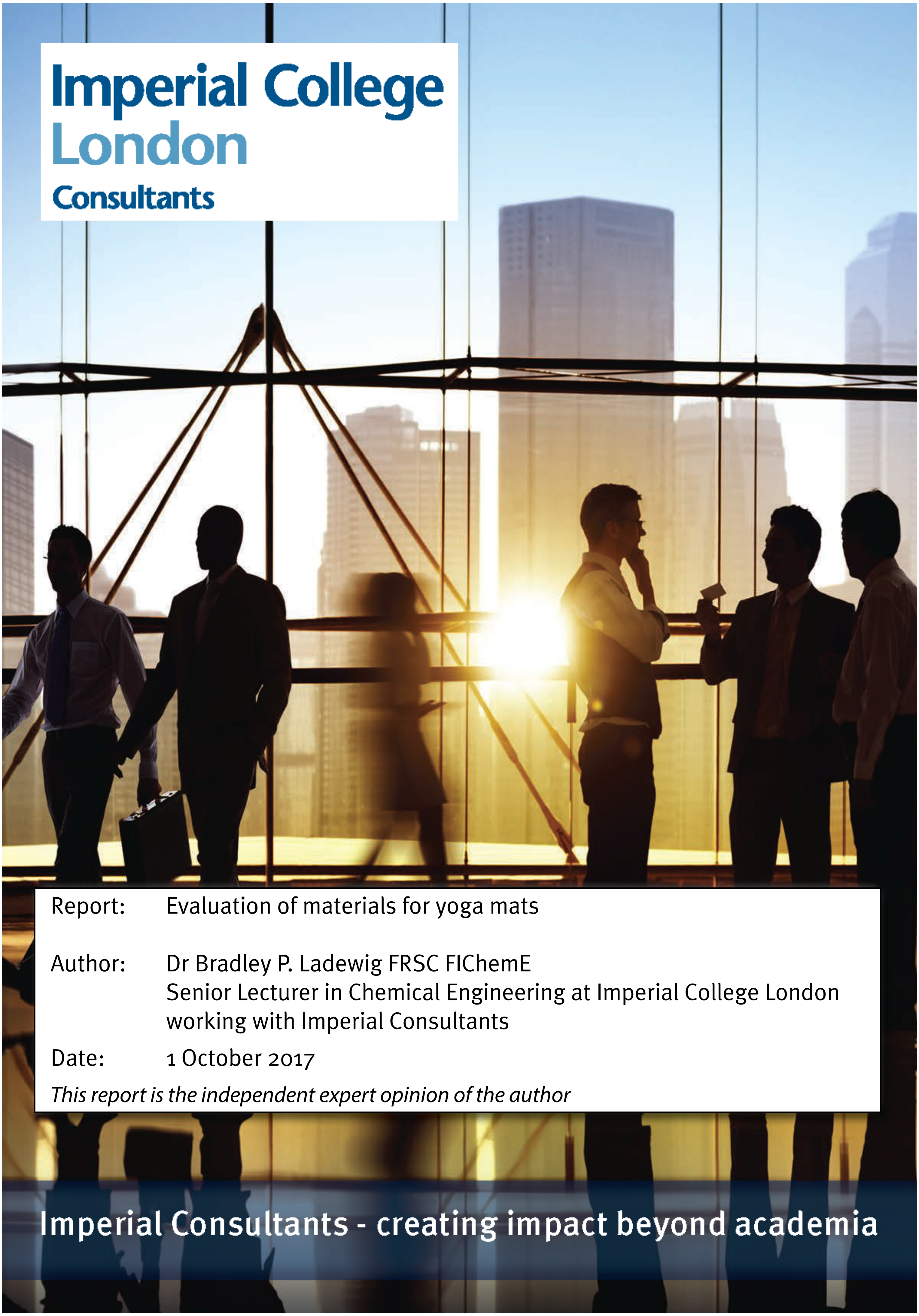


Imperial College London
Consultants

Report: Evaluation of materials for yoga mats

Author: Dr Bradley P. Ladewig FRSC FIChemE
Senior Lecturer in Chemical Engineering at Imperial College London
working with Imperial Consultants

Date: 1 October 2017

This report is the independent expert opinion of the author

Imperial Consultants - creating impact beyond academia

EXECUTIVE SUMMARY

Objective

To provide a clear, evidence-based evaluation of the environmental impacts of various yoga mat materials.

