Transport Research Laboratory

Life Cycle Assessment of the Use of Solid Waste Materials in Highway Construction

by M Wayman, B Cordell & E Houghton

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FINAL PROJECT REPORT

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Project Record:	**Life Cycle Assessment of the Use of Recycled Solid Waste Materials in Highway Construction**
Prepared for:	**Transport Research Foundation**
Client:	**(Prof. Rod Kimber)**

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Contents

List of Figures

List of Tables

Executive summary

Sustainable consumption and production, leading to increased resource efficiency, is now high on the political agenda. Recycling and reuse of materials is now far more commonplace, not least in resource intensive activities such as the construction of infrastructure including highways. A vast range of secondary and recycled materials now commonly replace virgin aggregates; including both those which originate from deconstructed highways and other demolition projects, to those which arise in other waste streams quite unrelated to highways. The range of materials incorporated includes recycled asphalt planings, recycled concrete, ashes, slags, foundry sand, glass, plastic and rubber. Feasibility studies concerning the potential for the use of these materials are plentiful and some studies exist which have considered the environmental credentials of such practices. There are still opportunities available to improve the sustainability of such systems, especially where there are several different options available for recycling a given waste material. This particular study summarises work conducted to date and investigates the environmental performance of recycling systems which use glass to replace aggregate in bitumen bound surface layers, comparing it to other recycling options for glass including closed-loop recycling to new containers.

Improved resource efficiency is often coupled with improvements in other environmental impacts. This project investigated whether this was the case in the systems investigated for a number of environmental impacts which included:

- Abiotic Depletion
- Climate Change
- Ozone Depletion
- Summer Smog Production
- Human Toxicity
- Terrestrial, Aquatic and Marine Ecotoxicity
- Eutrophication
- Acidification

The technique used to analyse these impacts was Life Cycle Assessment (LCA), following the established standards for LCA (ISO 14040 & ISO 14044). LCA was chosen since it could be used to provide a quantitative analysis of the environmental impacts of the systems under consideration. It could also provide a suitable medium in which different scenarios, all leading to a given highway system as an end product, could easily be compared.

Overall the research yielded some interesting results and provided some recommendations as to how glass waste management practices could be improved in sustainability terms. The process of turning cullet into an aggregate substitute was found to be largely favourable when compared to producing virgin aggregate, across the range of impacts investigated. Material transport distances and modes of transport selected were found to be a key contributing factor in determining whether recycled glass or virgin aggregate based highway systems were environmentally favourable when compared to traditional alternatives. In terms of local government recyclate collection strategies it is recommended that co-mingled collections for glass are minimised, since the closed-loop recycling systems which can be pursued with colour-separated cullet yielded greater environmental benefits. This is the case even when colour separated cullet is exported to Europe for closed-loop recycling.

It is hoped that this study provides a framework by which dilemmas concerning other waste materials can be investigated and solved in the future.

Abstract

Achieving more resource efficient practices and the benefits that they yield are high on the political agenda. Practices which utilise solid waste materials as a substitute for virgin highway construction materials have long been integral to highway construction. This research summarises past studies which have been conducted into recycling waste materials in these applications. It also investigates the environmental credentials of using glass as a virgin aggregate replacement in bitumen bound surface layers using Life Cycle Assessment (LCA). The study concludes with a number of recommendations for recycling systems which utilise glass as a stone aggregate replacement material, in order to improve environmental performance overall.

1 Introduction

Sustainable development has never been higher on the political agenda. *Securing the Future* (Defra, 2005) sets out the UK Government's strategy for achieving sustainable development. It states four priorities:

- Sustainable consumption and production
- Natural resource protection and environmental enhancement
- Sustainable communities
- Climate change and energy

Recycling non-renewable resources[1], which is the central theme of this research, embraces each of these priorities to some degree, but is perhaps most aligned to achieving 'sustainable consumption and production', which is often summarised as 'achieving more with less', thereby increasing 'resource efficiency'. In essence this means using materials and energy efficiently and gaining the maximum output for the minimum input. Increasing sustainable consumption and production is often coupled with reduced emissions and energy use and a corresponding reduced contribution to climate change and other environmental impacts.

The recycling of non-renewable resources in highway construction and maintenance is a widespread and well established practice. A considerable amount of research exists which has investigated the feasibility of reusing highway derived and non-highway derived materials in highway applications. For example, Merrill *et al.* (2004) provided guidance on the use and specification of cold recycled materials in pavement maintenance and Carswell *et al.* (2005) investigated the feasibility of recycling thin surfacing back into thin surfacing. A review of the use of solid waste materials in asphalt pavements is provided by Huang *et al*. (2007) and a comprehensive overview of the use of both highway derived and non-highway materials has been conducted by Reid *et al*. (2007). The use of recycled and secondary aggregates is facilitated to some extent by Highways Agency documents including the *Specification for Highways Works* (particularly series 500, 600, 800, 900 and 1000) and section HD 35/04 of the *Design Manual for Roads and Bridges* on the *Conservation and the Use of Secondary and Recycled Materials*.

Now that the paradigm shift to achieving greater resource conservation in highway construction is underway, there still remains considerable scope to refine these practices further and improve them in sustainability terms. Opportunities for refinement particularly exist when the decision is made as to which application a particular reprocessed material should be used in. Often there are several options open to any given reprocessed material: 'closed-loop' recycling is usually one, where a material gets recycled to its original use, along with several 'open-loop' recycling options (sometimes called 'down cycling' options), where waste materials arising are reprocessed for incorporation into a product which was not the original use. Environmental assessment techniques such as Life Cycle Assessment (LCA) facilitate a comparison of the options on the grounds of environmental sustainability. This research evaluates the environmental sustainability of some of the options available for reprocessed glass using LCA.

1.1 Drivers to recycle

The overarching aspiration of achieving sustainable development has been reinforced by the implementation of policy interventions and legislation in many areas. The waste management and infrastructure sectors are not unaffected by this. Other factors also provide an impetus to recycle, such as the quest for greater efficiency, in both material

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[1] Minerals such as sand, gravel and stone, fossil fuels, metal ores, gypsum and clay are termed 'non-renewable' because they cannot be replenished within a human lifetime (Defra, 2005).

and energy terms. Efficiency in these terms usually translates to cost savings for manufacturers and material processors which are ultimately passed on in some form to the consumer. Increased material or energy efficiency almost invariably equates to environmental improvements too.

Some of the drivers to recycle are described in more detail in this section.

1.1.1 Policy & legislation

The *Strategy for Sustainable Construction* (BERR, 2008a) aims to provide the construction sector with a clear understanding of the Government's vision for achieving more sustainable practice in the construction industry by bringing together the diverse range of regulations and initiatives into a single document. The strategy also sets higher standards to help achieve sustainability in specific areas. Waste management practice in the industry is an integral part of the strategy. The principle target the strategy sets for waste management (or conversely resource efficiency) is a 50% reduction of construction, demolition and excavation (CD&E) waste to landfill compared to 2008 levels. This target excludes aggregates used for backfilling quarries, site restoration or those which are legitimately spread on exempt sites.

A variety of legislative and fiscal tools are proposed to increase resource efficiency rates and achieve lower levels of waste production. The 2008 budget resulted in an increase in the tax per tonne of inactive waste (the category which the majority of highway construction materials fall into) from £2 per tonne to £2.50 per tonne, with further increases a possibility due to the nature of the 'landfill tax escalator'.

A levy targeted at the extraction and use of virgin aggregates is also in place. From 2009, the tax levied will be £2 per tonne of aggregate extracted. The levy was introduced to address the environmental costs of quarrying that are not covered already by legislation. Environmental costs include noise, dust, visual intrusion, loss of amenity and damage to biodiversity. The levy attempts to account for the additional cost of these effects and thereby make the alternative use of un-levied (i.e. recycled and secondary materials) more financially attractive (BERR, 2008). Part of the revenue raised from the aggregates levy is put in to the Aggregates Levy Sustainability Fund which aims to promote environmentally beneficial practices, including the use of recycled aggregates (HM Customs & Revenue, 2003). The Government target for the use of recycled aggregates by 2016 is 60 million tonnes (ODPM, 2003). However, the Waste and Resources Action Programme estimates that the use of 70 million tonnes is not unfeasible (WRAP, 2008a).

Aside from the resource efficiency targets which are set specifically for the construction sector, targets also exist for waste produced from households. The current targets for the recycling and composting of household waste are set at 40% by 2010, 45% by 2015 and 50% by 2020 (DEFRA, 2007). Whilst this represents a particular challenge in terms of changing the general public's approach to waste disposal, in order to make more material available to be managed in a more sustainable way, it also represents a challenge for the waste management sector to find suitable facilities to reprocess the increasing volumes of household materials which are collected. Furthermore, suitable outlets need to be found for the reprocessed materials in terms of applications in which they can be used. Due to these factors, recycled household materials commonly end up in open-loop recycling routes, with resource hungry industries including the highway construction often being the recipient.

1.1.2 Embodied energy

By and large, recycling has an environmental benefit. These environmental benefits are principally achieved by conserving embodied energy by avoiding the use of virgin materials by using recycled materials in their place. Embodied energy is conserved in recycled products by using 'closed-loop' recycling i.e. recycling waste products to their original uses. Typically, the energy required to reprocess a waste material back to a state where it can then be reused for its original purpose is less than the original 'embodied' amount of energy which was required to process the virgin raw materials to the same point in the first place. Hence there is a net energy saving. A net energy saving usually corresponds to a reduction in environmental impacts since it requires less consumption of resources (e.g. fuels), less energy production and therefore a lower production of harmful emissions (CO_2, NO_x, and SO_x amongst others). This is just a broad indication, however, since using alternative energy sources for reprocessing may cause emissions levels to vary in quantity and type. Any use of alternative materials in reprocessing compared to production would also cause other environmental impacts to change. To analyse these differences in environmental impact an appropriate tool is required, we chose to use Life Cycle Assessment (LCA) for this purpose, as described in Section 1.2.

An indication of embodied energy savings achieved by the closed-loop recycling of different materials is indicated in Figure 1 (adapted from Sound Resource Management, 2001).

