particularly difficult as these substances do not degrade near the emission sources but may be transported into pristine remote areas. A reference to PBTs in the literature is typically preceded by the risk phrase “very high concern”. PBTs of the very highest concern are known as persistent organic pollutants (POPs). These POPs have been banned internationally under the Stockholm Convention[2] on Persistent Organic Pollutants of 2001. The most well-known of the POPs is perhaps DDT which inspired Rachel Carson’s 1962 *Silent Spring*. Other descriptions of PBTs include very persistent and very bio-accumulative (vPvB), very persistent and toxic (vPT) or very bio-accumulative and toxic (vBT) (Lent et al, 2010). Once PBTs are dispersed in the environment, the risk of exposure is very difficult to reverse.

Box 1: Case study 1 – PBT in thermal insulation: HBCD

The main reason for significant global production of the flame retardant HBCD, sometimes abbreviated as HBCDD, is its use in expanded polystyrene (EPS) and extruded polystyrene (XPS) rigid insulation boards, which are widely used in the building industry. HBCD was added to The Stockholm Convention’s list of POPs in September 2013. The signatories to The Convention are required to phase out production, importation/exportation and use of HBCD as a flame retardant. The target “sunset” date already set by the European Union is August 2015. An exemption was granted, on appeal by manufacturers, for the main use in EPS/XPS building insulation to continue for a period of five years until September 2018 (ChemicalWatch, 2013).

In December 2013, the World Wildlife Fund (WWF) DetoX Campaign conducted a bio-monitoring study to determine the human blood serum content of 101 predominantly PBT chemicals. The blood samples were taken from 47 volunteers from 17 European countries (WWF, 2013). 13 chemicals were found in the blood of every volunteer tested for that chemical – the details of these chemicals are provided in Table 1.

[2] As a signatory to The Stockholm Convention, South Africa in July 2014 published regulations under the National Environmental Management Act (NEMA) of 1998 to phase-out the use of PCBs by the year 2023 (Gilder and Govender, 2014). PCBs fall under the description of POPs. PCBs may be found in building products such as adhesives, oil-based paints and floor coverings

Of the 13 chemicals, 8 can be linked to popular floor coverings as shown in Table 1. All eight are SVOCs. All 8 are listed under the Stockholm Convention. One of the chemicals, HCB, is a manufacturing by-product which could nevertheless be present in the final product, such as PVC flooring, as a contaminant (Lent et al, 2010, Barber et al, 2005).

The remaining 7 perfluorinated compounds are commonly used by manufacturers as the active ingredient in stain and water repellents for carpets, paints, and wall/floor coatings. The "parent" of the perfluorinated chemicals is perfluorooctane sulfuric acid (PFOS) also known as perfluorooctane sulfonate. The derivatives or salts of PFOS include MeFOSE and EtFOSE (Weschler and Nazaroff, 2008). In terms of the Stockholm convention Annex B, PFOS, and all its salts, is currently prohibited from use in building products. Box 2 provides more information on the current status of PFOS.

Box 2: Case study 2 – PBT in floor and wall coatings/ coating additives: PFOS

- In December 2002 PFOS was formally identified as a PBT during the 34th meeting of the OECD Chemical committee (CIRS, 2015)
- In May 2009, PFOS was added to Annex B of the Stockholm Convention list of POPs. Annex B specifically prohibits the further use of PFOS in carpets and in coatings/coating additives (this would include varnishes and paints) (CHMPOPs, 2015).
- In September 2009, the European Parliament placed a restriction on the marketing and use of PFOS and derivatives. PFOS is included on the chemical policy REACH[3] Annex XVII list of restricted chemicals dated September 2012 (SSS EU, 2015).

Table 1: Link between common building products; and PBTs found in blood of WWF study volunteers

Chemical of concern	Number of products	% volunteers	Hazard	Use in building product	Probable building product source
HCB	1	100	PBT/POP	Manufacturing by-product	PVC floor/wall covering
PFOS	7	100	PBT/POP	Stain or water repellent	Carpet, floor /wall coating
DEHP	1	100	CMR	Plasticiser	PVC or SBR floor/wall covering

Carcinogenic, mutagenic and/or reproductive (CMR) toxicants

Chemicals that are carcinogenic, mutagenic or toxic to reproduction (CMR) are of specific concern due to the long-term and serious effects that they may have on human health (ECHA, 2015c). CMRs are typically identified in the literature by the risk phrase "high concern". The most hazardous of the CMRs, based on evidence from scientific studies, may be elevated to the same level as PBTs by the risk phrase "very high concern". CMRs can interfere with DNA – our genetic blueprint – and change it by causing uncontrolled growth of cells (cancer) or cause heritable genetic damage (mutation) or impair fertility (reproduction).

As depicted in Table 1 above, DEHP is one of the 13 substances found in the blood of volunteers who participated in the 2013 WWF Detox Study. DEHP is a plasticiser primarily found in SBR flooring and PVC floor/wall coverings – PVC flooring may contain up to 30% by mass DEHP plasticiser ((Weschler and Nazaroff, 2008; Lent et al, 2010). The European Union recently classified DEHP as an endocrine

[3] This is the European Union policy on the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH). It entered into force on 1st June 2007.

disruptor[4] under the chemical policy, REACH; and issued a sunset date of February 2015 for termination of the use of this chemical in most products (QMED, 2014). Table 2 provides examples of CMR toxicants in the life cycle of common building products.

