**Construction Materials**

**The environmental impact of phenolic foam insulation boards**
Densley Tingley, Hathway, Davison and Allwood

ice | proceedings

**Proceedings of the Institution of Civil Engineers**

http://dx.doi.org/10.1680/coma.14.00022
**Paper 1400022**
Received 20/05/2014 Accepted 12/11/2014
**Keywords:** resins & plastics/rehabilitation, reclamation & renovation/sustainability

ice
Institution of Civil Engineers
publishing

# The environmental impact of phenolic foam insulation boards

**Danielle Densley Tingley** MEng, PhD
Research Associate, Department of Engineering, University of Cambridge, Cambridge, UK; formerly Research Associate, Department of Civil and Structural Engineering, The University of Sheffield, Sheffield, UK

**Abigail Hathway** MEng, PhD, CEng, MCIBSE
Lecturer, Department of Civil and Structural Engineering, The University of Sheffield, Sheffield, UK

**Buick Davison** BEng, PhD, CEng, MICE
Professor of Structural Engineering, Department of Civil and Structural Engineering, The University of Sheffield, Sheffield, UK

**Dan Allwood** BSc, PhD
Reader, Department of Materials Science and Engineering, The University of Sheffield, Sheffield, UK

**The use of external wall insulation is on the increase, with phenolic foam being a popular insulation choice. However, if designers are to make informed decisions on material choices, the environmental impact of the insulation should be considered and the payback period of the associated impacts evaluated. There is a lack of information for phenolic foam insulation; this paper seeks to fill this gap. Results are given utilising the international reference life-cycle data system methodology to ensure they are easily comparable and can be used in other studies. Considering the whole life cycle, the impacts from water depletion and freshwater ecotoxicity see the longest payback times; these are recommended for targeted reduction.**

## 1. Introduction

The main use of phenolic foam in construction is as an insulation material, usually around pipes or in board form applied to the building fabric to improve its thermal efficiency. The thermal efficiency of the existing building stock is of prime concern if carbon emissions targets are to be met (Climate Change Act 2008, 2008; United Nations Framework Convention on Climate Change, 2013). For those homes with solid walls, external wall insulation can be an effective method of improving their thermal efficiency. Phenolic foam is a popular material choice for external wall insulation systems owing to its low thermal conductivity and good fire performance (EPFA, 2013). Estimates suggest that 13 000 homes in the UK must be refurbished per week in order to meet 2050 emissions targets (National Refurbishment Centre, 2012), so the need to retrofit is clearly important. When considering the scale of the retrofit challenge it is also important to think about the quantity of materials that will be used during the retrofits and the environmental impact of these materials. Although there are environmental impact data available for some insulation materials, such as expanded polystyrene (EPS) and mineral wool (Hammond and Jones, 2011; SimaPro, 2013), there is limited freely available, transparent, cradle-to-gate environmental impact information for phenolic foam. The only data found (BRE, 2009) is for an unspecified thickness of insulation over a 60-year study period, but it is not clear which life-cycle stages are included. Lack of information prevents designers from taking into account environmental impact when assessing insulation options. There is a growing need for availability of environmental impact information for insulation materials as more homes are targeted for retrofit. Although differences in the environmental impact of one insulation compared to another may seem small on a per house basis, once the savings are scaled up to a whole estate, area or country they could become significant. A full comparison will only be possible with life-cycle assessments (LCAs) of materials. Environmental impact information is also an effective way to check that environmental paybacks are within the lifetime of a material. The aim of this paper is therefore to provide a transparent estimate for the environmental impacts of phenolic foam that will allow others to make informed decisions on insulation choices.

Phenolic foam is made from three main components: phenolic resin, a blowing agent and an acid catalyst; a number of additives can also be utilised to develop specific properties within the foam. There are patents and other information available (Kingspan Holdings Limited, 2006; Schroer *et al.*, 2013) that describe the chemicals used to manufacture phenolic foam; these have been used as the basis for the environmental impact analysis.

## 2. Method

The study takes a LCA approach, with quantitative assessment of the environmental impacts of phenolic foam from cradle to gate. Transport of chemicals to the production facility of the phenolic foam is not included in the study as the source of the chemicals is unknown. The type and distance of transport could also vary significantly depending on where materials are sourced; the impacts associated with transport are therefore not assessed. Process analysis (estimating inputs and outputs to the process) will be used to quantify the environmental impacts, utilising SimaPro 7 (PRE Consultants, the Netherlands) software to provide and handle the available data. Throughout, if accessible, patent information is utilised for inputs and process information. For some input chemicals, the reactions and molar masses are used to calculate input information; unless otherwise specified 100% yield is assumed, owing to a lack of more detailed information. It is acknowledged that this may result in an underestimation of the environmental impacts. For the input chemicals, the relative environmental impacts will be compared graphically in order to highlight the compound with the lowest impact in each environmental impact category. The most recent patent found (Kingspan Holdings Limited, 2006) gives example mixes. The first mix is used as the basis for the mass inputs of different chemicals to manufacture phenolic foam.

The life-cycle impact assessment (LCIA) method used is the international reference life-cycle data system (ILCD) midpoint method. This is derived from analysis of different LCIA methods and their impact categories; it makes recommendations from the analysis, providing methods and characterisation factors which can be used for analysis (JRC-IES, 2011). The ILCD method was developed to provide categories with robust characterisation factors and to give results in a form that could be easily compared with other studies; it is for these reasons that the methodology has been chosen. The impact categories utilised in the study, along with units and a short explanation, can be found in Table 1. By investigating a wide range of categories a complete picture of the environmental impact of phenolic foam and its component chemicals has been obtained.

## 3. Chemical components

The chemical components that are used to make phenolic foam are summarised in Figure 1, this is based on mix 1 from the latest available patent (Kingspan Holdings Limited, 2006).

### 3.1 Phenolic resin

Phenolic resin is the main component of phenolic foam. There is environmental impact data available for it within the ecoinvent database contained in SimaPro. It has a reasonably high embodied carbon at 4·15 kg/kg $CO_2$ eq (SimaPro, 2013), which suggests that the resulting phenolic foam will also have substantial embodied carbon.

### 3.2 Acid catalysts

Odian (1991, p. 127) states that an acid catalyst such as toluene or xylene sulfonic acid should be used during the manufacture of phenolic foam (Gordiziella *et al.*, 2000, pp. 158–169; Klempner and Sendijarevic, 2004, pp. 447–456; Schroer *et al.*, 2013). A recent patent (Kingspan Holdings Limited, 2006) suggests that a mixture of the two acids should be used; all three options will therefore be explored. As there are no existing life-cycle impact (LCI) data in SimaPro for toluene sulfonic acid or xylene sulfonic acid, the environmental impacts of these were estimated, as outlined in the following sections.