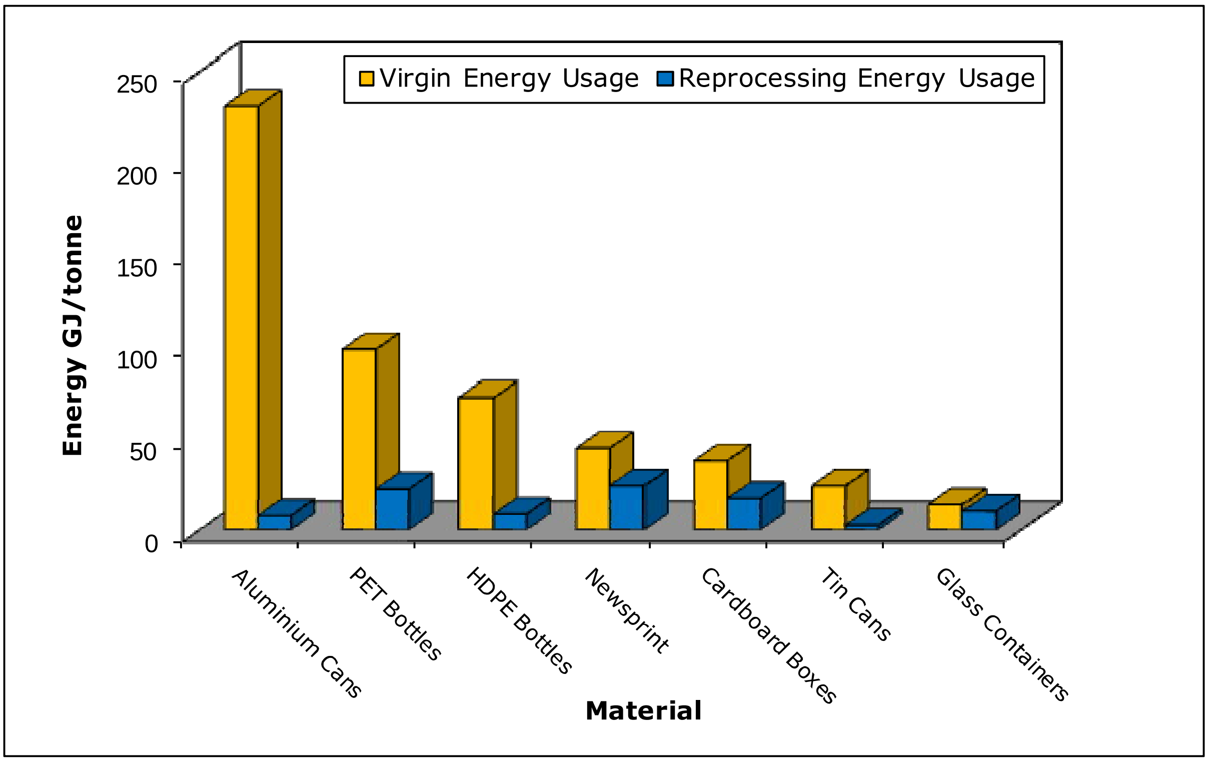

Figure 1. Indicative energy consumption for virgin production vs. reprocessing for a range of materials

1.2 Life cycle assessment (LCA)

Life cycle assessment (LCA) is a technique which allows the environmental impacts of a product or service to be assessed and quantified. It also allows product or service systems, which set out to achieve the same goal, to be compared on an environmental basis. The technique of LCA has developed alongside the increasing awareness of the need for environmental protection, starting in the 1960s and gathering pace in the last decade with the advent of formal agreements to reduce the impact of humankind on the environment, such as the Rio Declaration on Environment and Development in 1992, and the Kyoto Protocol which was adopted in 1997 and came into force in 2005 after it was ratified by the required number of national governments.

Life cycle assessment is a technique which is essentially borne from chemical engineering; process engineering to be more precise. The underlying principle of process engineering is to optimise the system in order to improve the outputs (in terms of yield, quality of product, or efficiency). The same principle underlies life-cycle thinking and the technique of LCA: evaluate (and ultimately optimise) the system to improve the environmental outcomes. Environmental solutions which result from applying LCA differ from more basic 'end-of-pipe' solutions, in the sense that they address the process to prevent emissions to the environment before they are produced, rather than addressing the emissions after they have already occurred. A life-cycle solution might, for example, be using an alternative raw material which results in fewer harmful emissions than the original material. Conversely, an end-of-pipe solution would be the remediation of water or soil which have been contaminated by heavy metals as the result of the process.

Furthermore, the pure science which underlies the LCA technique is chemistry. Inputs as raw materials, energy etc. are converted into products and emissions to air, water and land by chemical processes in the 'inventory analysis' stage of an LCA. The chemical interaction of these emissions on the environment is quantified in the 'impact assessment' stage of an LCA. The process in Figure 2, which is one of many which an LCA would facilitate the evaluation of, demonstrates some of the underlying chemistry.

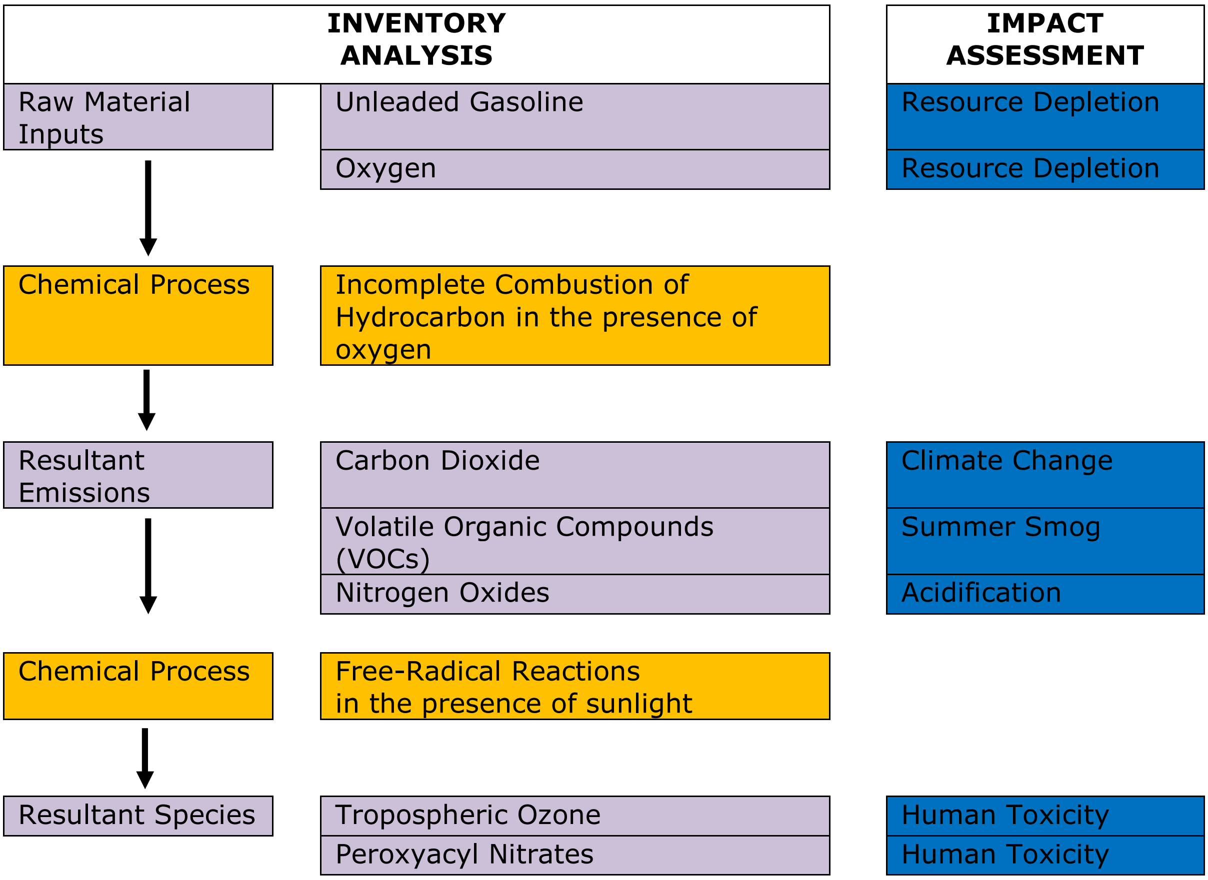

Figure 2. One of many series of chemical reactions analysed within a typical LCA

The established standards for conducting LCA are the ISO 14040 series (BSi, 2006). This series encompasses the following guides:

- ISO 14040 – Life Cycle Assessment – Principles and Framework
- ISO 14044 – Life Cycle Assessment – Requirements and Guidelines

These standards were followed throughout this research project.

1.3 Materials used for pavement construction

The traditional combination of bound and unbound aggregates used for pavement construction offers many opportunities for material substitution, using reprocessed materials in the place of virgin materials. Opportunities exist to replace the various grades of aggregate, from filler to the coarsest grades, which are required for the bound surface, binder and base courses of aggregate as well as unbound sub-base, bedding and drainage material. Opportunities also exist to substitute binding materials with recycled derivatives. The pozzolanic properties of silica-based waste materials make them possible substitutes for cement. The bitumen coating of recycled aggregates derived from asphalt sources is still partly active in subsequent applications, and can be used to offset the quantity of bitumen added to new asphalt mixtures (e.g. in Schiavi *et al*., 2008).

Document HD 35/04 of Volume 7 Section 1 of the *Design Manual for Roads and Bridges* summarises the recycled and secondary materials which are permitted in highway construction by application, as shown in Table 1.

The colour coding in Table 1 further defines the materials by source. Materials in red text are *secondary* materials and those in blue text are *recycled*. The distinction is made between secondary and recycled materials since this research was primarily concerned with recycled materials, for the reasons explained below. The list of materials is not exhaustive as far as the incorporation of recycled and secondary materials into highway construction goes; use of other materials can be considered by the Highways Agency on a case-by-case basis and may be added to HD 35 in the future.