Table 2: CMR toxicants in the life cycle of major flooring systems

Building product	Constituent	Chemical of concern	Chemical group
Carpet system	Backing,100% recycled tyre	Naphthalene Lent et al, 2010	VOC
Ceramic tile wall/floor system	Primary glaze, boron-based	Arsenic Nicoletti et al, 2000	Heavy metal
Linoleum flooring system	Agro-chemical, synthetic fertiliser	E.g. Bromoxynil Lent et al, 2010	SVOC
Synthetic rubber flooring system	Manufacturing content (and emissions)	Styrene Lent et al, 2010	VOC
	Manufacturing residual	Aniline Lent et al, 2010	VOC

Chemicals of equivalent level of concern (ELoC)

As compared to the bioaccumulative nature of the PBTs and the generally toxic nature of CMRs, the health concern in respect of ELoC chemicals is sensitisation or specific organ toxicity arising from acute or chronic exposure. A skin sensitizer will produce an allergic response following skin contact. The allergic skin reaction generally disappears when exposure to the sensitising agent comes to an end, although severe reactions can occur. Exposure to a respiratory sensitizer induces a range of reactions from the immune system (ECHA, 2015d). These may vary in severity from coughing and wheezing to development of asthma. The chemicals included in this group can be identified on a case-by-case basis and moved into the previously discussed hazard categories of greater concern where there is scientific proof to allow such reclassification. The chemicals listed in Table 2 below serve as an example of chemicals in this hazard category which are known to contribute to asthma or are suspected of contributing to the onset of asthma

Table 3: ELoC chemicals in the life cycle of common building products
Source: Lott and Vallette, 2013

Example of ELoC chemical	Example of uses in building product	Human exposure pathway	Chemical group
Acid anhydrides – PAN, MA	Epoxy resins, high performance coatings	Breathing, skin contact, contact between food and indoor dust	SVOC
Acrylates – MMA, PMMA	Paints, fluid applied floors, lacquers	Breathing, skin contact, contact between food and indoor dust	SVOC
Formaldehyde	Laminates, insulation, adhesives	Breathing in	VOC
Styrene	Carpets, SBR flooring	Breathing in	VOC

Eco-system health categories

Eco-toxicity is a reference to the impact of toxic substances on freshwater and marine and land-based ecosystems. Eco-toxicity can further be split into the three sub categories, namely, aquatic eco-

[4] An endocrine disrupting substance is of equivalent concern when compared to substances in the CMR category

toxicity, marine eco-toxicity and terrestrial eco-toxicity. Toxic substances do not generally remain in the environmental compartment[5] into which they are emitted, but tend to spread to other compartments, where they may do more damage (Guinee, 2002). For example, when a flax or hemp crop, which is destined to be used as carpet fibre, is sprayed with a biocide, some of the airborne spray will eventually end up in local freshwater bodies, causing severe harm to the freshwater species.

Table 4: Example of building product, chemical of concern and eco-toxicity pathway

Chemical of concern	Example of uses in building product	Ecosystem exposure route	Chemical group
Arsenic Mercury	Cement production – (alternative fuels use)	Manufacturing air release South Africa, 2010	Heavy metals
Fluorine	Clay brick, ceramic tile - (natural clay content)	Manufacturing air release, Nicoletti et al, 2000	Halogen
Nickel	Plant-based carpet fibre - (synthetic fertiliser use)	Emissions to soil Corbière-Nicollier et al, 2000	Heavy metal
Ag-NP	Ceramic tile – (antimicrobial use)	Emissions to water EC, 2014	

Furthermore the synthetic fertilisers applied during cultivation of industrial crops almost always result in the emission of a range of heavy metals[6] – copper, cadmium, cobalt, mercury, nickel and zinc – to the soil as a residual after crop uptake (Corbière-Nicollier et al, 2001; van der Werf, 2004). These heavy metals have negative toxicological effects, resulting in eco-toxicity. If food crops were to be planted right after the harvesting of the industrial crops, a significant fraction of the heavy metals will enter the human diet (Corbière-Nicollier et al, 2001).

Hazardous chemical classes of concern in the building product life cycle

A growing body of research suggests that there are two major groups of hazardous chemicals associated with the building product life cycle – volatile organic compounds (VOCs) and semi-volatile organic compounds (SVOCs). Exposure to a chemical in one of these two groups can result in short or long term adverse effects on human health and comfort. The VOC group has been subjected to extensive research resulting in a heightened awareness about the potential health risks. As compared to VOCs, analytical challenges in measurement have impeded progress in studying SVOCs resulting in limited dissemination of information. This section presents a brief literature survey on the contribution of VOCs and SVOCs to chemical hazard in the building product life cycle.

Volatile organic compounds (VOCs)

Volatile organic compounds (VOCs) are a large group of organic chemicals that easily evaporate at room temperature. They are residuals from the manufacturing processes of building products. Within the VOC group, there are very volatile organic compounds (VVOC) that are differentiated from VOCs by their very low boiling point range – this is depicted in Table 5. Due to the generally low boiling point of VOCs, concentrations can increase very rapidly in an enclosed space (REF) and peak within 12 hours. Thereafter, the emission rates decrease drastically. The concentrations of VOCs in indoor air

[5] There are three environmental compartments – air, soil/land and water

[6] Heavy metals originate from both natural and industrial sources. Some heavy metals are beneficial provided that exposure does not exceed the amount which naturally occurs in the human body. The beneficial heavy metals include copper, zinc and iron. The main threats to human health and the environment arise from over exposure, via manufacturing releases, to the toxic heavy metals – these include arsenic, cadmium, mercury and lead (Jӓrup, 2003).

can be up to 10 times greater than outdoors (Lidell et al, 2008). Because they are airborne, the principal pathway for exposure to VOCs is through inhalation.