Goals

To consider the manufacturing and composition of various yoga mat materials, and summarise these.
To provide an assessment of the environmental impacts associated with disposal of various yoga mat materials, including common disposal routes such as incineration and landfill.
To examine the available evidence for any human impacts associated with use of the various yoga mat materials considered.

Project Outline

The project provides a detailed literature review of the materials and their manufacturing considerations. The composition of the materials is discussed, along with any chemical and environmental considerations associated with disposal.

LITERATURE REVIEW

Materials considered

A wide range of materials were examined as part of this project. In terms of broad classes of materials, these can be summarised as follows.

1. Polyvinylchloride (PVC) - several of the mats examined were comprised of dense or foamed PVC, the most commonly used material for yoga mats.
2. Rubber - sometimes referred to as natural rubber, including the rubber used for Liforme yoga mats.
3. Polyurethane (PU) - specifically the engineered PU used for Liforme materials.
4. Ethylene vinyl acetate (EVA).
5. Thermoplastic elastomer (TPE) - including materials which were a blend of TPE and EVA and/or other materials.
6. Cork - which was a blend of cork and other binding/adhesive agents.
7. Other materials - some mats included fibres or fabrics such as microfibre.

The focus of this report is on PVC (as an example of a more commonly used and less environmentally responsible yoga mat material, as explained further in this report) and Liforme's specific form of PU (which was demonstrated by this study to be a more environmentally responsible material).

PVC - Production

Polyvinyl chloride is a vinyl chloride polymer produced, in the simplest sense, from the polymerisation of the vinyl chloride monomers, shown in Figure 1.

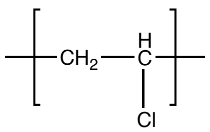


Figure 1. Vinyl chloride monomer

PVC is produced in vast quantities globally and has a variety of uses. For the purposes of this report, the focus will be on the types of PVC used in human contact products (but not products with medical applications, which is beyond the scope of this report) and with a specific focus on the PVC used for yoga mats.

PVC is rarely prepared as a pure material, and in fact many other components must usually be added to PVC to obtain the material properties for the desired application. Among the key added components are plasticisers, which render the final material pliable or deformable. In this way, PVC materials can be classified as either unplasticised (uPVC) or plasticised (pPVC), according to the definition of Titow [1]. uPVC are rigid PVC materials, such as those used in pipes and will not be considered further. pPVC can be semi-rigid with plasticiser contents up to around 20 phr[1], while the softest pPVC may have plasticiser contents as high as 100 phr..

The composition of pPVC materials can vary widely, but focusing on materials used for products such as yoga mats, it is likely that all these PVC materials contain the following:

PVC polymer - the base polymer material. Various forms and compositions are available.

Heat stabilisers - most PVC materials will be processed thermally at least once, and the use of heat stabilisers (which are complex multicomponent materials themselves) prevent the polymer from degrading during thermal processing. For certain applications heat stability may be an in-service requirement, however this is outside the scope of this report. A key aspect of stabilisers is that they often contain heavy metals including barium, cadmium, lead, zinc, tin, antimony and others.

Plasticisers - impart flexibility. For pPVC materials (such as yoga mats) the plasticiser content may be very high. The most common class of plasticisers are *phthalates*, the most common of which is di-2-ethylhexl phthalate (or dioctyl phthalate), as shown in Figure 2.

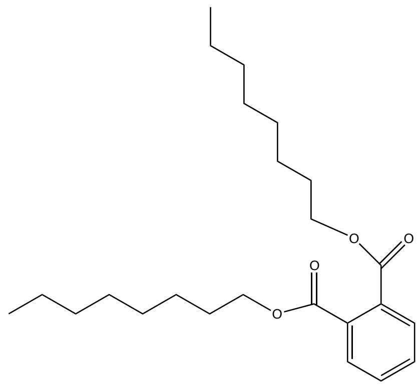


Figure 2. Di-2-ethylhexl phthalate

Many other plasticisers are available and they are often used in combination with one another to achieve the optimum or desired materials properties with the lowest possible cost. Table 1 is taken from [1] and provides some general features of common PVC plasticisers.

Lubricants - reduce the friction between the polymer and working surfaces during processing, and/or reduce the friction between particles or individual molecular chains during processing.

Polymeric modifiers - materials that make the overall polymer blend easier to process (process aids) and/or give the material improved impact resistance.

[1] phr - parts per hundred rubber, or parts of filler/plasticiser material per one hundred parts of the unmodified polymer. This is a mass ratio and not a percentage of the total weight, so a value of 100 phr refers to a material with 100 parts filler (which may be expressed in any weight units, e.g. g, kg, tonnes) per 100 parts of polymer.