Table 1. Recycled and secondary materials permitted in HD35/04

Application and Series Material	Pipe Bedding 500	Embankment and Fill 600	Capping 600	Unbound Mixtures for Sub-base 800	Hydraulically Bound Mixtures for Sub-base and Base 800	Bitumen Bound Layers 900	Pavement Quality Concrete 1000
Blast Furnace Slag	✓	✓	✓	✓	✓	✓	✓
Burnt Colliery Spoil	✗	✓	✓	✓	✓	✗	✗
China Clay Sand/ Stent	✓	✓	✓	✓	✓	✓	✓
Coal Fly Ash/ Pulverised Fuel Ash (CFA/PFA)	✓	✓	✓	✗	✓	✓	✓
Foundry Sand	✓	✓	✓	✓	✓	✓	✓
Furnace Bottom Ash (FBA)	✓	✓	✓	✗	✓	✗	✗
Incinerator Bottom Ash Aggregate (IBAA)	✓	✓	✓	✓	✓	✓	✓
Phosphoric Slag	✓	✓	✓	✓	✓	✓	✓
Recycled Aggregate (RA)	✓	✓	✓	✓	✓	✓	✓
Recycled Asphalt (RAP)	✓	✓	✓	✓	✓	✓	✓
Recycled Concrete (RCA)	✓	✓	✓	✓	✓	✓	✓
Recycled Glass	✓	✓	✓	✓	✓	✓	✗
Slate Aggregate	✓	✓	✓	✓	✓	✓	✓
Spent Oil Shale	✗	✓	✓	✓	✓	✗	✗
Steel Slag	✓	✓	✓	✓	✓	✓	✗
Unburnt Colliery Spoil	✗	✓	✗	✗	✓	✗	✗

Some important notes sit alongside Table 1 in the design manual. These are as follows:

1. Table 1 is for guidance only and reference must be made to the accompanying text (of HD 35/04) and the Specification (MCHW 1). Materials indicated as complying with the Specification (MCHW 1) for a particular application may not necessarily comply with all the requirements of the series listed, only particular clauses. For example in the 600 Series, Unburnt Colliery Spoil can satisfy the Specification as a general fill, but is excluded as a structural fill; and in Series 1000 recycled or secondary materials are not permitted within the running surface of pavement quality (PQ) concrete. Reference should also be made to the Specification (MCHW 1) for any maximum constituent percentages of specific recycled or secondary aggregates. For example, in the 1000 Series, the maximum by mass constituent of Recycled Asphalt is given under the limits for 'other material' (Table 10/2) within the Specification (MCHW 1).
2. There is no Specific or General Provision for the use of recycled glass as an aggregate in PQ concrete or Hydraulically Bound Mixtures due to the potential for deleterious alkali-silica reaction (ASR). However, its use may be permitted by the Overseeing Organisation if sufficient provisions to minimise the risk of deleterious ASR are included in the mixture design.
3. There is no Specific or general Provision for the use of steel slag as an aggregate in PQ concrete or Hydraulically Bound Mixtures due to the potential for volume instability. However, its use may be permitted by the Overseeing Organisation if sufficient assurance of volume stability is provided.

1.3.1 Secondary materials

Secondary materials are typically by-products of industrial processes which, if not utilised in an appropriate application, would otherwise be disposed of to landfill. Secondary materials can be further divided into those which arise from industrial processes (e.g. pulverised fuel ash) and those which arise from extraction processes (e.g. china clay waste, slate waste).

Beyond use in construction applications, other potential applications of the secondary materials listed in **Table 1** are limited. Hence, the environmental benefit of utilising secondary materials as a substitute for virgin materials in highway construction applications is fairly easy to realise, providing that the following assumptions are true:

- The transport undertaken from source to use is not excessive (ideally not exceeding that which would normally be undertaken by virgin materials);
- Any required material crushing is comparable to that which is required by a virgin aggregate;
- All of the impacts of the industrial process which produces the primary and secondary material are allocated to the primary material only (and none to the secondary material)[2].

The environmental gains associated with utilising secondary materials to replace virgin aggregates are mostly realised in terms of resource conservation. Two classes of secondary materials, granulated blast furnace slag and pulverised fuel ash, offer far greater environmental gains should they be used as binding materials as an alternative to traditional Portland cement. Research has identified the embodied energy of Portland cement to be in the region of 4.6 GJ per tonne, on average (Jones & Hammond, 2008). Using a substitute material in this way not only conserves the virgin resources used to make cement, but also reduces many of the environmental impacts which would be associated with this energy use; this energy use is far in excess of the transport, drying and crushing required to prepare the secondary materials for use.

Hence, where utilisation of secondary materials is concerned, the picture is fairly unambiguous in environmental terms for the materials discussed. Most of the materials can either be utilised in a construction application with environmental benefit or landfilled. In the case of secondary materials which demonstrate good pozzolanic properties, these materials should be utilised to substitute for conventional binding material wherever possible.

Steel slag provides an almost perfect example of the application of secondary material as a highway construction material. It can be collected easily from a small number of steel plants and is of a consistent quality. The UK has reached 100% efficiency in recycling steel slag, 98% of which is used in surface aggregates mainly in concrete or asphalt, although due to its properties it is particularly valued in asphalt pavements. The angular shape, hardness and roughly textured surface give steel slag the ability to substitute coarse aggregate in situations where stability of the mix may be questioned. Research by the US Strategic Highway Research Program (SHRP) and the University of Petroleum and Minerals in Saudi Arabia found that the steel aggregate improved the durability of the mix when the coarse aggregates were supplemented with limestone filler and fine aggregates (Huang *et al*., 2007).

1.3.2 Recycling municipal solid waste materials

Municipal solid waste (MSW) is the term applied to the multitude of waste materials which arise from households and other sources including streets, public parks and

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[2] Allocation is a contentious issue in LCA, particularly where the use of secondary materials are concerned. Allocation issues are dealt with for this study in Section 3.1.3.

gardens, the management of which falls under the jurisdiction of Local Government waste management authorities. As previously mentioned in Section 1.1.1, ever increasing recycling targets for materials arising from these sources means that alternative viable applications in which they can be used are always being sought, alongside the more traditional closed-loop options by which they are returned to their original use. As more potential applications for MSW materials are realised, other factors start to influence the choice of application which is actually pursued, including economics, quality of material arising, politics etc. The multitude of potential applications which are available to reprocessed MSW materials also presents an interesting conundrum in sustainability terms: which route is best? Since recycled materials arise from the quest for more sustainable resource use in the first place, it seems natural that the most sustainable application should always be chosen, but is this always the case? How does use as a highway construction material fare in the range of applications which are available in sustainability terms?

1.4 Existing studies concerning the use of recycled MSW materials in highway construction

Some commonly arising MSW materials and their potential applications, with a particular focus on highways applications, are explored in this section.

1.4.1 Recycled glass

Glass arises in MSW predominantly in the form of containers used for packaging. A non-exhaustive list of recycling options for MSW glass is as follows (WRAP, 2008b):

- Brick – Recycling to powdered glass can be used as a ‘fluxing agent’ during brick and tile manufacture;
- Water Filtration – Recycling to filtration media can replace more traditional sand based filters;
- Grit Blasting – ‘Glass grit’ is a totally inert material that can be used as an abrasive;
- Cement and Concrete – Ground glass can be used as a natural sand replacement and pozzolan. Hence it can be used to replace cement and fill material in concrete based products;
- Sand Replacement – Ground glass is a suitable replacement for bedding sand which is used to position paving slabs;
- Fibreglass Insulation – Glass is used extensively in this application;
- Container Glass – Closed-loop recycling to new glass containers;
- Unbound Aggregate - Crushed glass can be used in place of virgin unbound aggregates;
- Bituminous Materials – Glass can be used to replace up to 30% of aggregate in asphalt.

Huang *et al.* (2007) reported that in total around 33% (1.1Mt) of waste glass was recycled in 2003, with 66% of that (0.73Mt) being fed to other glass manufacture and 13% (0.14Mt) being used as secondary aggregates. However, the remaining 67% of glass was still sent to landfill.

HD35 states that although recycled glass could comply as a bulk fill and selected granular fill for earthworks applications, it is unlikely to be used in such circumstances due to the high volume requirements of these applications. In the USA, cullet has been used as a replacement for gravel in backfill operations. It was found to be different to work compared to primary material but the performance was similar (AggRegain, 2004). Recycled glass has also been used for pipe bedding in the USA as a replacement for primary aggregates. The compaction and handling of the glass was claimed to be comparable to that of the primary aggregates. The only comments concerned the guarantee of supply of the material for high volume used such as these (*ibid*.).

The use of waste glass for cement and concrete was reviewed extensively by Shi & Zheng (2007). One focus of the paper was to address the adverse effects of using glass as an aggregate substitute in Portland cement, with the aim of providing direction for further development in the use of glass as an appropriate substitute. Shi and Zheng concluded that using waste glass as concrete aggregate has a slight negative effect on the workability, strength and freeze-thaw resistance of cement concrete. The main concern surrounding the use of glass in concrete as an aggregate is its expansion and contraction causing the cracking of the concrete. pH control (below 12) is required to maintain the integrity of the concrete structure and keep the glass from corroding and potentially splitting the concrete. This can be achieved by replacing the Portland cement with fly ash, silica fume and metakaolin. Glass ground into powder exhibits the correct properties for it to be used as a cement replacement, although it again may be supplemented by fly ash, silica fume and metakaolin. The report concludes with a summary of the environmental and economic benefits of the use of glass as an aggregate and deems the possible benefits as ‘significant’ depending on the end use and the scale of production (*ibid.*).

The use of crushed glass in concrete also has a durability concern due to the alkali-silica reaction (ASR). The amorphous silica in glass reacts with the alkalis of cement forming expansive products of silica gel, leading to concrete cracking and premature deterioration. As a result of the ASR, crushed glass is not permitted by the SHW for use in pavement quality concrete. The susceptibility to ASR could be minimised with the use of low alkali cement and cement replacement materials. Research on glass concrete has indicated that expansion due to ASR is dependent also on the glass particle size, content, type and colour. Clear glass was the most reactive followed by amber, whereas the green glass caused no ASR expansion (Jin *et al.,* 2000).

In the USA, many highway agencies allow the use of crushed glass in hot mix asphalt with a maximum of 15% crushed glass with 100% passing the 9.5 mm sieve and a maximum of 6% passing the 0.075mm sieve. However, laboratory tests have indicated that the mixtures containing either coarse or fine crushed glass had lower Marshall Stability[3] values than the control. Therefore, there have been proposals to add requirements for moisture conditioning and tensile strength testing (Kandhal, 1993). A concern about using glass in asphalt mixtures is the adhesion between the bituminous binder and the smooth glass surface (Hassan *et al.,* 2004a). Furthermore, the potential for polishing militates against its use in the surface course layer. Trials in the UK (Nicholls and Lay, 2002) have demonstrated no significant stripping on mixtures with 30% glass, even after 3 years in service. Furthermore, anti-stripping agents can be used to improve the bond characteristics with glass particles Solaimanian *et al.* (1993).