Table 5: Comparison of exposure pathways of VOCs and SVOCs
Source: Wensing et al, 2005

Organic compound	Abbreviation	Boiling point range °C	Chemical state	Exposure pathway
Very volatile organic compounds	VVOC	0 – 6	Gas phase	Inhalation
Volatile organic compounds	VOC	6 – 290	Gas phase	Inhalation
Semi-volatile organic compounds	SVOC	290 – 400	Airborne particles	Inhalation Ingestion
			Settled dust	Ingestion Dermal

The major building product-related sources contributing to outdoor concentrations of VOCs are manufacturing releases; and painting activities which involve the use of decorative paints, solvents and varnishes. VOCs released to the external air from these sources combine with nitrous oxide (NO_X) in the presence of sunlight to form ground level ozone (USEPA, 2015). Exposure to ground level zone can trigger a variety of health problems including chest pain and throat irritation. It can worsen existing conditions such as bronchitis and asthma. Ground level ozone is also a health hazard for sensitive ecosystems; and contributes to global warming (Jönsson, 2000).

Due to the large surfaces that they represent, building products that are used as finishes for floors, walls and ceilings are the main sources of VOC emissions to indoor air (Levin, 2010). The high VOC concentration in indoor air poses three types of health hazard, namely (Jönsson, 2000):

- Perception of odours which affects comfort levels[7];
- Irritation of the mucous membranes – eyes, nose and throat[8]; and
- Long-term toxic reactions[9]

Some jurisdictions have passed regulations to limit the outdoor abundance of VOCs. Examples include the European Union's Directive 1999/13/EC and the State of California's South Coast Air Quality Management District (SCAQMD) VOC Regulations. The purpose of VOC regulation is to reduce *VOC content* – not *VOC emissions* – and thereby protect human and environmental health. The main strategy aimed at reducing indoor air VOC concentrations is substitution of standard building products with low-emitting building products. For the following reasons, this indoor strategy is less easy to apply, namely:

- A VOC test does not cover all VOCs present in the tested building product. This is because VOCs belong to different chemical classes. The air concentrations at which a VOC affects health differs from one class to the other – VOC test results can therefore not be generalised and a test needs to be developed for each class of VOCs
- A VOC test does not assess all possible health effects associated with the assessed chemical – the test is concerned with non-cancer issues only

[7] For example, the VOC known as 4-PCH has been identified through a number of studies as the "culprit" that causes the "new carpet smell"

[8] This may progress to sensitization and development of diseases such as asthma

[9] Long-term toxic reactions include cancer, endocrine disruption and neurological, developmental and reproductive effects

Furthermore, non-VOC hazardous chemicals such as SVOCs may still be present even in products that have been tested, certified and labelled as “low emitting”.

Table 6: VOCs emitted from common building products installed indoors

VOC of concern	Examples of uses in building products	Health hazard
4-PCH	Carpet system	ELoC
Ethyl hexanol	Carpet system	ELoC
Styrene	Carpet system, synthetic rubber flooring	Possibly CMR
Formaldehyde	Particleboard, MDF	CMR
Ethylbenzene	Carpet	CMR
Toluene	Carpet	Possibly CMR

Semi-volatile organic compounds (SVOCs)

Semi-volatile organic compound (SVOC) is a collective term for organic compounds covering a boiling point range of 290-400 °C (Wensing et al, 2005). SVOCs are added to the formulation of building products as flame retardants, plasticisers, antimicrobials/ biocides, stain repellents and waxes/polishes (Weschler and Nazaroff, 2008). SVOCs are also found in a wide range of every day products including electronic devices, garden hose pipes, toys, household cleaning products, insecticides and cosmetics.

Unlike VOCs, to which people are exposed via inhalation, SVOCs are found in indoor air as gas, airborne particles or settled dust (Wensing et al, 2005). Improved ventilation and selection of low-VOC building products is therefore an effective management strategy for VOCs. Avoiding or reducing exposure to SVOCs in the indoor environment is however much more difficult to achieve because exposure can occur through a variety of pathways:

- Inhalation (breathing in airborne particles) or
- Dermal contact (skin absorbs dust) or
- Ingestion (airborne particles or dust is absorbed by food/drink prior to consumption) or
- Combinations of all the three listed above
-

The difference between the exposure pathways for VOCs and SVOCs is illustrated in Table 5. When released from an indoor source, VOC concentrations normally increase to a high point in the first few hours, followed by a decrease to much lower levels over a few days. By contrast, when released from a source, SVOCs sink/adsorb into nearby surfaces, making it difficult to measure their air concentrations (Horn et al, 2002; Weschler and Nazaroff, 2008; Wensing et al, 2005). Due to this “sink effect” an SVOC can persist for years after the source is introduced into a building. For example, DDT was banned internationally in the 1970s, but continues to have measurable levels in indoor air (Weschler and Nazaroff, 2008) and human blood (WWF, 2013) – thus parallels can be drawn between indoor persistent SVOCs and outdoor POPs (Weschler and Nazaroff, 2008).