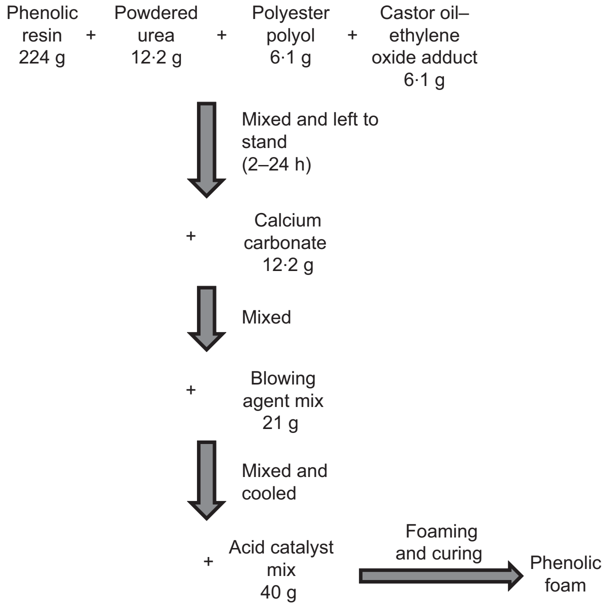

Figure 1. Chemical mix example for making 30 × 30 × 5 cm phenolic foam (based on Kingspan Holdings Limited (2006))

### 3.2.1 Toluene sulfonic acid

Toluene sulfonic acid is produced from a reaction between toluene and concentrated sulfuric acid (Norris, 1915). From MendelSet (2013) it can be seen below that one mole of toluene reacts with one mole of sulfuric acid to form one mole of toluene sulfonic acid; this assumes a 100% yield from the reaction. The toluene sulfonic acid formed contains a benzene ring, methyl and sulfonate groups.

I. $C_6H_5CH_3 + H_2SO_4 \rightarrow C_7H_8O_3S + H_2O$

Using this equation as a basis and the respective molar masses (Table 2) of the contributing chemicals, the environmental impacts of toluene sulfonic acid were modelled with SimaPro. Figure 2 shows the environmental impact contribution of the component chemicals for one mole of toluene sulfonic acid.

The contribution of each compound varies significantly depending on the environmental impact category. As can be seen in Figure 2, toluene accounts for the majority of the impact in the climate change category and significant amounts in five other categories. Sulfuric acid contributes the majority of the impact in five categories and has a substantial impact across

| Impact category | Unit | Explanation |
|---|---|---|
| Climate change | kg $CO_2$ eq | Greenhouse gases that cause climate change added up as carbon dioxide equivalents; uses global warming potentials from the 2007 report from the Intergovernmental Panel on Climate Change (IPCC) over 100-year timeframe. |
| Ozone depletion | kg CFC-11 eq | Ozone depletion potentials (ODPs) from the World Meteorological Organisation used to convert gases to CFC-11 equivalent. |
| Human toxicity, cancer effects | CTUh | Comparative toxic unit for humans used, includes outdoor inhalation, ingestion of drinking water and indirect ingestion of toxins, for example, those that have built up in plants, animals and fish (Rosenbaum *et al.*, 2011). |
| Human toxicity, non-cancer effects | CTUh | Comparative toxic unit for humans used, details as above. |
| Particulate matter | kg PM2·5 eq | Intake fraction of fine particles estimated from emissions. |
| Ionising radiation, human health | kg U235 eq | Includes transfer of contamination to the environment and potential exposure. Some uncertainty associated with the long half-life of many radioactive materials. |
| Ionising radiation, ecosystems (interim) | CTUe | Comparative toxic unit for ecosystems used, current model focuses on effects in freshwater. Interim category recommended by the ILCD as characterisation factors have yet to be outlined in a peer-reviewed publication. |
| Photochemical ozone formation | kg NMVOC eq | Emissions that cause increasing ozone concentration in the troposphere are characterised to non-methane volatile organic compounds eq. Low-level ozone can damage vegetation and cause impacts on human health. |
| Acidification | molc $H^+$ eq | Based on accumulated exceedance, this includes atmospheric transportation and deposition of emissions, while accounting for vulnerabilities of different ecosystems; for more details see Seppala *et al.* (2006). |
| Terrestrial eutrophication[a] | molc N eq | Based on accumulated exceedance, assessment of soil and atmospheric conditions and accounts for sensitivities of biodiversity in different areas (Seppala *et al.*, 2006). |
| Freshwater eutrophication | kg P eq | Estimates nutrient concentrations that have transferred to a freshwater aquatic environment, focusing on phosphorous. |
| Marine eutrophication | kg N eq | As above, but focuses on marine aquatic environments, assessing nitrogen equivalent concentrations. |
| Freshwater ecotoxicity | CTUe | Comparative toxic unit for ecosystems used; this accounts for exposure, potential transport and effects on ecosystems (Henderson *et al.*, 2011). |
| Land use | kg C deficit | Assesses the quality deficit of the land occupied, using soil organic matter as a quality indicator. |
| Water resource depletion | $m^3$ water eq | Considers water use and relates this to local scarcity. |
| Mineral, fossil and renewable resource depletion | kg Sb eq | Utilises abiotic (physical, non-biological resources) depletion potential, a ratio between the annual resource extraction and the reserves available. All resources converted to antimony equivalents. |

[a] Eutrophication refers to large supplies of nutrients (e.g. nitrogen and phosphorus) to an environmental system which can cause excessive growth of plants and disrupt ecosystems. For more information on the impacts of eutrophication see Smith *et al.* (1999).

**Table 1.** Impact categories (Information taken from JRC-IES (2011) unless otherwise specified)

| Chemical | Molar mass: g | Source |
|---|---|---|
| Toluene | 92·14 | Sigma-Aldrich (2013a) |
| Sulfuric acid | 98·08 | ChemSpider (2013a) |
| Toluene sulfonic acid | 172·02 | ChemSpider (2013b) |

**Table 2.** Molar masses for toluene sulfonic acid

three more. The relative severity of the different categories is not shown in the comparison graph. The quantified impacts show the climate change category as having one of the highest impacts, although across the categories the impacts are reasonably small.

### 3.2.2 Xylene sulfonic acid

Xylene sulfonic acid is synthesised from a reaction between xylene and sulfuric acid with a suggested molar ratio between 1:1·4 and 1:1·9 (Nobuyuki and Seiji, 1983). As increasing sulfuric acid amounts will result in a larger environmental impact and a need for more materials, the lowest concentration ratio (1·4) in this range has been chosen, as this seems most likely from a commercial view. A reaction will still occur at lower ratios, but may leave unreacted xylene and thus produce a lower yield of xylene sulfonic acid. Table 3 shows the molar masses on which the environmental impacts were estimated. The environmental impact breakdown can be seen in Figure 3.

| Chemical | Molar mass: g/mol | Source |
|---|---|---|
| Xylene | 106·16 | US EPA (2007) |
| Sulfuric acid | 98·08 | ChemSpider (2013a) |
| Xylene sulfonic acid | 186·23 | Sigma-Aldrich (2013b) |

**Table 3.** Molar masses of xylene sulfonic acid

The environmental impact of the xylene sulfonic acid components shows a similar pattern to that of toluene sulfonic acid (Figure 2). This perhaps reflects the chemical similarity of toluene and xylene as aromatic hydrocarbons.

### 3.2.3 Environmental impact comparison of acid catalysts

Three different acid catalyst options have been discussed for the manufacture of phenolic foam. Figure 4 compares the environmental impact of the following acids

- toluene sulfonic acid
- xylene sulfonic acid
- acid mix: 65% toluene sulfonic acid, 35% xylene sulfonic acid; this is suggested for use in the patent from Kingspan Holdings Limited (2006).