Fillers - broad class of materials that can be added to PVC to impart particular properties to the final product. One common use of fillers is to simply extend the material, so called *cheapening extenders*. These are often fine particles of low-cost minerals such as calcium carbonate. High loadings of these fillers increase the density of the material and lead to decreased performance properties, however this may be quite acceptable for certain applications, for example very low-cost yoga mats.

Colourants - critical additive to impart the desired product colour.

Characteristics required	Typically relevant plasticiser types	Examples of application
Price economy	Selected phthalates, extenders	Wide range of cheaper-grade compositions for various purposes
Important features of behaviour of plasticiser in composition: (a) High compatibility with PVC resin (i.e. suitability for use in high proportions in composition) (b) Permanence (low volatility, resistance to extraction and migration in compositions)	Many phthalates, triaryl phosphates Polymeric plasticisers for some purposes, trimellitates, high-molecular-weight phthalate, solid blending resins (e.g. chlorinate PE, EVA copolymers, nitrate rubber)	Very soft, flexible products, including past mouldings and coatings
Processing properties: (a) Ease of solvation, fusion and gelation (b) Effect on viscosity of pastes: Low viscosity High viscosity	BBP, DBP, triaryl phosphates, phthalates Aliphatic diesters and extenders BBP, DBP, triaryl phosphates, polymeric plasticisers	Foamed coatings
End-use properties imparted to compositions: (a) Good colour (b) Good chemical resistance (c) Good low-temperature properties (d) Electrical properties High resistivity Low resistivity (e) Food-contact applications (f) Mechanical properties High tensile strength High extensibility	 Phthalates Polymeric plasticisers Aliphatic diesters (sebacates, adipates, AGS esters) Triaryl phosphates Sebacates Individual plasticisers (high-purity grade) Triaryl phosphates Sebacates	 Clear compositions Protective clothing Tarpaulins, flexible tubing for use in cold conditions Packaging films

Table 1. Common plasticisers in PVC [1]

PVC concerns around use in human contact products

The principal concerns regarding the human safety of PVC materials are briefly outlined below.

Vinyl chloride monomer (VCM) - the principal monomer from which PVC is made, is highly toxic. It has been known since the 1970s that it can cause various types of cancer including Angiosarcoma (a cancer of the liver) and cancer of the mouth. For this reason strict environmental controls are in place in PVC manufacturing facilities, especially to limit the quantity of VCM that is emitted to the workplace atmosphere. Due to the fundamental polymerisation mechanism of PVC, there is always unreacted VCM which must be removed from the PVC product. Concerns about the ability to adequately remove VCM meant that PVC was not used for food-contact applications for many years, until PVC production methods improved and greater understanding was obtained regarding the extent to which residual VCM may transfer from PVC to any food in contact with it.

Some of the PVC constituents mentioned previously are themselves toxic. This is well known for the heavy metals including lead and cadmium. Other components such as the phthalate plasticisers have been shown *in vitro* to have weak estrogenic effects [2], that is, they affect the male reproductive tract, and may contribute to breast and testicular cancers.

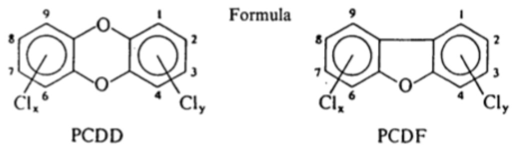
The main points of contention regarding these constituents are to what extent they are released from the product during normal (and abnormal use). For example, lead/cadmium-based stabilisers may be completely immobilised in a PVC-based yoga mat and not released during standard contact with the skin, but in abnormal use scenarios (for example a small child chewing on the mat) these could be released. There are, to the best knowledge of the author, no scientific studies which demonstrate any adverse effects of using PVC as a yoga mat material, however by the same token, there are no studies which involve the unique usage scenario (i.e. physical contact, abrasion with the skin, and especially exposure to sweat and body oils during use in yoga practice).

The final concern with PVC relates to decomposition/combustion by-products. This is addressed in the next section on disposal.

PVC - End-of-life and disposal aspects

Despite being a thermoplastic (which in principle can be heated and re-worked to some extent), PVC is rarely recycled. Partly this is due to the very low economic incentive to do so [3], almost one thousand times less than aluminium for example. However this is also attributed to the fact that in practice all PVC products are complex formulated products, and cannot be easily substituted for virgin material to manufacture new PVC products (as opposed to aluminium for example).