Table 7: examples of SVOCs and their applications in common building products

Additive category	Uses in building products	Additive name / chemical of concern	Bio-monitoring data source	Hazard
Stain repellent	Carpets	EtFOSE, MeFOSE	Blood	PBT/POP
Plasticiser (phthalate)	Resilient flooring	BBzP	Urine	ELoC
Plasticiser (phthalate)	Resilient flooring	DEHP	Urine	CMR
Flame retardant	Carpet padding	penta-BDE	Blood	PBT/POP

Flame retardant	Building insulation, ceiling board	TCPP		Acute toxicity
Flame retardant	Resilient flooring, building insulation	PBDE	Breast milk	CMR

The majority of SVOCs used as additives in building products are classified as hazardous or must be regarded as potentially hazardous to health. Bio-monitoring studies have revealed high bodily burdens of more than 100 SVOCs. Table 5 provides examples of SVOCs of the highest concern, their applications in building products and the human health risk implications. A number of these chemicals have been removed from commercial use, or have become subject to restricted use (Weschler and Nazaroff, 2008).

Major floor coverings and health hazards

In the South African context, the demand for both resilient and non-resilient floor covering products accounts for about 9% of the market for the major building products. The demand is split over three leading materials as follows (CIDB, 2007):

- Ceramic tiles – 60% market share
- Carpeting (stretch and tiles) – 30% market share
- Polyvinyl Chloride (PVC) (tiles and sheeting) – 5%

The sections which follow make use of the literature to highlight human and environmental health hazards associated with these major floor coverings and their installation products.

Ceramic tiles

Ceramic tiles, which are used for both structural and decorative purposes, may constitute 50% of all materials in existing buildings worldwide (Tikul and Srichandr, 2010). Ceramic wall and floor tiles include mosaic, quarry, porcelain and speciality tiles. Although some floor tiles are produced unglazed, the majority of wall/floor tiles are glazed (Nicoletti et al, 2002). The three components of a glazed ceramic tile are the body, which is produced from clay; and the primary and secondary glazes.

Open pit clay mining is a highly dusty process. Without adequate control, the fine particulates that are generated pose a health hazard to local people and to wildlife. Clay mining has been shown to cause asthma and silicosis in workers (HBN, 2015a). Furthermore, the atmospheric emissions which occur when clay-based products are manufactured almost always include fluorine which is naturally present in most deposits of clay and shale (Athena SMI, 1998; Nicoletti et al, 2002; HBN, 2015a). The fluorine emissions contribute to acidification of freshwater bodies; and damage to crops and forests.

The purpose of the primary glaze is to provide the clay tile with a vitreous coating which is impermeable, hard, durable and easy to clean (Nicoletti et al, 2002). The ceramic tile industry has relied on glazes made from basic carbonate white lead for hundreds of years. However, white lead and other lead oxides are more soluble than other forms of lead. The lead in ceramic tile glaze can therefore leach out over time (USEPA, 1998). It is therefore possible for lead, which is a human carcinogen, to be released to the interior of buildings through abrasion as the floor tiles wear out or are damaged over time HBN, 2015a). The US ceramic tile industry has largely responded to this solubility issue by eliminating most heavy metals – lead, cadmium and antimony – from use in glazes. To reduce the industry's atmospheric emissions of lead; and also avoid/minimise user exposure to lead, the Italian ceramic tile sector switched to a single glazing system which enables the manufacturer to replace a substantial proportion of lead with boron as the active ingredient in the glaze (Nicoletti et al, 2002). This approach makes it possible to label ceramic tiles as "low-lead" products. However, the use of boron-based glazing results in substantial atmospheric releases of arsenic, a classified PBT. Hence, the change in glazing technology may not necessarily have improved the toxicity profile of common ceramic floor/wall tiles.

The purpose of the secondary glazing is to ward off fungal and bacterial attack of the tile surface. The antimicrobials most commonly used by the ceramic tile industry include IBPC (Horn et al, 2002); and Ag-NP or Ag+TiO_2-NP (Sanchez et al). IBPC is a skin sensitizer and an aquatic toxicant (Allsop et al, 2005). Ag-NP has been shown to leach from products, wash down drains; and end up in water treatment facilities (Coffin, 2014). It is a potential human toxin and aquatic toxicant (EC, 2014). TiO_2 was initially considered to be inert but has been re-classified by the IARC[10] as possibly carcinogenic (CCOHS, 2014). Among others, TiO_2-NP has been shown to induce genotoxicity and DNA damage in animals exposed to it (Trouiller et al, 2009). It would therefore be prudent to avoid or drastically limit human exposure to this chemical.

Table 8: Generic toxicity profile of ceramic floor/ wall tile

Constituent	Chemical of concern	Hazard	Chemical group
Clay, tile body	Fluorine	Aquatic and terrestrial toxicant	Halogen
	Chlorine	Aquatic toxicant	Halogen
Primary glaze, lead-based	Lead	CMR	Heavy metal
Primary glaze, boron-based	Arsenic	CMR	Heavy metal
Secondary glaze, antimicrobial	Ag-NP	Potential human toxin Aquatic toxicant	

Carpet

A typical carpet is composed of fibres on a primary backing which is bonded with adhesive to a secondary backing. Most carpet fibres are dyed and many are protected with a factory applied stain repellent. Synthetic carpet fibres include nylon, polyester, polyamide and polypropylene all of which are made from specific hydrocarbons that are refined from either crude oil or natural gas. Synthetic fibres have a common upstream burden of PBTs and other toxic chemicals used in the extraction and refining process of fossil fuels.