Xylene sulfonic acid has the largest impact across the categories and toluene sulfonic acid the lowest impact across all categories, this is due to xylene having a higher environmental impact than

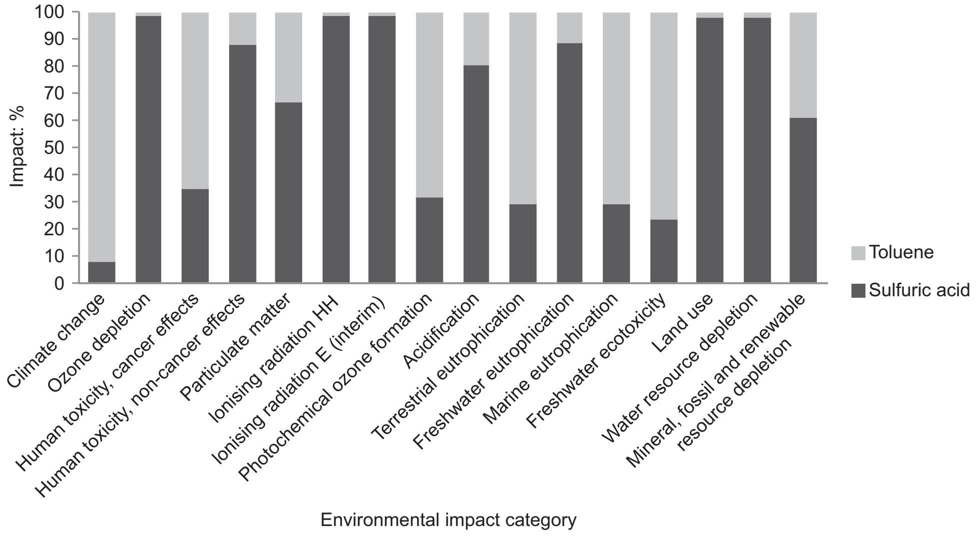

**Figure 2.** Environmental impact breakdown of toluene sulfonic acid, indicating which compound contributes the greatest impact in each category

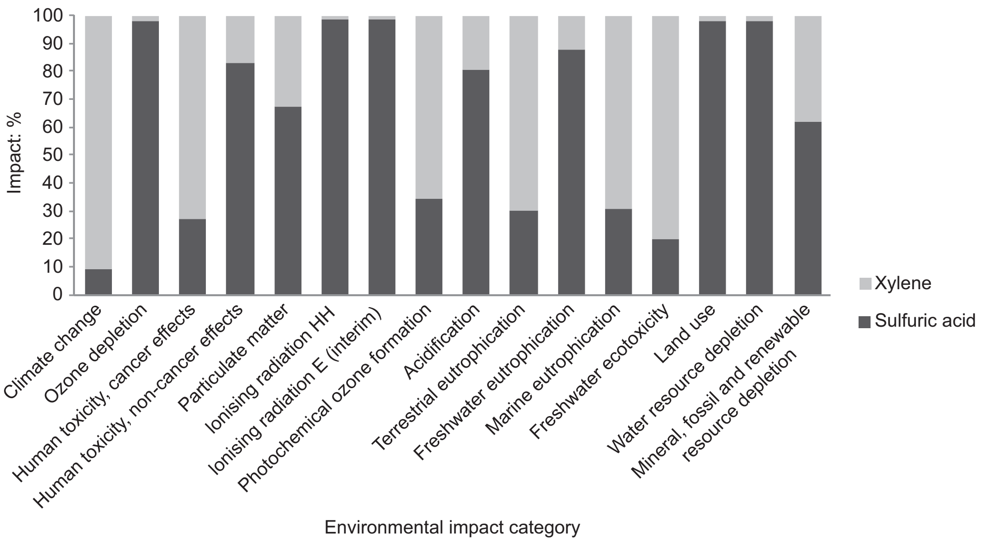

**Figure 3.** Environmental impact breakdown for xylene sulfonic acid, showing which compound contributes the greatest impact to each environmental impact category

toluene. As expected, the mixture of the two has a mid-range impact. To reduce the environmental impact of the mix, the proportion of toluene sulfonic acid could be increased. This would reduce human carcinogens and freshwater toxins in particular. The impacts of human toxicity, cancer effects are small ($1{\cdot}07 \times 10^{-9}$ CTUh for the mix) and thus reducing this would not be considered a priority. Freshwater toxicity levels are higher, 0·033 CTUe for the mix, xylene sulfonic acid, 0·043 CTUe, and toluene sulfonic acid, 0·028 CTUe. Increasing the proportion of toluene sulfonic acid would therefore reduce the impact of the mix more, but not substantially.

## 3.3 Blowing agents

Pentane is the blowing agent that is most often mentioned as being used in the manufacture of recent phenolic foam (LowEnergyHouse, 2013; Schroer *et al.*, 2013). However, the

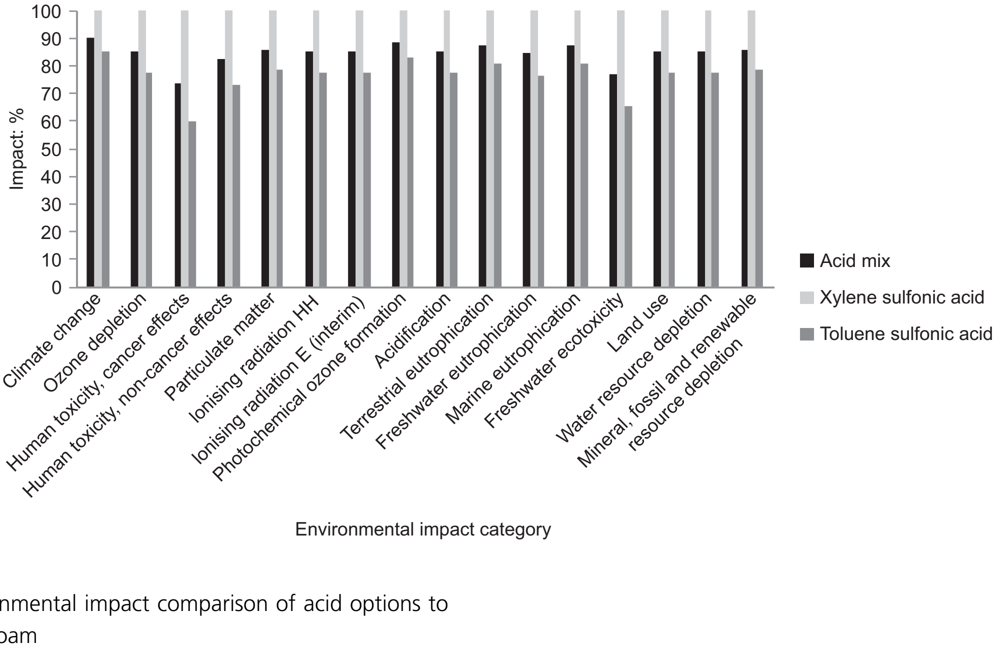

**Figure 4.** Environmental impact comparison of acid options to make phenolic foam

most recent patent (Kingspan Holdings Limited, 2006) suggests that a mix of isopropyl chloride and pentane in a 85:15 ratio should be used as the blowing agent. A comparison will therefore be made between the two options to investigate the environmental impact implications of the choice. There are currently no data on isopropyl chloride in SimaPro, so this will be estimated first.