Two LCA studies have been conducted which investigate the incorporation of glass into asphalt mixtures. A preliminary assessment of the use of glass in coated roadstone was made by the Arena Network (2003). The LCA was part of a wider study which investigated the benefits and barriers to the use of glass in bound applications. The study concluded that there were obvious benefits to using crushed glass as a replacement for stone aggregate, provided that transport distances were not excessive. There were some obvious limitations of the study, as stated by the authors, surrounding some of the data sources which were used. There are now additional limitations concerning the technologies that were considered, which have been updated since this study was conducted. The second study was of a completely theoretical nature

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[3] Marshall stability tests measure the maximum load that a cylindrical specimen of asphalt can accommodate before failing. A load increasing at 50.8 mm/min is applied to the cylinder which has been pre-heated to 60°C (The Shell Bitumen Handbook, 1990).

conducted by Chiu *et al*. (2008). This study concluded that the ecological burden associated with using glass in asphalt was approximately the same as for using traditional stone-based materials per kilometre of road laid, but, when maintenance cycles were considered, the ecological burden for glass-based asphalt was higher, since it required more frequent maintenance interventions. The basis for the maintenance cycles considered is unfounded, however, and no source of evidence is suggested for the cycles used. Existing studies (Nicholls and Lay, 2002) suggest that glass-based asphalt may be as robust as stone-based asphalt. Furthermore, some of the inventory data used is very approximate, e.g. data for the production of asphalt cement is approximated to the production of organic chemicals, which raises some questions about the accuracy of the study overall.

1.4.2 Recycled tyres

A range of recycling options for tyres is presented below:

- Retreads – This represents the closed-loop recycling option for tyres;
- Tyre Bales – Tyres are compacted into blocks and used for civil engineering applications;
- Artificial Reefs – Tyres are configured on the seabed to provide an artificial environment for sea life or waves for surfers;
- Shred – Suitable for use as an aggregate replacement in drainage or landfill engineering;
- Crumb Rubber – Used as a sand replacement on artificial sports pitches or as an aggregate in bituminous materials.

The Used Tyre Working Group (2005) estimates that the total waste tyre arisings in the UK amount to 0.49 Mt, with around 93% being recovered. In 2005, 51 million tyres were scrapped in the UK with 12% being re-treaded, 18% used for energy recovery, 33% recycled, 12% used in landfill engineering and 18% were physically re-used for other purposes. The high rate of recovery which has been achieved for tyres is mostly as a direct result of legislation; whole tyres were banned from landfill in 2003 as a result of the EU’s Landfill Directive. Around 50% of the weight of the scrapped tyre consists of rubber and this can be used in highway construction as an aggregate, back fill or in a number of other applications (Sherwood, 2001). However, the tyres do need processing before they can be used and there are significant differences between car tyres, which are generally synthetic rubber, and lorry tyres, which are generally natural rubber.

Rubber is added to asphalt mixtures to create rubberised asphalt for two main reasons; it can act as a binder modifier (as particularly fine particles) and also as a fine aggregate. Rubber modifies bitumen binder to create an asphalt mixture with improved elasticity and thereby increases the resistance to cracking and rutting when used in highway structures. Rubber can also be used as a direct replacement for virgin aggregate in bituminous mixtures with obvious benefits for resource conservation. Crumb is a fine grade of reprocessed rubber, with a size ranging from 5 mm down to powder. Rubber crumb is generally produced by crushing and grinding tyres at either room temperature (ambient crumb) or by freezing the tyres with liquid nitrogen (cryogenic crumb). Modified binder is produced by a wet process, whereby it is added directly to heated bitumen to create a modified bitumen suspension before adding it to aggregate. A dry process is used to produce rubberised asphalt, whereby crumb is added to the aggregate before any bitumen.

The use of rubberised asphalt has been most heavily advocated in the USA, where its use in hot mix asphalt was made mandatory by the Intermodal Surface Transportation Efficiency Act (ISTEA) in 1991. This mandatory requirement has since been revoked in 1996 for reasons of practicality, though it is still widely used in several states. In the UK, the predominance of the use of thin surfacing as opposed to hot rolled asphalt (HRA) in trunk roads has limited the use of rubberised asphalt, though there is still scope for its use in roads not under the management of the Highways Agency such as local or access roads.

Research has been conducted by TRL Limited in conjunction with EnviroCentre for the Waste and Resources Action Programme (WRAP) to produce environmental profiles for tyre-based materials (as yet unpublished). The environmental impacts of the production of tyre-based materials were compared to the production of the conventional materials which they substitute. The materials compared were as follows:

- Retreaded tyres to new tyres;
- Tyre bales to gabions;
- Tyre shred to aggregates (as used in landfill engineering).

The research found tyre-based materials to be ecological favourable (in terms of emissions contributing to climate change). Results comparing tyre crumb to virgin aggregate or sand use were not obtained, though the energy input which is required to reduce waste tyres to particles which are below 5 mm via mechanical or cryogenic means is likely to be considerable.

1.4.3 Recycled plastic

Plastic is a term which encompasses a wide range of synthetic and semi-synthetic polymers, each one providing a different group of properties and suitability for a different range of applications. The range of polymers in use provides a challenge for sustainable waste management, in the sense that it is hard to keep different polymer types segregated or separate them once they have become mixed, though this has improved with labelling initiatives in recent years.

Plastic arises in MSW predominantly in the form of packaging containers for food, film and bags. A non-exhaustive list of recycling options MSW plastic is as follows (WRAP, 2008c):

- Packaging - Recycled PET and HDPE is increasingly used in primary packaging by retailers and manufacturers for bottles and trays. This represents a closed-loop recycling option for some polymers;
- Construction - Recycled plastic is widely used in mainstream construction products such as damp proof membrane, drainage pipes, ducting and flooring, and more novel applications such as kerbstones;
- Landscaping and street furniture - Walkways, jetties, seating, bins, fences and signs are increasingly being made from recycled plastic which is a durable, low maintenance and a vandal resilient solution;
- Textile fibre/ clothing - Polyester fleece clothing and polyester filling for duvets, coats etc is frequently made from recycled PET bottles (e.g. soft drink and water bottles);
- Bin liners/ refuse sacks - Plastic film from sources such as pallet wrap, carrier bags, and agricultural film are made into new film products such as bin liners, carrier bags and refuse sacks on a large scale. This also represents as closed-loop recycling option for some polymers;
- Aggregate – Use as an aggregate substitute provides a suitable outlet for mixed plastics. It can also be used as a binder modifier.

The total amount of plastic waste arising in the UK is estimated at 5.9 Mt per annum. Just over half (3.1 Mt) of this is plastic film, with the other half (2.8 Mt) being dense plastic. About 2.3 Mt of the total arises in the municipal waste stream, around 2.5 Mt in the commercial waste stream, 0.8 Mt in the industrial waste stream and 0.1 Mt in the agricultural waste stream (ERM & Golder Associates, 2007). Approximately 22% of plastic packaging, the predominant type of plastic arising in MSW, was recycled in 2005.

Potential uses for recycled plastic in highway construction include as a lightweight aggregate, as a binder modifier, in geogrids or separation membranes or in soil stabilisation. Hassan *et al.* (2004b) indicated that asphalt binder course incorporating plastic aggregate showed adequate fatigue and deformation resistance. However, the mixture showed a degree of moisture sensitivity which would limit its use in surface courses. Concrete incorporating plastic aggregate, "Plas-Crete", is a substitute for conventional concrete products in various applications of low-density insulating concrete, moderate-strength lightweight concrete, as well as structural lightweight concrete.

Aggregates provide a good potential recycling outlet for mixed plastic sources, however take-up of this avenue has been limited to date since no specification for the use of waste plastic currently exists in the UK. Plastics would be incorporated into bituminous mixtures in processes similar to the dry and wet processes which are used to incorporate rubber. LDPE can be used to substitute a portion of between 15 and 30 % of aggregates.

The use of plastic as an aggregate in concrete has been explored by Siddique *et al*. (2007). This paper considered the use of plastic aggregates as replacements for conventional concrete aggregates and reports that when compared to conventional concrete, the bulk density was reduced by between 2.5% - 13% for concrete containing plastic aggregates when the plastic contained between 10% to 50% recycled plastics. There was a reduction in the compressive strength of the concrete as the concentration of plastic in the concrete increased. The splitting tensile strength of the product made with post consumer plastics was found to decrease with the increase in the percentage of plastic aggregates. Concrete containing more plastic aggregates was found to exhibit greater ductile properties than conventional concrete, highlighting a possible way of reducing the formation and propagation of cracks through the concrete (*ibid*.).

Another partially polymer-based, fairly complex material which cannot easily be reprocessed to its original use is carpet. Carpets have been used as an additive for concrete reinforcement. Shmidt and Cieślak (2008) investigated the use of carpet recyclate by assessing surface properties of components in the carpet-concrete composite. Surface energy evaluation of the different components of the composite illustrated that carpet recyclate with both fibre types forms strong, water-resistant bonds with the concrete. The final results of the study were positive given the early stages of development of this type of material (*ibid*.).

To date, no life cycle assessment studies have explored the environmental performance of using waste plastic materials to replace a portion of the virgin aggregate or binder material in highway structures.

1.5 Choice of material to evaluate in this study

Two criteria were considered in order to select an appropriate waste material from those discussed above to be taken forward in research. These were:

- Scale of use – how widespread is the use of the material in highway construction?
- Range of options – are there viable options to compare with the use of the material for highway construction?

Of the three MSW waste materials considered, the most widely used in highway construction in the UK is glass. In the USA, the more widely used material is likely to be tyres. Waste plastic utilisation in highway applications is relatively low. This is partly due to the wide range of options that are open to plastic recycling, which is possibly due to its relatively high value as a crude oil derivative which is reflected in it value as a recyclate. All three materials have viable alternative recycling options, other than in highways applications, there is therefore suitable scope for a comparative study in which different recycling options are compared (at least one closed-loop and one open-loop option).

A useful investigation could have been conducted into each one of these three materials. It was, however, decided to investigate glass due to its more widespread and advocated use (by HD/35) in the UK.