Natural carpet fibres include animal fibres and plant fibres. Wool, which is naturally stain resistant, is the animal fibre most commonly used in the production of carpets. However, not even the life cycle of 100% wool carpet is toxin-free. Chromium, a CMR, is a key ingredient in common wool carpet dyes. Materials containing organic compounds might be damaged through attack by fungi, microbes or insects. Biocides are therefore widely applied by manufacturers to protect natural carpet fibres against such potential attacks (Horn et al, 2002). The biocide most commonly used to protect wool carpet in this way is Permethrin, Similarly, plant-based carpet fibres are not toxin-free. Plant fibres are derived from industrial crops which are routinely sprayed with a range of toxic agro-chemicals during cultivation. For example, the pesticides approved for cultivation of flax in the USA are trifluran, mancozeb, bromoxynil and trichlorfon (Lent et al, 2010). Trifluran is a PBT. The remaining three chemicals are CMRs. Furthermore, the cultivation of industrial crops based on inorganic fertilisers

[10] International Agency for Research on Cancer (IARC)

invariably contributes to eco-toxicity due to emissions of the heavy metal content to the soil (Corbiere-Nicollier et al, 2001; van der Werf, 2004).

Carpet backings are made from materials ranging from natural materials, such as jute, to 100% recycled content materials such as fly ash or recycled car tyres. The carpet backing-specific toxicity issues, which are not discussed in the above paragraphs, are highlighted in Table 9 below.

Table 9: Toxicity profiles of common carpet constituents

Constituent	Chemical of concern	Hazard category	Chemical group
Fibre, synthetic	Furan	PBT/POP	SVOC
	Xylene	ELoC	VOC
	PAHs	Possibly CMR	SVOC
Fibre, plant fibre, pesticide	Bromoxynil	CMR	SVOC
Fibre, wool, antimicrobial	Permethrin	Possibly CMR	SVOC
Fibre, all, stain repellent,	EtFOSE/MeFOSE[11]	PBT/POP	SVOC
Fibre, wool, dye	Chromium	PBT	Heavy metal
Backing, SBR	Toluene	Possibly CMR	VOC
	Styrene	Possibly CMR	VOC
	4-PCH	ELoC	SVOC
Backing, plant fibre, antimicrobial	Permethrin	Possibly CMR	SVOC
Backing, recycled tyre	Naphthalene	CMR	VOC
	PAHs Lead Carbon nanoparticles	PBT CMR Possibly CMR	SVOC Heavy metal
Backing, fly ash	Arsenic Chromium	CMR CMR	Heavy metal Heavy metal
Backing, PVC	Formaldehyde	CMR	VOC
	Vinyl acetate	Possibly CMR	VOC
	Ethyl hexanol	ELoC	VOC

Poly vinyl chloride

The construction industry is responsible for more than 60% of worldwide PVC use of which a substantial proportion comprises floor coverings in the interior of buildings. PVC is a popular floor covering which is suitable for both residential and commercial buildings. It is usually manufactured in sheet or tile form. PVC wall coverings are commonly specified for hospitals and clinics. PVC floor/wall sheet is primarily composed of PVC resin, stabilisers, pigments, surface coatings, plasticisers and flame retardants.

All stages of PVC life cycle, from cradle-to-grave, raise human and environmental health concerns. The production of PVC resin results in the atmospheric release of HCB and a range of PCBs, all of which are on the Stockholm Convention's list of POPs (Lent et al, 2010). The major stabilisers used in PVC sheet production include lead and cadmium both of which are listed as human carcinogens (CMRs) by the IARC. The pigments commonly used are carbon black and titanium dioxide – both have been identified as possibly CMRs by the IARC. Research results indicate that PVC pigments could be inhaled as dust as a floor sheet wears out (Lent et al, 2010).

[11] According to REACH Annexure XVII, these chemicals can no longer be included in the formulation of building products

The purpose of using plasticisers in the formulation of PVC is to impart flexibility. PVC sheeting can comprise up to 30% by weight of phthalate[12] plasticisers such as DEHP and BBzP (Weschler and Nazaroff, 2008). Therefore twenty square metres of PVC floor covering could easily contain 20 kg of plasticiser. However, because plasticisers do not bond permanently with PVC, they can migrate to the surface of a product and into the surrounding environment – be it soil, waterways or body tissue (Qmed, 2014).

Flame retardants are included in the formulation of PVC sheet products to ensure that the finished product meets fire regulations. However, recent research findings raise very high concerns about common PVC flame retardants. These flame retardants are implicated as significant manufacturing releases (Barber et al, 2005), found in household dust studies (CPA, 2005), found in human breast milk and other bodily fluids (EWG, 2003), and released in rivers, lakes and streams from where they could enter the food chain (Hoh et al, 2006).