### 3.3.1 Isopropyl chloride

Isopropyl chloride can be made from a reaction between propylene and hydrogen chloride (Otrme, 1925; Kashima Chemical Company and Asahi Glass Company, 2004). Both compounds should be in a gaseous form for the reaction and the yield is increased through the use of a catalyst and a specific temperature and pressure. The catalyst could be either iron or halogenated aluminium oxide and the ideal temperature is 40–60°C (Kashima Chemical Company and Asahi Glass Company, 2004). The most recent patent found (Kashima Chemical Company and Asahi Glass Company, 2004) gives specific examples for the reaction and it is from this that reaction quantities (shown in Equation II) and yield are taken for input into SimaPro in order to estimate the environmental impact. The reaction can be seen in Equation II and the molar masses that are used to estimate quantities in Table 4.

II. $1{\cdot}05CH_3CHCH_2 + HCl \rightarrow C_3H_7Cl$

Although there are a number of different datasets for propylene in SimaPro, the econinvent dataset has been used, as this is aggregated across 19 different sites in Europe (SimaPro, 2013) and is therefore assumed to be representative of the propylene used within the isopropyl chloride reaction. The breakdown of percentage impacts for the components within isopropyl chloride is shown in Figure 5. Owing to the likelihood of alternative approaches being used by different manufacturers, the environmental impact of the catalyst (which could be reused) and those associated with temperature and pressure (which could be achieved using different fuels and methods) have not been included in the analysis. This suggests that estimates for the impact of isopropyl chloride will be conservative.

| Chemical | Molar mass: g | Source |
|---|---|---|
| Propylene | 42·08 | Sabic (2013) |
| Hydrogen chloride | 36·46 | Concoa (2013) |
| Isopropyl chloride | 78·54 | Sigma-Aldrich (2013c) |

Table 4. Molar masses of isopropyl chloride and associated components

It can be seen (Figure 5) that propylene has the larger impact across ten categories and hydrogen chloride more of an impact across the remaining six.

### 3.3.2 Comparison of the environmental impact of blowing agent alternatives

The environmental impact of 21 g of blowing agent alternatives are compared, as this is the quantity required in the most recent patent acquired (Kingspan Holdings Limited, 2006). Pentane, isopropyl chloride and a mix of isopropyl chloride and pentane (85:15) are compared (see Figure 6).

Isopropyl chloride is included so that a direct comparison can be made with its environmental impacts and those of pentane. However, if used alone as a blowing agent it gives an undesirable foam structure with larger cells (Kingspan Holdings Limited, 2006). Isopropyl chloride has the largest impact in nine of the categories and pentane the greatest impact in seven categories. The gas mixture falls in-between the two as would be expected.

## 3.4 Additives

There are four additives that are suggested for use (Kingspan Holdings Limited, 2006) in the manufacture of phenolic foam: a surfactant (castor oil–ethylene oxide adduct), a plasticiser (polyester polyol), an organic modifier (urea) and an inorganic filler (calcium carbonate). There is existing environmental impact information for urea in the SimaPro datasets; however, there is no information for the remaining three additives, so the environmental impacts of these have been estimated as discussed in the following sections.

### 3.4.1 Plasticiser: polyester polyol

A polyester polyol is suggested for use as a plasticiser; it should be mixed with the phenolic resin and left to stand for between 2 and 24 h (Kingspan Holdings Limited, 2006). Although there are no LCI data available in SimaPro 7 for the polyester polyol, an eco-profile has been put together for PU Europe (Polyurethane Insulation Industry group) (Schindler *et al.*, 2010). The eco-profile gives detailed input materials and emissions; these have been input into SimaPro to estimate the environmental impacts of the aromatic polyester polyol. Aromatic polyester polyols are used in this analysis as they are used in the manufacture of PIR and PUR foams (Invista, 2013).

It is acknowledged that there is a range of materials that could be used to make polyester polyols (Poliuretanos, 2013). However, much of the process information is considered proprietary. No specific details are given in the relevant patent (Kingspan Holdings Limited, 2006) for what type of polyester polyol is used in the manufacture. Therefore the LCI data available for aromatic polyester polyols have been used here to approximate the likely impacts.

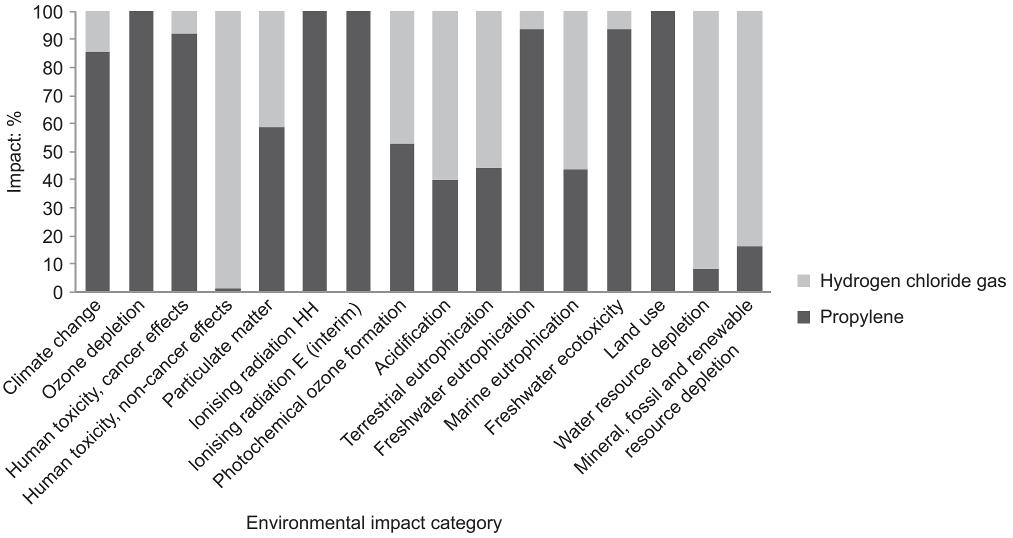

**Figure 5.** Environmental impact breakdown of isopropyl chloride, showing which compound makes the largest contribution in each category

### 3.4.2 Organic modifier: urea

Powdered urea is added and mixed with the phenolic resin. The inclusion of urea can lower the thermal conductivity of the foam and increase its strength (Kingspan Holdings Limited, 2006). Urea for industrial use is synthesised from ammonia and carbon dioxide, and it is often used in the agricultural industry as a fertiliser (Copplestone and Kirk, 2013); this paper assumes the urea used results from this production route. There are data available in SimaPro 7 for urea and these have been used in the study.