In fact most PVC ends up in landfill, where the fate of the constituent components varies widely depending on landfill conditions (for example if the landfill is lined, what other components are present, aerobic/anaerobic conditions etc.). The long-term environmental impact of PVC in landfill is largely unknown, as it is a highly stable material that biodegrades very slowly. From the very few studies available, it is known that PVC is degraded very slowly (at most a few percent by mass each year) by bacteria [4], which means that in the best possible scenario, a PVC yoga mat may decay fairly completely in 100+ years. Under non-ideal conditions (for example at lower temperatures or in the absence of a suitable bacterial strain) it would likely take more than 1000 years for a hard PVC mat to biodegrade. Slightly faster degradation may be achieved using certain types of fungi under controlled conditions [5], however even if the material can be structurally and/or partially chemically decomposed, there still remains a large fraction of halogenated organic compounds, which could be environmentally detrimental should they leach out of landfills.



Of greater concern though are the combustion products formed when PVC is combusted, for example in municipal incinerators (or in some locations, open fire burning - only likely in developing countries). Combustion of PVC results in the formation of complex halogenated organic by-products, one class of which are polychlorinated dibenzo-*p*-dioxins (PCDD) and the closely related polychlorinated dibenzofurans (PCDF).

These molecules can have between one and eight chlorine substituents, which leads to 75 possible PCDDs and 135 possible PCDFs [6]. Together, these are referred to as *dioxins* and they are one of the most concerning environmental toxins, due to their significant impact on living organisms (studied extensively on rodents and guinea pigs, where they have been shown to be lethal in doses measured in micrograms per kg of subject weight [7]), and also because they are long-lasting, bioaccumulative, lipophilic compounds. That is, they accumulate in fatty tissue and move up the food chain. This class of chemicals are amongst the most toxic ever created by humans.

PVC - Summary

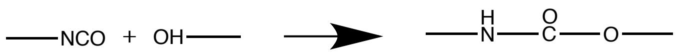
PVC is a highly versatile material which has been used extensively for a wide range of products, including consumer products such as yoga mats. Many of the constituents involved in the manufacture of PVC, especially plasticised, soft PVC, are toxic including the vinyl chloride monomer, lead and cadmium, and there are other human health concerns associated with the organic additives including (but not necessarily limited to) phthalates. There is no clear evidence that any of these toxic or harmful chemicals are leached out of plasticised PVC during typical use as a yoga mat, however no evidence could be found where PVC mats had been tested in any scenario similar to this.

PVC poses multiple end-of-life challenges. It is a an environmentally recalcitrant material withstanding biodegradation under standard landfill conditions. Even if PVC were to degrade, very slowly, the result would be fragmented polymer chains or complex halogenated organic molecules, which are themselves known environmental toxins, especially should they leach out of the containment zone. Where PVC is combusted in municipal waste incinerators, harmful dioxins are formed which are highly stable compounds and which accumulate in the environment.

It may not seem obvious, but there are almost equivalent end-of-life problems associated with soft PVC (as used in yoga mats) and typical hard PVC (for example used in piping), as both are chemically very similar. When biodegrading in landfill conditions, both will take a very long period of time to break down, and when they do, they will both consist of environmentally harmful, halogenated polymer fragments. Likewise, if combusted (for example in a municipal waste incinerator), the harmful by-products formed will be almost identical from both hard- and soft-PVC.

Polyurethane - production

Polyurethanes (PU) are a broad class of polymers that share the urethane group as a common molecular building block. This is shown below where an isocyanate group reacts with a hydroxyl group to form a urethane group.



PU can be incredibly diverse, as the monomers can vary enormously in their chemical properties, chain length and much more - so long as the molecules have two or more isocyanate groups that can react with two or more hydroxyl groups, then in principle, the polymer can form. It has been produced at large scale since the 1940s and is now used as a base material in a very wide range of industries, as foams, rubbery (elastomeric) materials, paints, adhesives, fibres and as type of artificial leather [8]. Of these different PU forms, foams are the most common, and are estimated to account for 2 - 3% of the entire global production of all polymer materials [8].

One fascinating aspect of PU materials is that in their early stages of development, they were not always considered suitable in many applications due to their susceptibility to microbial attack [9]. This meant that they did not always have the long-term stability which was desired in many polymer products. However in recent years as the end-of-life and disposal considerations of polymer materials has been given very serious attention, this almost unique ability of PU to undergo microbial degradation has become a key, desirable materials property, as it means that PU materials (specifically PU foams) are biodegradable [10]. It should be noted that the microbial degradability of modern PU materials is specifically relevant to their biodegradation under *landfill* conditions - if a PU yoga mat is kept clean and dry between use, it would not undergo microbial degradation under normal usage conditions.