Table 10: Toxicity profile of PVC floor/wall covering ingredients
Data sources: Lent et al, 2010; HBN Pharos building products library

Constituent	Chemical of concern	Hazard category	Chemical group
PVC resin	Chlorine gas	Acute toxicity	
	Ethylene oxide	CMR	VOC
	EDC	Possibly CMR	VOC
	Dioxin	PBT/POP	SVOC
	Mercury	Possibly CMR	Heavy metal
Stabiliser	Cadmium	CMR	Heavy metal
	Lead	Possibly CMR	Heavy metal
Pigment	Carbon black	Possibly CMR	
	Titanium dioxide	Possibly CMR	
Surface coating	Acetaldehyde	CMR	VOC
	Ethylbenzene	CMR	VOC
Plasticizer	BBzP	ELoC	SVOC
	DEHP	CMR	SVOC
	DnHP	Possibly CMR	SVOC
Flame retardant	PBDE	PBT, aquatic toxicant	SVOC
	Deca-BDE	CMR, aquatic toxicant	SVOC

Flooring installation products

Ceramic tile installation products[13]

The installation of ceramic tiles requires mortars and grouts. Mortar is used to bond the back of tiles to the substrate. Grout is applied after tiles have been set in place, to fill the spaces between the tiles. Some products are formulated to serve a dual purpose as mortar/grout. Others are formulated to strictly function as a mortar or a grout. Common mortars and grouts rely on a wide range of chemicals which may significantly influence the environmental and health profiles of the floor/wall coverings that they are used to install.

[12] Phthalates are a sub-group within the semi volatile organic compound (SVOC) group
[13] This section is largely based on Healthy Building Network (HBN) / Pharos Building Product library category overview available at http://api.pharosproject.net/product_category/show/id/116

Cement-based mortars

Cement-based mortar is a specialised blend of Portland cement, filler, and a water retention agent, such as cellulose or glass fibre. The difference between a cement-based mortar and a polymer-modified cement-based mortar is that a polymer, such as styrene butadiene rubber (SBR), is added to the blend to increase bonding strength. The fillers used in cement-based mortars include quartz sand, blast furnace slag, fly ash and FGD[14] gypsum. Quartz is listed as a human carcinogen by the IARC.

Blast furnace slag, fly ash and FGD gypsum are industrial wastes – therefore the mortars that they are used to formulate are recycled content or "green" mortars. However, blast furnace slag is a possible carcinogen (USS, 2015). Fly ash can contain heavy metals such as mercury and arsenic. The IARC describes mercury is a possible carcinogen; and arsenic is listed by the WHO[15] as a human carcinogen. Like fly ash, FGD contains heavy metals, especially mercury. The manufacturing phases of the other ingredients, such as Portland cement, glass fibre, cellulose derivatives and the SBR polymer are associated with CMRs and PBTs (HBN, 2015b). The toxicity profile for cement-based mortar is indicated in Table 11.

Table 11: Toxicity profiles of common grouts and mortars
Source: HBN Pharos building products library

Building product	Constituent material	Chemical of concern	Hazard class	Chemical group
Cement-based mortar / cement-based mortar with additive	Binder, Portland cement	Mercury Dioxin	Possible CMR CMR	N/A
	Filler, quartz sand	Quartz	CMR	
	Filler, blast furnace slag	None	Possibly CMR	N/A
	Filler, fly ash	Mercury Arsenic	Possibly CMR PBT	Heavy metal Heavy metal
	Filler, synthetic gypsum	Mercury	Possibly CMR	Heavy metal
	Water retention agent, cellulose		PBT	
	Water retention agent, glass fibre		PBT	
	Bonding additive, SBR	Styrene	Possibly CMR	VOC
Epoxy grout / epoxy mortar (100% solid)	Epoxy part A	BPA	Potential toxin[16]	Residual
	Epoxy part B	Epichlorohydrin	Possibly CMR	Residual
	Filler	Quartz	CMR	Mineral
Epoxy grout / epoxy mortar (emulsion)	Epoxy part A	BPA	Potential toxin	Residual
	Epoxy part B	Epichlorohydrin	Possibly CMR	Residual
	Binder, Portland cement	Mercury	Possibly CMR	Heavy metal
	Filler, ordinary sand	None	N/A	Inert
Urethane (pre-mixed grout)		Acetaldehyde	CMR	VOC
		Ethylbenzene	CMR	VOC

Epoxy mortar/grout (solid)

100% solid epoxy systems dry with a smooth surface, and are more resilient than their cement-based counterparts. Because of this, epoxy systems are generally used as grouts, but many epoxy grouts on the market can also be used as mortar (HBN). Like all epoxies, these systems rely on the standard 2-part epoxy reaction, requiring Bisphenol-A (BPA), epichlorohydrin, and various catalyzing amines. The fillers used in epoxy systems are quartz sand or glass. According to the IARC, BPA is

[14] Flue gas desulfurization
[15] World Health Organisation
[16] Potential endocrine disruptor

not classifiable as to its carcinogenicity. However, the results of studies show that at the very least, BPA is a potential endocrine disruptor (CCS, 2015). Epichlorohydrin, which is primarily produced for use as an epoxy hardener, is listed by both the United States Environmental Protection Agency (USEPA) and the IACR as a probable carcinogen – it is also a potent eye and respiratory irritant. Epoxy and urethane grouts may use both post-industrial and post-consumer recycled glass as filler. Epoxy mortar/grout formulations may include antimicrobials and stain repellents. The toxicity profiles of the mortar/grout and additives are indicated in Tables 11 and 12 respectively.