### 3.4.3 Surfactant: castor oil–ethylene oxide adduct

The surfactant is added to the phenolic resin before it is mixed with the blowing agent and acid catalyst. It is designed to

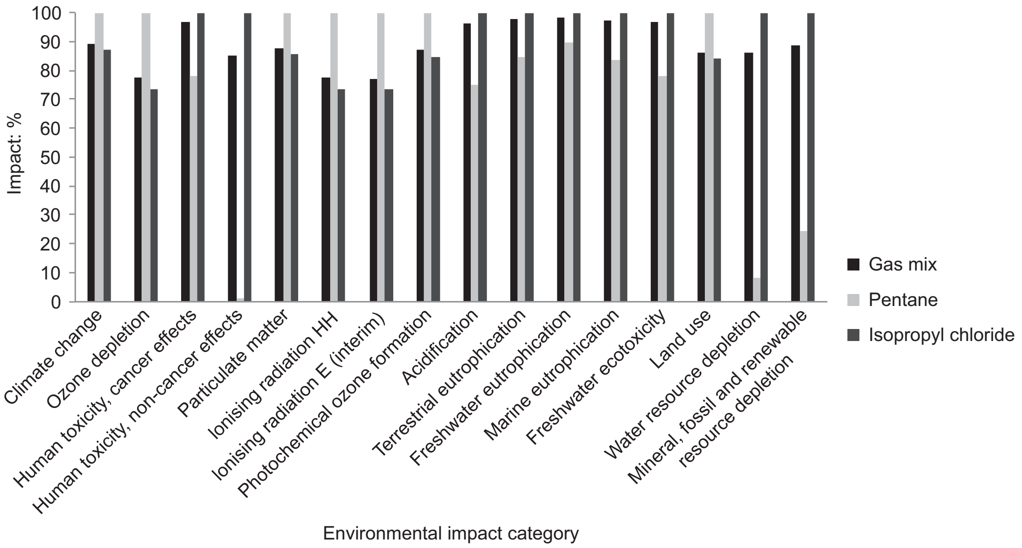

**Figure 6.** Environmental impact comparison of blowing agent alternatives

stabilise the cells within the phenolic foam, reducing the likelihood of cracks in the cell walls (Zeggelarr, 2010). The surfactant is formed from a reaction of ethylene oxide and castor oil in the ratio of 1 mole of castor oil to 21–38 moles of ethylene oxide. An example mixture is given by Zeggelarr (2010).

There is insufficient LCA information on castor oil, as highlighted by Upshaw *et al.* (2008) and Helling and Russell (2009), which is problematic when modelling the environmental impact of the castor oil–ethylene oxide adduct. Both studies note that castor oil has a negative climate change impact as it sequesters carbon dioxide during the growth of the plant (Upshaw *et al.*, 2008; Helling and Russell, 2009). The data available are characterised (i.e. all emissions for an impact category are converted to a single unit, e.g. gases with global warming potential are converted to carbon dioxide equivalent, $CO_2$ eq) and are therefore unsuitable for this study, first because the impact categories have been condensed and so do not match those in this study, and second, for those categories which are the same, different characterisation factors are used and thus the data are not comparable. The data, however, do show that water intake is a high impact area (Upshaw *et al.*, 2008). Owing to the lack of data at this time for castor oil the environmental impacts of this component have not been modelled.

There are available environmental impact data for ethylene oxide, so this can be modelled. It is assumed that half the mass of castor oil–ethylene oxide adduct is made from ethylene oxide (Zeggelarr, 2010); this will therefore be included as such in the environmental impact estimate. It is acknowledged that this does not take into account yield losses, but information on this is not available so simplified estimates are made. It is also noted that on a mass basis ethylene oxide has a high environmental impact. However, as only small quantities are used during the manufacture of phenolic foam the environmental impact appears small compared to other component chemicals.

### 3.4.4 Inorganic modifier: calcium carbonate

Calcium carbonate may be used as an inorganic filler in the manufacture of phenolic foam, mixed into the mixture of phenolic resin, urea and polyester polyol, and is used to regulate the pH of the foam. The average particle size should be 170 μm (Kingspan Holdings Limited, 2006). There are LCI data available for calcium carbonate ($>63$ μm) that are representative for Europe (ELCD 3.0, 2013). These have been input into SimaPro 7 in order to estimate environmental impacts.

## 4. Results and discussion

### 4.1 Breakdown of impact from components

All the main components and additives were modelled with SimaPro on the basis of the most recent patent, specified mix 1, shown in Figure 1 (Kingspan Holdings Limited, 2006). The contribution breakdown of the impacts can be seen in Figure 7. The majority of the impact in all categories is from the phenolic resin, although the foaming/expanding process makes a

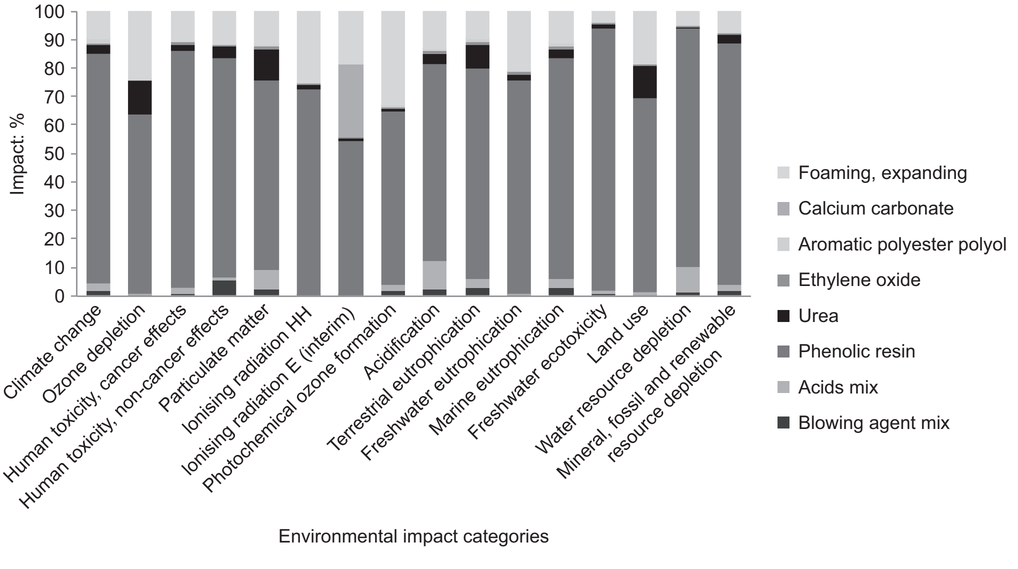

**Figure 7.** Breakdown of environmental impacts for phenolic foam components, indicating which contributes the greatest impact in each category

| Impact category | 1 kg Phenolic foam | Unit | Equivalent kg of bricks |
|---|---|---|---|
| Climate change | 7·021 | kg CO2 eq | 29·5 |
| Ozone depletion | 2·94E-07 | kg CFC-11 eq | 16·5 |
| Human toxicity, cancer effects | 3·01E-07 | CTUh | 54·8 |
| Human toxicity, non-cancer effects | 2·77E-07 | CTUh | 62·1 |
| Particulate matter | 0·0028 | kg PM2·5 eq | 54·4 |
| Ionising radiation HH | 1·32 | kg U235 eq | 68 |
| Ionising radiation E (interim) | 5·49E-06 | CTUe | 91 |
| Photochemical ozone formation | 0·035 | kg NMVOC eq | 54·9 |
| Acidification | 0·031 | molc $H^+$ eq | 45 |
| Terrestrial eutrophication | 0·051 | molc N eq | 25·5 |
| Freshwater eutrophication | 0·0019 | kg P eq | 55·6 |
| Marine eutrophication | 0·0047 | kg N eq | 25·3 |
| Freshwater ecotoxicity | 14·83 | CTUe | 200·9 |
| Land use | 2·48 | kg C deficit | 17·7 |
| Water resource depletion | 0·013 | $m^3$ water eq | 188·4 |
| Mineral, fossil and renewable resource depletion | 1·9E-05 | kg Sb eq | 44·9 |