1.6 Glass waste management in the UK

In the UK, there are essentially three main mechanisms which are used to collect municipal glass recyclate which derives principally from households, these are:

- Segregated colour collections in ‘bring’ banks;
- Segregated colour collections by door-to-door kerbside collections;
- Mixed colour collections by door-to-door kerbside collections.

The decision as to which strategy to pursue is largely down to individual local authorities. Colour segregated glass collections generally go to closed-loop recycling sites to new glass containers. Mixed glass is used in open-loop applications, mainly to aggregate. A colour imbalance exists in the UK between that which is produced in the UK and that which is present in the market, which includes imported glass in addition to the UK produced glass (Waste Online, 2004). Clear and amber glass are predominantly produced in the UK, mainly for spirit bottles and jars, however, at present around twice as much green glass exists in the market than is produced in the UK, largely due to imports of wine bottles from the rest of Europe. Excesses of green cullet (which is the term for glass destined for recycling) have existed in the past. In the UK presently, attempts are being made to recycle as much of each coloured cullet as possible into more containers via closed-loop systems, some of which is conducted overseas. An alternative option for the excess green cullet would be an open-loop recycling option.

The nature of the UK’s glass waste management situation raises some interesting environmental quandaries:

- What is better for the environment: closed- or open-loop recycling options?
- What is the best thing to do with excess green cullet: open-loop recycling or export?
- Should segregated or mixed glass collections be maximised?

These issues and more were investigated in the course of this research.

2 Goal and scope definition

This chapter describes the LCA study that was carried out in accordance BS EN ISO 14044 (BSi, 2006). The section headings used are as recommended by the standard in order to correctly document the study.

2.1 Goal

The goal of this study was to evaluate the environmental sustainability of using reprocessed glass as a component of highways, replacing the conventional stone aggregates in bituminous mixtures. The use of waste glass was compared to the use of traditional aggregate in varying quantities and in closed-loop recycling to new glass bottles both domestically and abroad.

2.2 Scope of the study

2.2.1 Functional unit

The ‘functional unit’ is the quantitative flow that the product or service provided by the system being investigated is scaled against. In this study, the functional unit is a 1km long, 7.3m wide stretch of single carriageway.

The flexible pavement surface of the highway is constructed of 3 layers:

- The base course has a thickness of 100mm and is a 0/32 dense coated macadam 40/60 containing 4% bitumen and 5% fines. This corresponds to a total of 1693 tonnes of material in 1 km. [BS4987 part 1, 5.2] (British Standards Institution, 2005).
- The binder course has a thickness of 60mm and is a 0/20 dense macadam 40/60 containing 5% bitumen and 5% fines. This course is 942 tonnes in total. [BS4987 part 1, 6.5] (British Standards Institution, 2005).
- The surface course has a thickness of 46mm and is 0/14 close graded hot rolled asphalt (HRA) containing 7% bitumen and 4% fines. This course is a total of 649 tonnes. [BS4987 part 1, 7.3] (British Standards Institution, 2005).

The service life for the purposes of the study is assumed to be 40 years, which is in-keeping with literature on the subject (Stripple, 2000). Maintenance of the pavement has been deemed outside the system boundary, as it is assumed that a pavement containing glass will have a similar durability to a pavement made of more traditional materials, and will therefore not require more or less maintenance than a normal highway.

2.2.2 System boundaries

The system boundaries determine which stages of the life cycle and contributing product life cycles are included in the foreground of the study and which are in the background. Since this is a comparative LCA it was decided to exclude areas of the system which were not affected by the material substitution, since no changes in the impacts of the system will result.

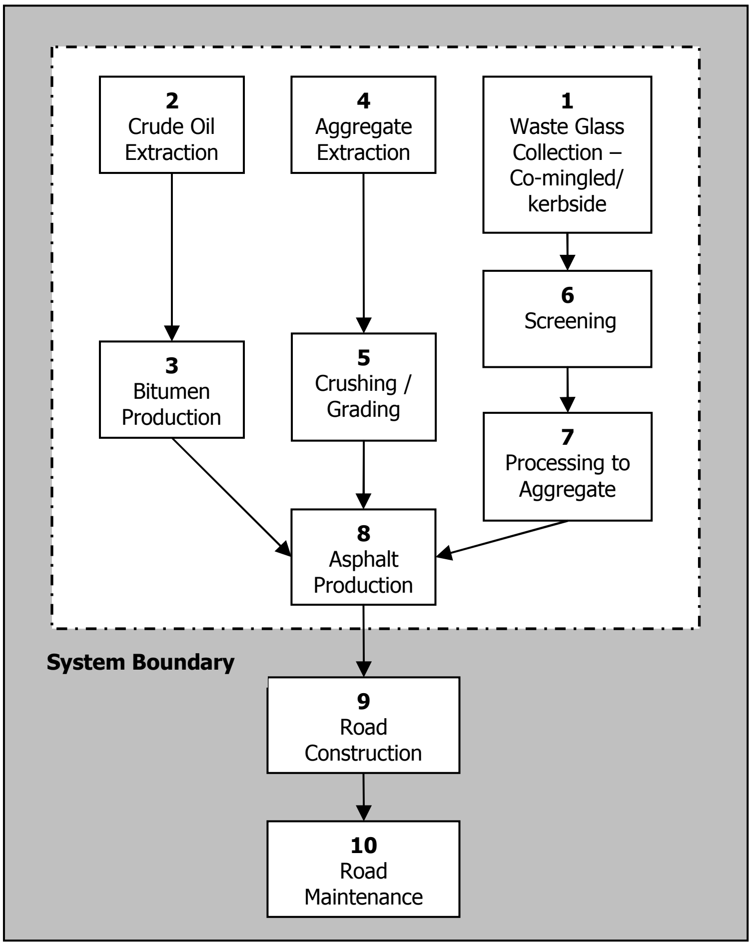

Figure 3. Boundary of the glass to aggregate study

Table 2. Study stage descriptions

Stage	Description
1 – Waste Glass Collection	Removal of glass from the waste stream and diversion to recycling. Can be separated, mixed glass, co-mingled or business collection.
2 – Crude Oil Extraction	Process of locating, drilling and extracting crude oil.
3 – Bitumen Production	Fractional distillation of crude oil into products.
4 – Aggregate Extraction	Quarrying of aggregate materials e.g. sand, gravel, limestone.
5 –Crushing/Grading	Processing raw aggregate into desired size and shape characteristics.
6 – Screening	Removal of contaminants from glass waste stream.
7 – Processing to Aggregate	Crushing and washing of glass bottles to a uniform size/range.
8 – Asphalt Production	Heating and mixing of components and additives to coat aggregate with bitumen and produce asphalt.
9 – Highway Construction	Preparation of site, laying and compacting of asphalt layers.
10 – Highway maintenance	Periodic maintenance of highway surface. Planning and resurfacing.

Figure 3 shows the highway system model and the system boundary. Highway construction and maintenance is outside the boundary as communication with industry, contractors and literature has determined that the impact of glass on the processes of laying and maintaining (Hannah, A., 2008; Hills, M., 2008), and indeed the potential recycling of the asphalt (Day, A., 2008), is not significantly different compared to virgin aggregate. It has even been reported, anecdotally, to have benefits, specifically that the glass holds heat energy longer than primary aggregate so it can make the asphalt easier to work in cold conditions and allows more leeway in laying times.

Collection of the waste glass is included within the system boundary. This is also included in the closed-loop glass recycling system as there are differences between the two systems. Glass collection varies greatly between local authorities and councils. Waste glass can be collected in colour separated bottle banks, colour separated doorstep collection, mixed colour doorstep collection, co-mingled doorstep collection and business collections from restaurants and bars. For the glass to highway aggregate system, the glass originates from business collections and material recycling facilities (MRFs) where co-mingled doorstep collections end up. As a high proportion of the waste glass comes from MRFs, this will be modelled as the pathway.

Collection impacts for the systems were modelled data (adapted from Wayman, M., unpublished data). Recycling systems can vary greatly in their operation. Detailed analysis of these methods from is outside the scope of this study, hence average figures were used for this process.

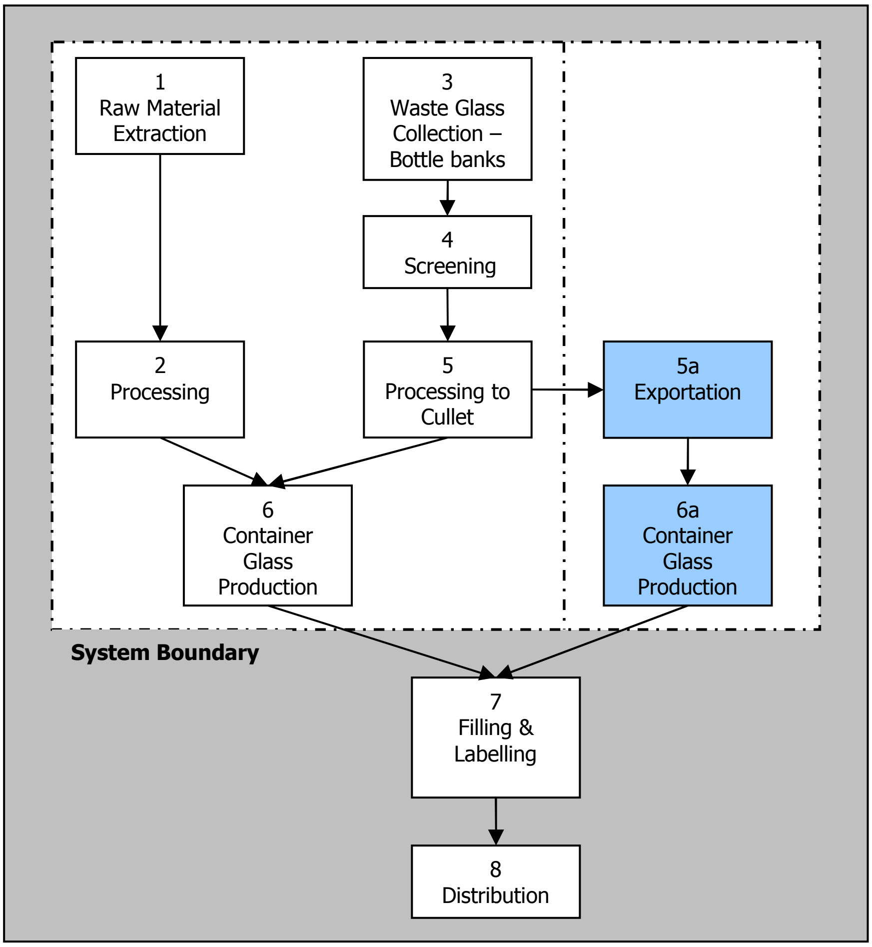

Figure 4. Closed-loop glass recycling system

Figure 4 shows the system diagram for the closed-loop glass recycling. The system in focus ends after new bottles have been produced but before they are used again as containers. Table 3 explains each of the steps in more detail.