Epoxy mortar/grout (emulsion)

Unlike 100% solid epoxies, epoxy emulsions blend the two-part epoxy formulation with Portland cement and sand, and function more as a polymer-modified cement-based mortar or grout than a true epoxy. And, because epoxy emulsions are porous, they tend to absorb liquids and stains. Stain repellent and antimicrobial additives are therefore included in epoxy emulsion formulations. The toxicity profiles of epoxy mortar/grout and common additives are indicated in Tables 11 and 12 respectively.

Urethane grout

Urethane is the latest chemistry to be used in grouts. Unlike most cement-based and epoxy systems, urethane grouts come premixed. Product literature reveals very little about the specific urethane ingredients used. However, the technology behind the grout is likely to be similar to that of the urethane clear coat technology used on all cars today. The key ingredients are therefore likely to be acetaldehyde and ethylbenzene, both of which are listed by several agencies for their cancer-causing potential. The antimicrobials most likely to be included in the formulation of urethane grouts are Diuron, a pesticide, or silver nanoparticles (Ag-NP). Diuron has been found to be acutely toxic in aquatic environments. Ag-NP is a confirmed aquatic toxicant (lethal). Human toxicity has not been negated or confirmed (EC, 2014). Moreover, there is evidence that Ag-NP can leach out of the product to which it is added. This means that the antimicrobial property of the grout will be lost with time. Because of the very small size of Ag-NP, and its ability to easily enter living cells, this tendency towards leaching may have grave consequences for human and environmental health (Coffin, 2014). The toxicity profiles of urethane mortar/grout and common additives are indicated in Tables 11 and 12 respectively.

Table 12: Toxicity profile of additives commonly included in grouts, mortars and adhesives
Source: HBN Pharos building products library

Additive category	Commonly used in	Additive name	Known or suspected human and environmental health hazard
Stain repellent	Grouts, mortars	D4	Very high concern, PBT / vPvB (HBN, 2015b)
Stain repellent	Grouts, mortars	EtFOSE/MeFOSE	PBT/POP
Antimicrobial	Grouts, mortars, adhesives	Ag-NP	Aquatic toxicant (lethal), potential human toxicity (EC, 2014)
Antimicrobial	Adhesives	Triclosan	CMR Aquatic toxicant
Surfactant	Adhesives	4-Nonylphenol	CMR Aquatic toxicant

Carpet and resilient flooring installation adhesives

Adhesives are used to bond floor coverings, through non-mechanical means, to the substrate. Floor coverings commonly installed with adhesives include carpet and resilient and wood floor coverings. Adhesives are generally composed of a binder, which is the primary ingredient, and a range of secondary ingredients (Ullman, 1985). The secondary ingredients may include plasticisers, fillers, thickeners, hardeners, non-reactive resins and setting retarders. Common binders in adhesives include acrylate polymers, epoxy, synthetic latex and polyurethane.

Table 13: Toxicity profile of non-VOC ingredients commonly included in adhesives for wall /floor coverings

Source: HBN Pharos building products library

Adhesive type	Constituent material	Chemical of concern	Hazard class	Chemical group
Acrylic / latex (solution-based)	Content	NP	Sensitizer	
	Content	NPE	Sensitizer	
	Content	Antimicrobial	CMR	VOC
Epoxy (reactive)	Epoxy part A	BADGE	CMR	SVOC
	Epoxy part B	Epichlorohydrin	Possibly CMR	
Polyurethane (reactive)	Content	Diisocyanates (MDI)	ELoC	
	Content	BADGE	CMR	

There are four types of adhesive in general use – solution-based, solventless, reactive and pressure-sensitive (OECD, 2009). The adhesives most commonly used to install floor coverings are the solution-based and reactive types (HBN, 2015c). Adhesives described as solution-based may be water-based or organic solvent-based systems. In response to environmental regulation, manufacturers have largely discontinued the production of organic solvent-based systems therefore contemporary markets rely mainly on the aqueous dispersions of acrylate polymer and synthetic latex. The most common reactive adhesive systems include single and two-part epoxy and polyurethane systems.

In a review of carpet adhesive toxicity, HBN researchers found that carpet was almost always likely to be installed with water-based acrylic or latex adhesives. By contrast, resilient flooring was likely to be installed by any adhesive type including but not limited to acrylic, latex, epoxy and polyurethane. When the HBN researchers compared the solution-based to the reactive adhesive systems, the researchers concluded that the solution-based systems were a bit better than the reactive systems. This is because the reactive systems utilise more toxic content (HBN, 2015c). Table 13 indicates the toxicity profile of common non-VOC ingredients used in the formulation of different types of flooring adhesives.

Flooring adhesives are a significant VOC emission source – they may also play a central role in sick building syndrome (SBS) complaints, namely:

- When Katsoyiannis et al (2008) used four types of emission chambers to compare PVC and carpet samples; they found that 4-PCH had a strong odour. As compared to other VOCs investigated in the study, the concentrations of 4-PCH were higher; and did not dissipate in a few hours. They concluded that the primary source of 4-PCH was the flooring adhesive
- In conclusion to an investigation on the source of VOC emissions to indoor air, Sjoberg et al (2009) found that 2E1H emissions, which were off-gassed from flooring adhesive, correlated well to SBS complaints
- Similarly, Chino et al (2012) concluded that 2E1H had a strong odour; and that the off-gassing of this chemical from the adhesives dominated overall VOC emissions rates from PVC and carpet flooring systems.