Table 5. Environmental Impact of 1 kg of phenolic foam (density = 40·5 kg/$m^3$) compared to the equivalent kg of bricks (density = 2000 kg/$m^3$)

significant contribution, in particular to the ozone depletion, ionising radiation and photochemical ozone formation categories. The acid mix has a minimal impact in most categories, except particulate matter, acidification and water resource depletion. The blowing agent mix has very little impact across the categories, with the largest impact seen in the human toxicity, non-cancer effects category. Urea has the greatest impact of the additives, with a visible contribution across most categories, in particular, ozone depletion, particulate matter, terrestrial eutrophication and land use. Calcium carbonate makes a significant contribution to the ionising radiation E category, which is likely to be attributable to radioactive substances emitted to air, water and soil, but impact is minimal elsewhere. Figure 7 shows the percentage contribution of each component to the environmental impact, but it does not demonstrate what the impacts are – this will be explored in the next section.

## 4.2 Estimated environmental impact of phenolic foam

The environmental impacts of 1 kg of phenolic foam (density = 40·5 kg/$m^3$) are shown (Table 5) for each of the impact categories. In order to give an idea of the scale of these impacts, for each category, the mass of standard, clay bricks required to produce the same impact is given, as estimated within SimaPro 7 (the mass of a standard brick is approximately 2·86 kg, with a density of approximately 2000 kg/$m^3$). It can be seen that across the impact categories 1 kg phenolic foam has substantially more impact than a typical brick, although freshwater ecotoxicity and water resource depletion see equivalent masses of up to 200 kg, potentially signalling these as areas of concern. The environmental impact of bricks is low across impact categories; water resource depletion in particular is quite low at $6{\cdot}9 \times 10^{-5}$ $m^3$ per kg of brick, which in part accounts for high equivalent kilograms, but phenolic foam insulation does also have a high water demand.

In order to gain a full picture of the environmental impact of a material it is important to explore the remaining life-cycle stages. This is particularly important for an insulation material which will accrue environmental impact savings during its use, as discussed in the following section.

## 4.3 Remaining life-cycle stages

Once manufactured, phenolic foam will need to be transported from the factory to the construction site; in the UK this is likely to be by truck. The environmental impacts of this journey are not included within the estimates in Table 5, as the distance transported will be site dependent. Carbon dioxide equivalent estimates are given in CESMM4 (2013) and full environmental impacts could be estimated using SimaPro (2013) if site-specific studies with information on material sources were to be conducted.

The installation of phenolic foam insulation as part of an external wall system requires the use of hand drills, therefore the energy inputs are minimal. Contractors estimate that 4 litres of diesel will be used on a typical house for the installation of the whole system, including adhesives and render (R. Storton, personal communication, 2012).

As already mentioned, phenolic foam will give in-use environmental savings by improving the thermal performance of the building it is installed on. A case study building was used to estimate the reduction in gas use for heating once the external wall insulation was installed. Utilising UK weather data from the United States Department of Energy (2012) and assuming an internal temperature of 20℃, the heat loss through the wall was calculated over a year pre- and post-retrofit. The difference in heat loss was equated to the gas requirements for heating, assuming use of a condensing, modulating gas boiler. This is a simplified estimate for the potential gas saving, as occupant behaviour would significantly influence internal temperatures and heating usage. The environmental impact saving from the reduced gas use was calculated using SimaPro; the dataset takes into account standard boiler efficiency. The environmental impact of the phenolic foam was also estimated for the example house. The wall area of applied insulation is 40 $m^2$ and, assuming approximately 10% wastage, 44 $m^2$ of 60 mm ($R = 3$ $m^2$/K per W) phenolic foam insulation is used for the estimation. A comparison of the initial impacts of phenolic foam to the impact saving from the reduced gas use is shown in Figure 8 and the payback time of the initial impact can be seen in Table 6. When compared to initial impacts, there are significant environmental impact savings in three categories: climate change, ozone depletion and land use. The longest payback times are for water depletion at just over 11 years and freshwater ecotoxicity at nearly 6·5 years. This suggests that these two categories would benefit most from reduction when considering the whole life cycle. It is acknowledged that there is little water use from gas extraction and use; the savings will therefore be small, extending potential payback periods. The majority of the impact for these categories is from phenolic resin, so reducing the impact of the resin would be the most effective way to reduce the overall impact of water depletion and freshwater ecotoxicity for phenolic foam. It is important to bear in mind that gas savings would be much less if lower internal temperatures were maintained or if heating was restricted to specified hours. This would extend payback times. It is also possible that the u-value of the insulation could be less than expected, if poorly installed, which would affect potential gas savings.

Although the water depletion category has the longest payback period, this does not assess the relative scale of water consumption within the UK; 1·37 $m^3$ of water are required for the manufacture of 2·58 $m^3$ of phenolic foam insulation, which is sufficient to insulate the mid-terrace, case study building. When this is compared to the average person's consumption of water over a year at 55 $m^3$ (South West Water, 2010) it is clear that, although phenolic foam manufacture consumes significant quantities of water, it is not a major source of water depletion in the UK. The comparison of phenolic foam with the equivalent weight in kilograms of bricks (see Table 5) shows a significantly higher impact in the freshwater ecotoxicity category.

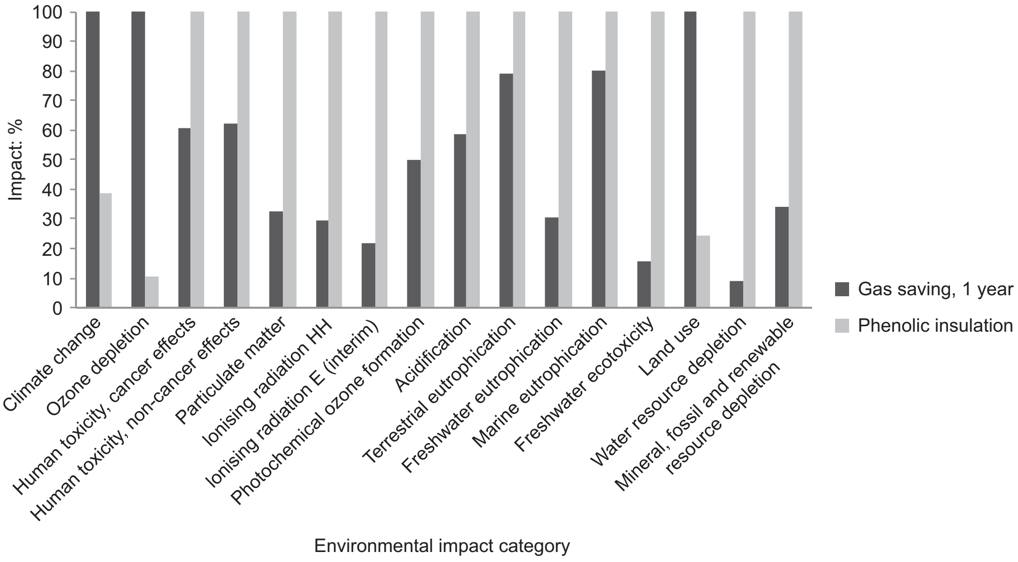

**Figure 8.** Environmental impact comparison between impacts of phenolic foam and the environmental impact saving from reduced gas usage in 1 year post-retrofit