Table 3. Closed-loop glass recycling stage description

Stage	Description
1 – Raw Material Extraction	Mining of limestone, dolomite, silica sand etc.
2 – Processing	Crushing, grading and screening of raw materials into useable form for glass manufacture.
3 – Waste Glass Collection	Removal of glass from the waste stream and diversion to recycling. Can be separated, mixed glass only.
4 – Screening	Removal of almost all contaminants from glass waste.
5 – Processing to Cullet	Crushing and washing of glass bottles to a uniform size/range.
5a – Exportation	Freight of cullet by container ship.
6 – Container Glass Production	Mixing of the raw materials and recovered glass & processing into container glass in the UK.
6a – Container Glass Production	Mixing of the raw materials and recovered glass & processing into container glass (after export).
7 – Filling & Labelling	Filling of the containers in a bottling plant and adhesion of labels.
8 – Distribution	Transport of full containers to retailers.

The system boundaries are drawn to include all essential processes and therefore environmental impacts of the system under investigation.

2.2.3 Scenarios

LCA facilitated the comparison of a number of different scenarios. This allows greater appreciation of the system under investigation, its associated impacts and the key contributing processes. It allows for the analysis of 'hotspots' (areas of the life cycle with high environmental burdens) and 'tipping points' (where environmentally advantageous systems become disadvantageous because of subtle changes) to be identified.

This study was primarily concerned with the investigation and comparison of impacts of substituting glass for virgin aggregate in the binder course of a highway surface. The following scenarios were explored during this process to build up an appreciation for the systems under study:

- Different proportions of glass in the asphalt mixture from 0% to 30%. This is the range of glass concentrations available from common asphalt suppliers.
- Comparison of the production of aggregate from virgin material and waste glass in isolation from the rest of the system.
- The differing processes for sorting glass to the applicable standards for re-melting and use as an aggregate.
    - The higher standard cullet required by furnaces for glass production was diverted into aggregate use in a scenario to determine the theoretical affects of doing so.
- Closed-loop glass recycling.

- The UK exported an estimated 270,000 tonnes of cullet in 2006, due to the imbalance in the colour of glass entering the UK waste stream and the domestic glass production. Closed-loop recycling of glass was modelled in the UK and with the added transport of exporting cullet to Portugal (WRAP, 2007).
- The model was designed to extrapolate the distance at which the environmental costs of exporting the glass match and then surpass the environmental benefits of using recycled cullet in glass production.

2.2.4 Life cycle impact assessment methodology

There are a number of Life Cycle Impact Assessment (LCIA) methodologies suitable for this study. LCIA is an area of constant research and development and the choice between the existing methods comes down to a preference for particular methods within the industry that the LCIA is taking place. The most recent expert revision (December 2007) of the CML2001 characterisation method has been used in this study. The CML assessment methodology was developed by the University of Leiden, Netherlands.

Alternative impact assessment methods can be applied to the model to map disparities between them.

The impacts included in this study are:

Abiotic Depletion (AD)
Abiotic resources are 'natural resources', including energy resources which are regarded as non-living. Examples of abiotic resources include ores and fossil fuels. The Abiotic Depletion Factor (ADP) is determined for each extraction of minerals and fossil fuels, and is measured as [kg of Antimony equivalents] / [kg extraction]. The classification method is based on that originally developed by Heijungs *et al*. (1992). Antimony is used purely as a reference material to facilitate use of the indicator for comparative purposes. The rate of extraction divided by the ultimate quantity of reserves for resources used in the system are always equated to the reference ratio for Antimony (Guinée *et al*., 2002).

Climate Change (GWP)
The impact of human emissions on the radiative forcing (i.e. heat radiation absorption) of the atmosphere. This effect may have adverse impacts on the health of humans, animals, terrestrial and aquatic ecosystems, and biochemical processes. Anthropogenic emissions enhance radiative forcing above natural levels, causing the temperature at the Earth's surface to rise which is thought to affect climate. The characterisation factors developed by the Intergovernmental Panel on Climate Change (IPCC) that are used in this category are expressed as the Global Warming Potential for a time horizon of 100 years (GWP_{100}), and is measured as [kg carbon dioxide] / [kg emission]. Houghton *et al*. (1996) developed the original method by which the effect scores for greenhouse gases are calculated.

Ozone Layer Depletion (ODP)
The stratospheric ozone layer can be thinned by releases of certain anthropogenic emissions. Reduced levels of ozone in the stratosphere allow higher levels of UV-B radiation to reach the Earth's surface from the Sun. Elevated levels of UV-B can have harmful impacts on human health, animal health, terrestrial and aquatic ecosystems, biochemical cycles and on materials. The World Meteorological Organisation (1991) defines the ozone depletion potential of different emissions relative to that of CFC-11, measured as [kg CFC-11] / [kg emission].

Human Toxicity & Ecotoxicity (HTP, MAETP, FAETP & TETP)
These 4 impact categories are concerned with the impacts of toxic substances on human health, marine and freshwater environments and terrestrial ecosystems. The indicators

include scores for emissions to air, water and soil. The characterisation factors are calculated to describe the fate, exposure and effects of toxic substances in the various environments. Factors used in the CML baseline v2.1 model were calculated using the Uniform System for the Evaluation of Substance (USES-LCA) model (Huijbregts *et al.*, 2000). For all factors, toxicity levels of substances are expressed as [kg 1,4-dichlorobenzene equivalents] / [kg emission].

Photochemical Oxidation (Summer Smog Production) (POCP)
Photo-oxidant formation is the formation of reactive chemicals such as ozone by the reaction of sunlight with certain primary air pollutants. These reactive chemicals can harm the health of humans, ecosystems and crops. Photochemical reactions of volatile organic compounds (VOCs) and Carbon Monoxide in the presence of UV light from the Sun and Nitrogen Oxides (NO_x) create 'summer smog'. Photochemical ozone creation potentials (POCPs) indicate the capacity of VOCs to produce ozone, and are calculated for the CML impact assessment method by a UN Economic Commission for Europe (UNECE) working group trajectory model (UNECE, 1991). POCPs are expressed in [kg ethylene equivalents] / [kg emission].

Acidification (AP)
Acidification causes a wide range of impacts on soil, water resources, organisms and ecosystems and materials. The main acidifying nutrients are SO_x, NO_x and NH_x. Notable examples of its impacts are the lowering of pH levels in Scandinavian lakes, causing the death of fish, and the reaction of acidified rain with building bricks, causing them to crumble. The RAINS 10 model is used to calculate acidification potentials (APs) of emissions to air in the CML baseline method. The RAINS method was developed to support treaty decisions on acid precipitation in Europe (Huijbregts, 1999). APs are expressed in [kg SO_2 equivalents / [kg emission].

Eutrophication (EP)
Eutrophication is otherwise described as 'nutrient enrichment', whereby elevated levels of nitrogen and phosphorous are produced. Eutrophication may cause shifts in species composition and elevated levels of biomass production in certain environments. High nutrient concentrations in water may make it unsuitable for drinking. Elevated biomass production in marine environments may deplete dissolved oxygen concentrations, and kill off other organisms. A typical example of this would be when 'algal blooms' occur in surface waters that receive run-off from fertilized farmland. Nutrification potentials (NPs) used in the selected impact assessment methodology are based on a stoichiometric method developed by Heijungs *et al*. (1992), whereby substances are assessed by their potential to produce organic matter relative to phosphate (PO_4). Values for this impact category are expressed as [kg PO_4 equivalents] / [kg emission].

2.2.5 Assumptions

Key assumptions in this study relate to the technical properties of the glass once in asphalt. Communication with researchers, contractors and manufacturers (Day, A., 2008; Hannah, A., 2008 & Hills, M., 2008) of asphalt containing a proportion of glass has established the assumptions that the inclusion of glass has:

- No affect on the process of asphalt production;
- No difference in equipment requirements for laying the road courses;
- No influence on the processes involved in laying the road courses;
- No difference in the maintenance requirements;
- No change in the handling of the asphalt when it is removed from the highway and or on its ability to be recycled.

2.2.6 Cut-off criteria

The inclusion of inputs and outputs in an LCA study can be assessed on the basis of mass, energy or environmental significance. If a particular input/ output falls short of the established cut-off criteria for the study, then the assumptions associated with the decision will be clearly documented. The cut-off criteria applied to this study was 5%.

3 Inventory analysis

3.1.1 Data sources used by life cycle stage with data quality assessment

Aggregate production was based on the EcoInvent report No. 7 (Kellenberger et al, 2007). Bitumen production data was gathered from the Eurobitume partial eco-profile of bitumen (Eurobitume, 1999) and the EcoInvent database entries which build on this original study were used.

Asphalt production, essentially the controlled mixing and coating of the aggregates and fines with bitumen was modelled based on the European average level of technology from the EcoInvent report No. 7 (Kellenberger et al, 2007). It was adapted to include the UK energy mix and the quantities and materials as used.

The data on the environmental impacts of the different transport systems used in the model come from the EcoInvent report No. 14 (Spielmann et al, 2007). The different specifications (i.e. capacity) of the vehicles used in the system were gathered from communication with contractors and literature in the public domain. All vehicles were assumed to be of a 'Euro 3' emissions standard and therefore less than 2 years old. This dataset was chosen due to the better quality data available for the emissions of these vehicles under various conditions of use.

Glass aggregate production information was supplied by Day Aggregates (Day, A., 2008). Specific information about Day's glass reprocessing facilities at Brentford in Middlesex was supplied. This included the amount of electricity and diesel used per tonne of glass aggregate produced. They were also able to provide details of the transport distances and vehicles used for transport to and from their site. Levels of contamination in the glass waste received, the composition and the disposal routes for the contaminants were explored where possible.