Considering the specific production processes of PU foams, the following components are involved.

Catalysts - to make a PU product with the desired properties requires very careful control of the reaction kinetics, for a variety of reasons (for more details refer to [11]). These include catalysts to accelerate the rate of (and influence the relative rates of competing reactions for) the NCO/NCO reaction, the NCO/OH reaction and the NCO/H_2O reaction. Table 2 shows typical examples of catalysts used in PU manufacture [11].

Structure/elements	Catalyst type
R1R2R3N	Amines
R3P	Phosphines
R-OMe (Me = alkali for example)	Alcoholates
MexOy	Metal oxides
RCOOMe (Me = K, Na, Ca, Fe, Mg, Hg, Ni, Pb, Co, Zn, Cr, Al, Sn, V, Ti)	Carboxylates

Structure/elements	Catalyst type
R-Me- (Me = Zn, Si, Sn, Pb, Sb) R2Me R3Me	Organo metal compounds Metal-chelates Hydrides
Organic, Inorganic and Lewis Acis	Acids
Amine-epoxides Amine-alkylenecarbonates Amine-imides	Combined catalysts

Table 2. Common catalysts used in PU manufacture

For example, considering a Liforme yoga mat, it is likely that Carboxylate and/or Organo Metal Trimerization catalysts have been employed, given that X-ray fluorescence analysis reveals the presence of many of the metals (denoted Me in Table 2) listed as common Carboxylate and/or Organo metal compounds. The quantities of these materials that remain in the finished product are minimal though (they are only detectable due to X-ray fluorescence being a particularly sensitive analytical technique), and they are not known to be mobile (that is, able to be liberated from the yoga mat).

Cross-linking and chain-extending agents - these are specific to particular PU applications and are used to modify the polymeric chains to provide mechanical reinforcement (basically making the materials stronger).

Blowing agents, surfactants - used to create a foam structure, essential in creating PU foams such as those used for yoga mats. Early generations of PU foam were produced using halogenated or volatile blowing agents [12], chemicals with significant health and environmental concerns. More recently, these have been substituted with completely benign CO_2 or water vapour as the blowing agent (Liforme yoga mats are produced using the water blowing method).

Pigments - used to produce coloured PU materials.

Fillers - improve certain properties (for example, stiffness) but also to reduce material costs, since the filler is almost always cheaper than the PU polymer.

PU - end of life and disposal considerations

The PU materials used for Liforme yoga mats (as examined within this study) would be expected to break down completely in standard landfill conditions within 1-5 years, owing to the specific details of the polymer itself, including its molecular orientation, crystallinity, cross-linking and chemical groups present in the molecular chains. The exact length of degradation time would be largely dependent on conditions of the specific landfill (for example temperature, humidity, pH) where bacterial degradation may be the dominant mechanism. Extensive reviews of the biodegradation of PU materials are available [13], and they address a wide range of degradation conditions including biological conditions (owing to the extensive use of PU in medical devices and implants).

Other possible end-of-life considerations are to do with the combustion of PU, if for example it is incinerated in a municipal waste incinerator, or in some locations, in open fire burning (only likely in developing countries).

This is obviously undesirable from an environmental perspective, however this is a very significant point of difference between PVC-based yoga mats and PU-based yoga mats. PVC-based yoga mats contain very high levels of chlorine (up to 18% in some of the PVC mats tested), which as mentioned previously can lead to highly toxic dioxin formation upon burning. PU-based yoga mats, contain relatively low levels of halides (< 450ppm chlorine in the case of a Liforme PU yoga mat - approximately 400 times less than in the typical PVC material tested in this study). This means it is reasonable to assume that from a dioxin-emission perspective, the combustion emissions from a PVC yoga mat are at least 400 times more harmful than those from a Liforme yoga mat.

Liforme Yoga Mats vs PVC yoga mats - Summary of Conclusions from this Study

Liforme yoga mats, as well as various PVC yoga mats, have been examined and tested as part of this study, and the following observations can be made.