Summary of findings

This chapter has documented a broad array of hazardous chemicals which commonly occur in the building product life cycle. The human and environmental health consequences of exposure to these chemicals are of grave concern. The health hazards could manifest at any stage of the building product life cycle, from cradle-to-grave. This chapter discusses the health risks arising from exposure under four headings, namely:

- “Very high concern” persistent and bio-accumulative toxicants (PBTs);
- “High concern” carcinogenic, mutagenic and reproductive (CMR) toxicants;
- “Moderate concern” substances of equivalent level of concern (ELoC); and
- Eco-toxicity.

Exposure to PBTs is a major health risk for both humans and ecosystems. The CMR and ELoC categories are specific to human health. Eco-toxicity is concerned with the health of various aquatic and terrestrial ecosystems.

The major groups of hazardous chemicals in the building product life cycle are volatile organic compounds, semi-volatile organic compounds and heavy metals. This chapter has focussed on VOCs and SVOCs both of which are more prevalent in the indoor environment than outdoors.

The human health effects arising from exposure to VOCs can vary from sensory irritation, due to odour, or to toxic reactions, for example, cancer. The key strategies for reducing human exposure to VOCs in the indoor environment are increased ventilation; and substitution of standard building products with low emitting products. In addition to this, some countries are using VOC regulation to limit outdoor abundance of VOCs, reduce the role of VOCs in ground level ozone formation and thereby protect both human and environmental health.

As compared to VOCs, exposure to SVOCs may represent a far higher level of risk for both human and ecosystem health. This is because the exposure pathways may make it extremely difficult to avoid contact once an SVOC is released into the environment.
A large proportion of SVOCs is already classified as PBTs or ought to be classified as such. A significant number of SVOCs have been banned under The Stockholm Convention on persistent organic pollutants (POPs). Furthermore, many SVOCs that are used as additives to enhance the properties of common building products are now subject to restrictions and limits under the European chemical policy, REACH.

The lessons learnt by identifying chemicals of concern in the building product life cycle; and linking them to health hazards, are applied in the case study to develop preliminary toxicity profiles for major South African floor/wall covering products. Amongst others, the results of the case study suggest that:

- None of the three major South African floor/wall covering products investigated in this study have a toxin-free profile. The choice of installation products – grouts, mortars, adhesives and their additives may exacerbate the toxic load.
- Not even 100% renewable content floor coverings are hazard-free. This is because of the generally toxic nature of key manufacturing additives, such as stain repellents; and farming practices which rely on synthetic fertilisers
- The “green” trend of selecting recycled content materials that incorporate waste from other industries – for example, fly ash, may save virgin raw materials and their embodied energy, but may exacerbate the problem of embodied toxicity.

Conclusion and future research

Awareness and management of chemical hazard in the building product life cycle is at least, in principle, now recognised as good practice. The main focus of current management strategies is one life stage – the use phase – one group of hazardous chemicals – VOCs – and one area of protection – human health. However, toxicity can manifest at any stage of the building product life cycle. It could be attributed to exposure to non-VOCs, in particular, SVOCs. Furthermore, exposure to hazardous chemicals can have adverse effects on both human and ecosystem health. For ecosystems, the issues extend beyond well-being to survival – there is a risk of exponential failure of natural systems which could in turn jeopardise human health.

Good practice should therefore shift towards a whole systems approach which can identify and address all human and environmental health hazards in a comprehensive manner. Such comprehensive frameworks for managing chemical hazards in the building product life cycle already exist in the European Union and in Japan. This chapter has been limited to a brief description of toxic chemicals in the life cycle of common building products. Major floor coverings and their installation products were included as a case study. A future chapter will explore the new approaches adopted or emerging within the European Union, Japan and elsewhere; and compare these to the South African status. New regulatory provisions and best practices that could fill the gap in the South African context will be identified and discussed.

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Appendix A

4-PCH	4-Phenylcyclohexene
Ag-NP	Silver nanoparticle
BADGE	Bisphenol A di-glycidyl ether
BBzP	Butylbenzyl phthalate
DEHP	Di-ethylhexyl phthalate
DDT	Dichloro diphenyl trichloroethane
D4	Octamethyl cyclotetra siloxane
Deca-BDE	Decabromo diphenyl ether
DnHP	Di-n-hexyl phthalate
EDC	Ethylene di-chloride
EtFOSE	N-ethyl perfluorooctane sufonamidoethanol
HCB	Hexachlorobenzene
HBCD, HBCDD	Hexabromocyclododecane
MA	Maleic anhydride/ acid anhydride
MeFOSE	N-methyl perfluorooctane sufonamidoethanol
MMA	Methyl methacrylate
MDI	Methylene diphenyl diisocyanate
PAN	Phthalic anhydride
PAHs	Polycyclic aromatic hydrocarbons
PBB	Polybrominated biphenyl
PBDE	Polybrominated diphenyl ethers
PCBs	Polychlorinated biphenyls
Penta-BDE	Pentabromodiphenyl ether
PFOS	Perfluorooctane sulfonate
PMMA	Poly-methyl methacrylate
TCPP	Tris (chloropropyl) phosphate
TDI	Toluene diisocyanate
TiO_2-NP	Titanium dioxide nanoparticles
Tris-BP	Tris dibromopropyl phosphate