| Impact category | Years payback |
|---|---|
| Climate change | 0·39 |
| Ozone depletion | 0·11 |
| Human toxicity, cancer effects | 1·65 |
| Human toxicity, non-cancer effects | 1·60 |
| Particulate matter | 3·08 |
| Ionizing radiation HH | 3·41 |
| Ionizing radiation E (interim) | 4·58 |
| Photochemical ozone formation | 2·00 |
| Acidification | 1·70 |
| Terrestrial eutrophication | 1·27 |
| Freshwater eutrophication | 3·25 |
| Marine eutrophication | 1·25 |
| Freshwater ecotoxicity | 6·38 |
| Land use | 0·25 |
| Water resource depletion | 11·22 |
| Mineral, fossil and renewable resource depletion | 2·93 |

Table 6. Payback period for initial environmental impacts of phenolic foam insulation

For this gas-saving scenario, all paybacks are within the expected lifetime of the insulation system. External wall systems have a predicted life span of at least 30 years (PermaRock, 2013; Wetherby, 2013). The insulation should not require maintenance during this time, although if cracks appear in the render finish then these may need repair to prevent water ingress. However, as there should be no maintenance required to the insulation, there will be no environmental impact from this life-cycle stage.

There is little published work on the end-of-life stage of phenolic foam external wall insulation systems. Although there is a take-back system in place for waste phenolic foam at the installation stage (Resource Efficiency Partnership, 2012), and uncontaminated waste could theoretically be mechanically recycled, there are fewer options for contaminated end-of-life waste. Owing to the layered nature of the systems, the use of adhesives and render, any insulation removed at end of life would be viewed as contaminated and would be likely to be sent to landfill, although it could be incinerated with energy recovery (Resource Efficiency Partnership, 2012). It is important to develop strategies for effective removal and disposal of external wall insulation systems which could be taken into account during system development.

Overall, from the quantified impacts, it can be concluded that phenolic foam insulation will have a net positive impact across its life cycle; meaning that those in-use savings from reduced gas use will outweigh the detrimental environmental impacts from manufacture. This is particularly the case for climate change, ozone depletion (although this is largely due to phenolic foam insulation having a small impact for this category) and land use.

## 5. Conclusion

This paper has investigated the environmental impacts of phenolic foam insulation across a range of impact categories, with detailed examination focusing on the cradle to gate, manufacturing stage. By showing the processes and calculation procedures, in combination with assumptions made, it is intended that the information reported is sufficiently transparent to enable others to utilise it in further building LCA studies, filling the gap in current environmental impact information. The impacts have been estimated and shown for 1 kg of phenolic foam so that the information can be utilised in specific case studies to explore impacts and payback times; the information presented should also make it possible to compare phenolic materials with other materials easily. Exploring the whole life cycle, two impact categories in particular see longer payback periods: water depletion and freshwater ecotoxicity. These should be targeted for reduction. Phenolic resin contributes the majority of impact to these two categories and therefore reducing the impact of this constituent would likely be the most effective way to reduce the impact of phenolic foam. Options for end of life are currently limited, and are likely to result in landfill or possible incineration; this is an area where further research by academia and industry would be useful. Overall, phenolic foam insulation should have a net positive effect across its life cycle, owing to its use in improving the thermal efficiency of buildings.

## Acknowledgements

This work forms part of the BIG Energy Upgrade project. This project (also known as ‘Energy Innovation in Deprived Communities’) is part financed by Yorkshire and Humber European Regional Development Fund Programme 2007 to 2013. The Department for Communities and Local Government is the managing authority for the European Regional Development Fund Programme, which is one of the funds established by the European Commission to help local areas stimulate their economic development by investing in projects which will support local business and create jobs.

## REFERENCES

BRE (Building Research Establishment) (2009) *Approved Environmental Profile, Kingspan Kooltherm (K3, K5)*. BRE, Watford, UK, see http://www.greenbooklive.com/pdfdocs/envprofiles/ENP410j.pdf (accessed 07/10/13).

CESMM4 (2013) *Carbon and Price Book* (Mott MacDonald (ed.)). ICE Publishing, London, UK.

Climate Change Act 2008 (2008) *Elizabeth II. Chapter 27*. The Stationary Office, London, UK, see http://www.legislation.

gov.uk/ukpga/2008/27/pdfs/ukpga_20080027_en.pdf (accessed 06/10/2014).

ChemSpider (2013a) *Sulphuric Acid*. See http://www.chemspider.com/Chemical-Structure.1086.html (accessed 07/08/2013).

ChemSpider (2013b) *p-Toluenesulfonic Acid*. See http://www.chemspider.com/Chemical-Structure.5876.html (accessed 07/08/2013).

Concoa (2013) *Precision Gas Controls, Hydrogen Chloride*. See http://www.concoa.com/hydrogen_cholride_properties.html (accessed 16/08/2013).

Copplestone JC and Kirk CM (2013) *Ammonia and Urea Production*. See http://nzic.org.nz/ChemProcesses/production/1A.pdf (accessed 02/10/2013).

ELCD 3.0 (European Reference Life Cycle Database) (2013) *Calcium Carbonate*. See http://elcd.jrc.ec.europa.eu/ELCD3/resource/processes/6006d87e-ccee-42b1-b203-f67c7c0bad97?format=html&version=03.00.000 (accessed 25/09/2013).

EPFA (2013) *Properties of Phenolic Foam*. See http://www.epfa.org.uk/properties.htm (accessed 30/09/2013).

Gordiziella A, Pilato LA and Knop A (2000) Phenolic foam. In *Phenolic Resins: Chemistry, Applications Standardization, Safety and Ecology,* 2nd edn. Springer, Berlin, Germany.

Hammond G and Jones C (2011) *Embodied Carbon: Inventory of Carbon and Energy (ICE)* (Lowrie F and P Tse (eds)). BSRIA Ltd, Bracknell, UK, BSRIA Guide, BG 10/2011.

Helling RK and Russell DA (2009) Use of life cycle assessment to characterize the environmental impacts of polyol production options. *Green Chemistry* **11(3)**: 380–389.

Henderson AD, Hauschild MZ, van de Meent D *et al.* (2011) USEtox fate and ecotoxicity factors for comparative assessment of toxic emissions in life cycle analysis: sensitivity to key chemical properties. *International Journal of Life Cycle Assessment* **16(8)**: 701–709.

Invista (2013) *TERATE Polyols*. See http://www.invista.com/en/brands/terate.html (accessed 25/09/2013).

JRC-IES (Institute for Environment and Sustainability in the European Commission Joint Research Centre) (2011) *ILCD Handbook*. Publication Office of the European Union, Luxembourg, International Reference Life Cycle Data System, Recommendations for Life Cycle Impact Assessment in the European context.