Organic flocculants are used in the on-site water treatment during the glass crushing process. The purpose of this in the process is to coagulate the suspended particles in the use water so that they sink in the settling tank and are able to be extracted. Unfortunately no data could be found that covers this substance or similar substances however, the aforementioned ISO 14044 cut off of 5% applies here due to the very small quantity being used.

Glass recycling for remelt into container glass can be processed in a couple of different ways. Communication with a number of waste glass handlers revealed that little or no glass from MRF sites are accepted into furnaces for remelting into container glass due to the high levels of contamination and the larger variety of contaminant material. For the reprocessors, it is economically unattractive to have to pass the material through their sorting system a number of times to obtain suitable cullet, compared to accepting less contaminated glass from separated bottle banks or sorted door step schemes.

An optical sorting method, which involves a higher level of technology, is able to distinguish between glass of different colours and separate them during the screening process. However, for reasons of energy efficiency (and therefore economy) this type of technology is not generally used to colour sort fully co-mingled glass collections, but instead to remove odd contaminants from single colour streams. Optical sorters did not feature in this particular study.

3.1.2 Calculations

A new model for the UK energy mix was compiled for the project. As specific life cycle impact data for UK power stations is not available, the standard European processes were used but their contribution to the energy mix was changed. The environmental intensity of the country's electricity production can have large impacts on the model since electricity use is integral to many of the other processes which are included.

Table 4 below shows the data that was used from BERR (2008b) Section 5.6: Commodity Balances from the (BERR Digest of UK Energy Statistics (DUKES) July 2008.

Table 4. Commodity balances used to generate energy mix

Primary and secondary production *(Gwh)*	
Nuclear	63,028
Hydro	5,088
Wind	5,285
Coal	136,545
Oil	4,641
Gas	164,473
Other renewables	10,505
Other	3,032
Total production	**392,597**

The volume of electricity supplied to the grid could have been taken as representative of the proportions of energy produced. However a certain amount of electricity produced by each generation method is used on site to power the infrastructure of the generating plant. These 'overheads' mean that the not all of the electricity produced makes it onto the grid. Hence it was decided that the total electricity produced as indicated in 'commodity balances', which include this overhead production were a more appropriate source of data for this LCA.

3.1.3 Allocation procedures

Allocation is the term used to describe the apportioning of inputs and outputs/ impacts of a process to the products in the system under study. When a number of products derive from a single process, and some of these products leave the system to enter another system, the inputs and outputs must be divided between the products to reflect the impact that they have truly had as closely as possible. The ISO 14040 standards have guidelines for allocation procedures. The initial recommendation is to use 'system expansion' with a view to isolating the individual sub-processes, therefore identifying the actual inputs and outputs to the sub-processes and avoiding allocation in the first place. Where this is not possible, the inputs and outputs need to be apportioned to attribute them to the different products based on the physical relationships between them (e.g. mass), as dictated by the system. Failing this, economic value of the products can be used as a basis for allocation. Allocation on the basis of economic value is the least favoured option and was not necessary in this study.

The multi-output system of crude oil refining using fractional distillation, of which bitumen is a product, is a classic allocation conundrum for LCA. The large number of co-products produced by the fractional distillation process requires different quantities of input energy to deliver them as useful end products and the sub-processes are difficult to separate out. There are few sites in the UK whose main remit is to produce bitumen only but the very limited data available for these sites which refine bitumen only forced their exclusion from the model. Allocation on the basis of mass was therefore used for bitumen to isolate it from the production of other products in the fractional distillation of crude oil. Burdens associated with graded aggregate products arising from multi-product quarries are also allocated on a mass basis.

Glass enters the system, both for aggregate and remelt, as a waste product. On this basis, it is determined that the glass does not bear the environmental burdens of its former production, and starts with a 'zero' impact balance when it enters the system. The glass was originally produced to fulfil an initial purpose, once that purpose has been fulfilled the glass becomes redundant for the first time. The impacts associated with this initial use of the product are therefore allocated to this original system only.

4 Impact assessment

4.1.1 Whole highway

The three layers that make up the highway have different levels of material use and impact contribution. Figure 5(A) shows the relative material consumption, and therefore Figure 5(B) shows the relative impact contribution for a highway constructed with traditional virgin aggregates. This analysis highlights that the while the binder course is responsible for a higher material consumption than the surface course, there is a much smaller difference in impact contributions between the layers. This difference is due to the proportions of each material in the different courses and their associated impacts as shown in Figure 5(C). The binder course is 14mm thicker than the surface course but it only contains approximately 1.5 tonnes more bitumen. The surface course asphalt mix contains 7% bitumen compared to the 5% bitumen in the binder course.

Figure 6 illustrates the percentage change in impacts of the highway materials when the binder layer contains 15% and 30% recycled glass material for the functional unit, when compared to a standard highway construction. All scenarios were modelled with transport of the glass in a vehicle of the specification that is most commonly used (20-26 tonne HGV). All of the environmental impact categories show an increase for the inclusion of glass except for AD and GWP. GWP decreases by just under 0.3% for the 30% glass mixture. This is a real saving of 0.9 and 1.9 tonnes of CO_2 equivalent GHG emissions for 15% and 30% glass concentrations respectively.

To put this figure in to context, if the 0.3% figure can be considered equivalent to a kilometre stretch of two lanes of motorway and we apply this to the recently completed M25 junction 12-15 widening (approximately 54km of new asphalt), the use of a 30% glass mixture would have saved the equivalent of 102 tonnes of CO_2 being released. This is the same saving that would be made by 46 people giving up road transport for a year[4].

Figure 7 shows the same scenario as Figure 6 but with a change to the specification of truck. In this scenario, the truck is the same that is used in the model to transport the aggregate from processing to the asphalt plant (32 tonne HGV). Here benefits associated with using glass are realised in 4 of the 10 impact categories. GWP decreases by 0.7% for a 30% which would mean that 5.0 tonnes of CO_2 equivalent emissions are not released into the atmosphere.

To repeat the example given previously of the M25 widening, the use of a 30% glass mixture in this transport scenario would have saved the equivalent of 270 tonnes of CO_2 being released. In this instance, more than 122 people would be taken off the road[5].

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[4], AEA (2008) reported a range of between 1.5 -2.5 tonnes per capita per year for road transport for different UK Regions. A figure of 2.2 has been used as a rough average.

[5] AEA (2008) As above.