1. The Liforme materials are, to the best knowledge of this author, completely non-toxic and suitable for use in human contact, i.e. for the intended purpose as a yoga mat (which involves user contact between their skin and the mat). This applies to all of the Liforme materials tested, both upper and lower surfaces. This is based in particular on the significant body of literature on the non-toxicity of PU materials, manufacturer assurances relating to Liforme materials, as well as laboratory testing to verify these manufacturer assurances relating to Liforme materials.

2. The Liforme materials examined are i) soft, flexible, water-vapour blown PU, and ii) foamed natural rubber. They will break down in landfill conditions, with an estimated time to near-complete degradation of 1-5 years. Detailed experimental studies would be required using samples of Liforme yoga mats under simulated landfill conditions to completely verify this timeframe, however this is a confident estimate.

3. The PVC materials are semi-rigid PVC and contain significant quantities of chlorine, up to 18% in the PVC yoga mat samples tested. These materials have virtually zero biodegradability and so would not be expected to degrade to any significant extent under landfill conditions. The yoga mat could still persist after one hundred, or even one thousand years.

4. The PVC materials have high chlorine content and would produce highly toxic dioxins under some combustion conditions (especially uncontrolled combustion). PVC is rarely recycled in practice and so there are no actual end-of-life outcomes for PVC mats that are considered environmentally positive, as both landfill and incineration have significant issues.

5. The Liforme yoga mats are relatively benign polymer materials, and of those tested, contained up to 99.6% carbon and hydrogen (Liforme PU) or 93.6% carbon and hydrogen (Liforme rubber) and only very low levels of chlorine (< 450 ppm for Liforme PU, < 550ppm for Liforme rubber).

REFERENCES

1. Titow, W.V., PVC plastics : properties, processing, and applications. 1990, London: Elsevier Applied Science.

2. Jobling, S., et al., A variety of environmentally persistent chemicals, including some phthalate plasticizers, are weakly estrogenic. Environmental Health Perspectives, 1995. **103**(6): p. 582-587.

3. Craighill, A.L. and J.C. Powell, Lifecycle assessment and economic evaluation of recycling: A case study. Resources, Conservation and Recycling, 1996. **17**(2): p. 75-96.

4. Booth, G.H., A.W. Cooper, and J.A. Robb, *Bacterial Degradation of Plasticized PVC.* Journal of Applied Bacteriology, 1968. **31**(3): p. 305-310.

5. Kirbaş, Z., N. Keskin, and A. Güner, *Biodegradation of polyvinylchloride (PVC) by white rot fungi.* Bulletin of Environmental Contamination and Toxicology, 1999. **63**(3): p. 335-342.

6. Fiedler, H. and O. Hutzinger, Dioxins: Sources of environmental load and human exposure. Toxicological & Environmental Chemistry, 1990. **29**(3): p. 157-234.

7. Safe, S., Polychlorinated biphenyls (PCBs), dibenzo-p-dioxins (PCDDs), dibenzofurans (PCDFs), and related compounds: Environmental and mechanistic considerations which support the development of toxic equivalency factors (TEFs). Critical Reviews in Toxicology, 1990. **21**(1): p. 51-88.

8. Nakajima-Kambe, T., et al., Microbial degradation of polyurethane, polyester polyurethanes and polyether polyurethanes. Applied Microbiology and Biotechnology, 1999. **51**(2): p. 134-140.

9. Morton, L.H.G. and S.B. Surman, *Biofilms in biodeterioration - a review.* International Biodeterioration and Biodegradation, 1994. **34**(3-4): p. 203-221.

10. Shimao, M., *Biodegradation of plastics.* Current Opinion in Biotechnology, 2001. **12**(3): p. 242-247.

11. Polyurethane handbook : chemistry, raw materials, processing, application, properties. 2nd ed, ed. L. Abele and G.n. Oertel. 1994, Munich: Hanser.

12. Avar, G., et al., *10.24 - Polyurethanes A2 - Matyjaszewski, Krzysztof*, in *Polymer Science: A Comprehensive Reference*, M. Möller, Editor. 2012, Elsevier: Amsterdam. p. 411-441.

13. Howard, G.T., *Biodegradation of polyurethane: a review.* International Biodeterioration & Biodegradation, 2002. **49**(4): p. 245-252.

Imperial Consultants (ICON)
58 Prince's Gate, Exhibition Road, South Kensington, London SW7 2PG

Tel: +44 (0)20 7594 6565 Fax: +44 (0)20 7594 6570
Email: consultants@imperial.ac.uk
Web: www.imperial-consultants.co.uk

LinkedIn: /IC-CONSULTANTS-LTD
Twitter: @ConsultImperial