Kashima Chemical Company and Asahi Glass Company (2004) *Process for Producing Isopropyl Chloride*. European Patent Application No. 1449820, 25 August.

Kingspan Holdings Limited (2006) *A Phenolic Foam*. International Patent Application No. PCT/IE2006/000096, 8 September.

Kelly PT (2004) Phenolic foams by Paul T. Kelly. In *Handbook of Polymeric Foam and Foam Technology* (Klempner D and Sendijarevic V (Eds)). 2nd edn. Hanser Publishers, Munich, Germany.

LowEnergyHouse (2013) *What Is Phenolic Insulation*? See http://www.lowenergyhouse.com/phenolic-insulation.html (accessed 19/08/2013).

MendelSet (2013) *Properties of Hydrocarbons*. See http://www.mendelset.com/articles/689/properties_hydrocarbons (accessed 04/10/2013).

National Refurbishment Centre (2012) *Refurbishing the Nation – Gathering the Evidence*. See http://www.rethinkingrefurbishment.com/filelibrary/nrc_pdf/NRC_reportSEP2012web.pdf (accessed 04/09/2013).

Nobuyuki T and Seiji K (1983) *Preparation of High-purity m-Xylene-4-Sulfonic Acid*. Japanese Patent Application No. JPS58154550, 14 September.

Norris JF (1915) Nitro compounds and sulphonic acids. In *Experimental Organic Chemistry*. McGraw-Hill Book Company, New York, USA, Ch. 16, see http://www.books-about-california.com/Pages/Experimental_Organic_Chemistry/Ex_Organic_Chem_Chap_16.html (accessed 02/07/2013).

Odian G (1991) *Principles of Polymerization,* 3rd edn. Wiley, New York, USA.

Otrme GO (1925) *Process of Making Isopropyl Chloride*. US Patent Application No. 1545742, 17 July.

PermaRock (2013) *External Wall Insulation Systems – Phenolic System*. See http://www.permarock.com/products/external_wall_insulation_systems/phenolic.aspx (accessed 07/10/2013).

Poliuretanos (2013) *Polyester Polyols*. See http://www.poliuretanos.com.br/Ingles/Chapter1/15Polyester.htm (accessed 11/12/2013).

Resource Efficiency Partnership (2012) *Building Insulation Foam, Resource Efficiency Action Plan*. See http://brufma.co.uk/wp-content/uploads/2013/03/REAP_Building_insulation_foam.pdf (accessed 07/10/13).

Rosenbaum RK, Huijbregts MAJ, Henderson AD *et al.* (2011) USEtox human exposure and toxicity factors for comparative assessment of toxic emissions in life cycle analysis: sensitivity to key chemical properties. *International Journal of Life Cycle Assessment* **16(??)**: 710–727.

Sabic (Saudi Basic Industries Corporation) (2013) *Propylene*. See http://www.sabic.com/corporate/en/productsandservices/chemicals/propylene (accessed 16/08/2013).

Schindler A, Habel F and Baitz M (2010) *Eco-profile of Aromatic Polyester Polyols (APP)*. Report by PE International for PU Europe, Federation of European Rigid Polyurethane Foam Associations, see http://www.pu-europe.eu/site/fileadmin/Reports_public/PU_10-204_PU_Europe_project_-_Eco-Profile_of_Aromatic_Polyester_Polyols__APP_.pdf (accessed 25/09/2013).

Schroer D, Hudack M, Soderquist M and Beulich I (2013) *Rigid Polymeric Foam Boardstock Technical Assessment*. The Dow Chemical Company, see http://msdssearch.

dow.com/PublishedLiteratureDOWCOM/dh_08ab/0901b803808ab35e.pdf?filepath=styrofoam/pdfs/noreg/179-04129.pdf&fromPage=GetDoc (accessed 19/08/2013).

Seppala J, Posch M, Johansson M and Hettelingh JP (2006) Country-dependent characterisation factors for acidification and terrestrial eutrophication based on accumulated exceedance as an impact category indicator. *International Journal of Life-Cycle Assessment* **11(6)**: 403–416.

SimaPro (2013) *SimaPro 7. Life Cycle Assessment Software*. PRé Consultants, Washington DC, USA.

Sigma-Aldrich (2013a) *Toluene Physical Properties*. See http://www.sigmaaldrich.com/chemistry/solvents/toluene-center.html (accessed 07/08/2013).

Sigma-Aldrich (2013b) *p-Xylene-2-Sulfonic Acid*. See http://www.sigmaaldrich.com/catalog/product/aldrich/x1376?lang=en&region=GB (accessed 07/10/2013).

Sigma-Aldrich (2013c) *2-Chloropropane – Properties*. See http://www.sigmaaldrich.com/catalog/product/fluka/59379?lang=en&region=GB (accessed 16/08/2013).

Smith VH, Tilman GD and Nekola JC (1999) Eutrophication: impacts of excess nutrient inputs on freshwater, marine and terrestrial ecosystems. *Environmental Pollution* **100(1–3)**: 179–196.

South West Water (2010) *What is the Average Use per Household on a Meter?* See http://southwestwater.custhelp.com/app/answers/detail/a_id/208/~/what-is-the-average-use-per-household-on-a-meter%3F (accessed 06/10/2014).

United Nations Framework Convention on Climate Change (2013) *Kyoto Protocol*. See http://unfccc.int/kyoto_protocol/items/2830.php (accessed 21/10/2013).

United States Department of Energy (2012) *Energy Plus Energy Simulation Software – Weather Data*. US Department of Energy, Washington DC, USA, see http://apps1.eere.energy.gov/buildings/energyplus/cfm/weather_data3.cfm/region=6_europe_wmo_region_6/country=GBR/cname=United%20Kingdom (accessed 14/10/2013).

Upshaw TA, Fisher WJ and Netemeyer EJ (2008) Natural oil polythiols and polyols – a life cycle comparison. *Proceedings of the ACS Green Chemistry and Engineering Conference*. June 25, 2008. Presentation available at: acs.confex.com/acs/green08/recordingredirect.cgi/id/231.

US EPA (United States Environmental Protection Agency) (2007) *Xylenes (Mixed Isomers)*. See http://www.epa.gov/ttnatw01/hlthef/xylenes.html (accessed 07/10/2013).

Wetherby (2013) *System Approvals*. Wetherby Ltd, see http://www.wbs-ltd.co.uk/wetherby-systems/system-approvals/ (accessed 07/10/2013).

Zeggelarr R (2010) *Surfactant for Phenolic Foam*. UK Patent No. 2440493, 10 March.

**WHAT DO YOU THINK?**

To discuss this paper, please email up to 500 words to the editor at journals@ice.org.uk. Your contribution will be forwarded to the author(s) for a reply and, if considered appropriate by the editorial panel, will be published as discussion in a future issue of the journal.

*Proceedings* journals rely entirely on contributions sent in by civil engineering professionals, academics and students. Papers should be 2000–5000 words long (briefing papers should be 1000–2000 words long), with adequate illustrations and references. You can submit your paper online via www.icevirtuallibrary.com/content/journals, where you will also find detailed author guidelines.