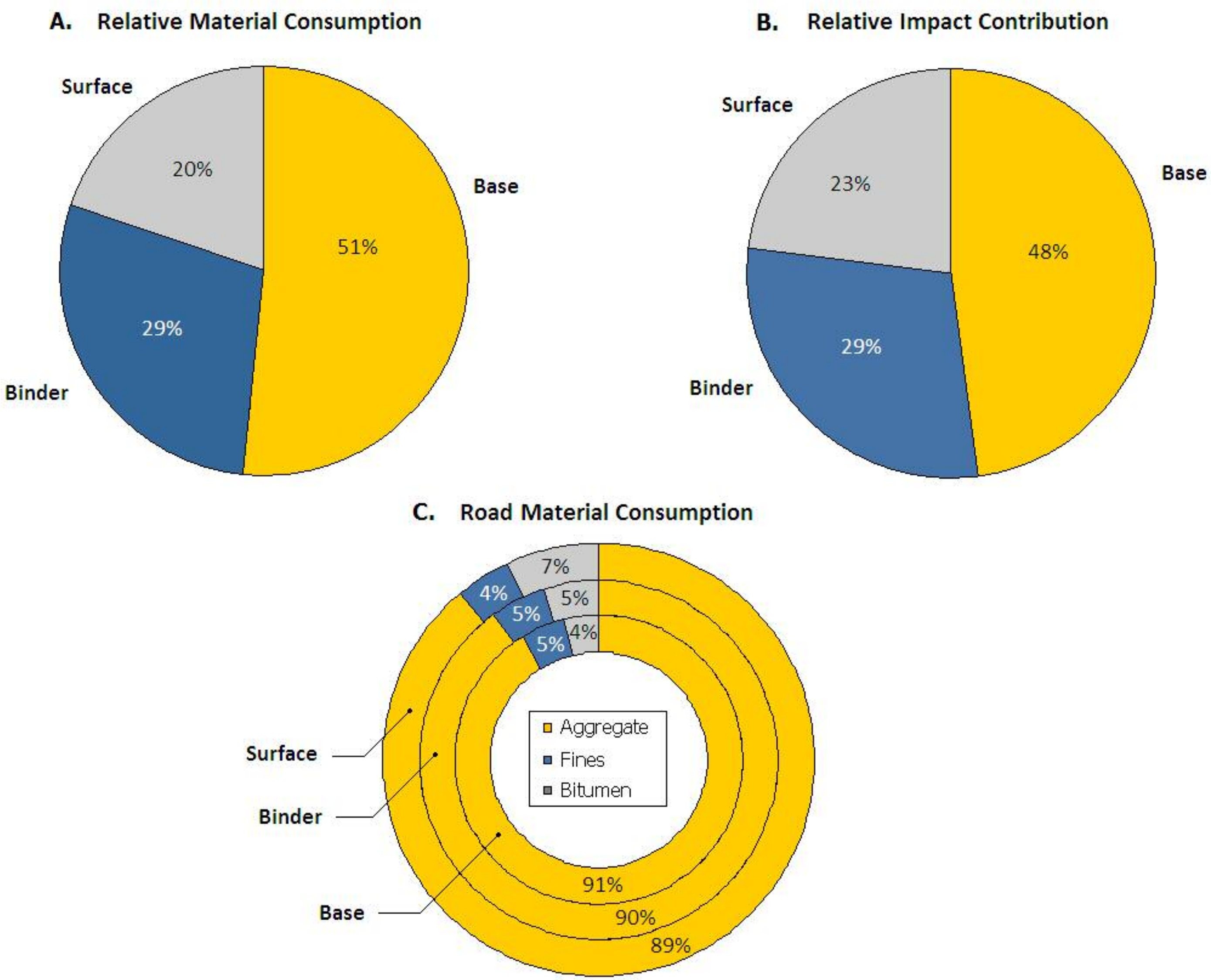

Figure 5. Ecological profiles of highway layers

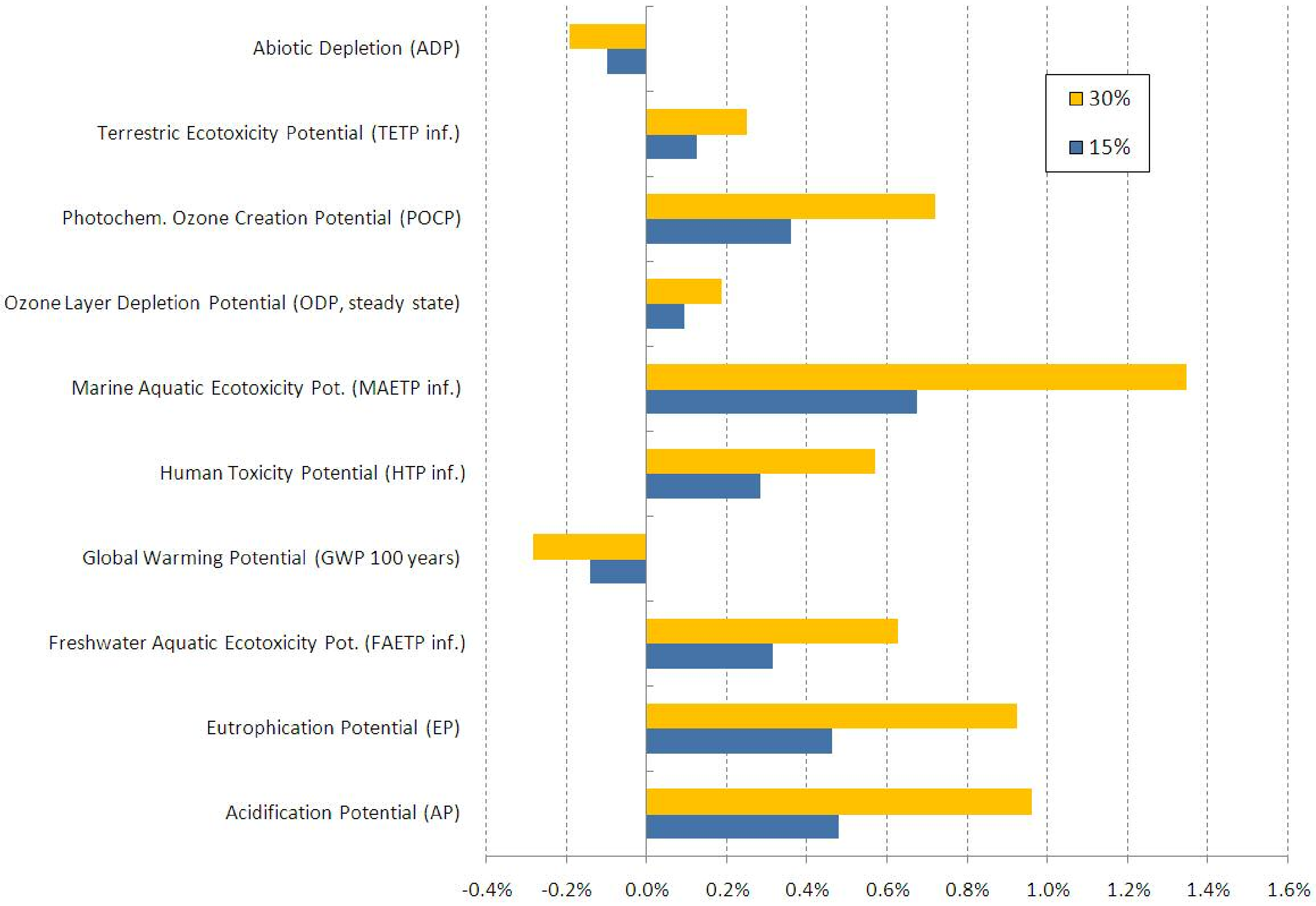

Figure 6. Impact profile for a highway containing 15% and 30% glass in the binder layer

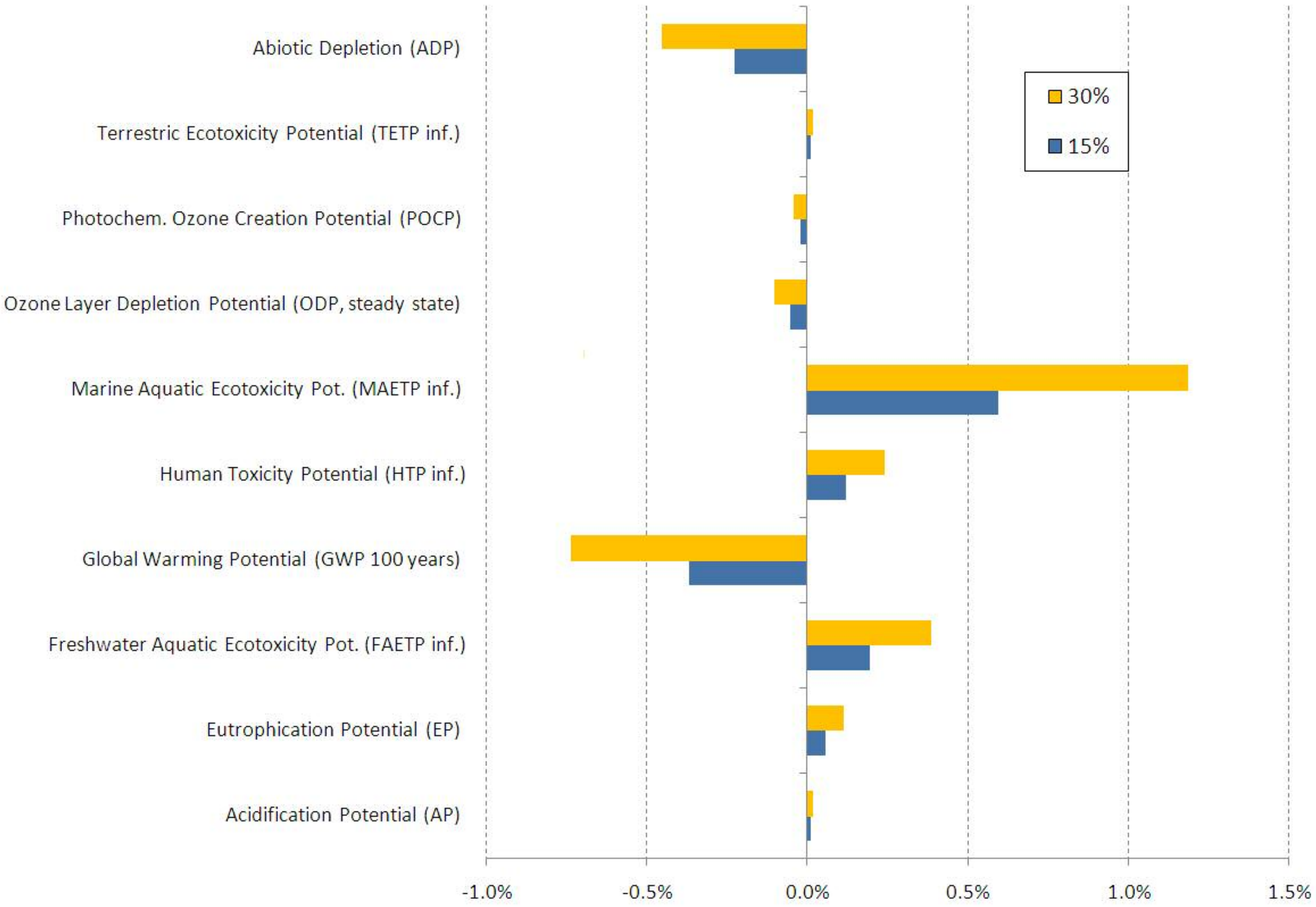

Figure 7. Theoretical impact profile for aggregate replacement with glass and use of a high capacity truck for aggregate collections

4.1.2 *Component impacts*

Looking at binder course component impacts without glass and with 30% glass aggregate in isolation, Figure 8 shows the relative contributions of each stage of the life cycle modelled for each impact category. A traditional binder course containing no glass is plotted alongside a highway with a 30% glass binder course.

From Figure 8 it is possible to determine that in 6 of the 10 impact categories the asphalt production process is the largest contributor. Asphalt production ranges from approximately 42% to 75% of the impacts, material production ranges from approximately 20% to 55% and transport from around 2% to 8%. Figure 8 also shows that the transport makes a greater relative impact across the board for the 30% glass binder course than for traditional virgin aggregate asphalt.

4.1.3 *Glass aggregate and virgin aggregate production*

Figure 9 shows the environmental impacts for the production of glass aggregate compared to that for virgin aggregate. Four of the 10 impact categories realise a saving whilst HTP and EP both show a large increase. This has been identified to be due to the higher electricity consumption relative to other fuels involved in the processing of waste glass into suitable aggregate material. UK electricity production relies heavily on coal and natural gas. Coal has significant emissions to the aquatic environment both during its extraction and combustion. For this reason also, MAETP and FAETP have shown increases of 500% & 600% respectively and have been truncated on the graph to avoid loss of detail across the other impacts.

4.1.4 *Glass recycling: domestic and export*

The impacts from closed-loop glass recycling (remelting back into containers) was modelled for the UK and for export to Portugal. Due to the colour imbalance in the UK glass consumption, the domestic requirement for green cullet in closed-loop recycling operations is satisfied very quickly. This collected, sorted, screened and crushed cullet is now commonly exported to Europe, in particular to Portugal (WRAP, 2007). Figure 10 shows the comparative impacts of domestic and exported glass recycling normalised to glass manufacture with no recycled content. The extra transport distance, estimated to be 1300km by sea, does have an effect on the overall environmental benefits of recycling. Savings across the impact categories are reduced by exportation by up to 60%. In the case of POCP and ODP slight increases in impact are seen, these are 2% and 4% respectively.

The model is in agreement with previous studies on the topic; the potential environmental benefits from using waste glass in the production of new container glass is substantial, even when involving export from the UK.

The model was then expanded to approximate the distance that the cullet could be moved by sea before benefits were lost. Figure 11 shows that the distance varies for each impact category. This prediction only takes into account the increase in shipping distances and does not include variations in the receiving countries’ energy supply mixture (default: UK) or road transport (default: 150km) in the receiving county. A sensitivity analysis or a complete model to explore these parameters and inclusion of other transport modes, such as rail, would give a better appreciation of which option for glass waste is best under specific conditions.

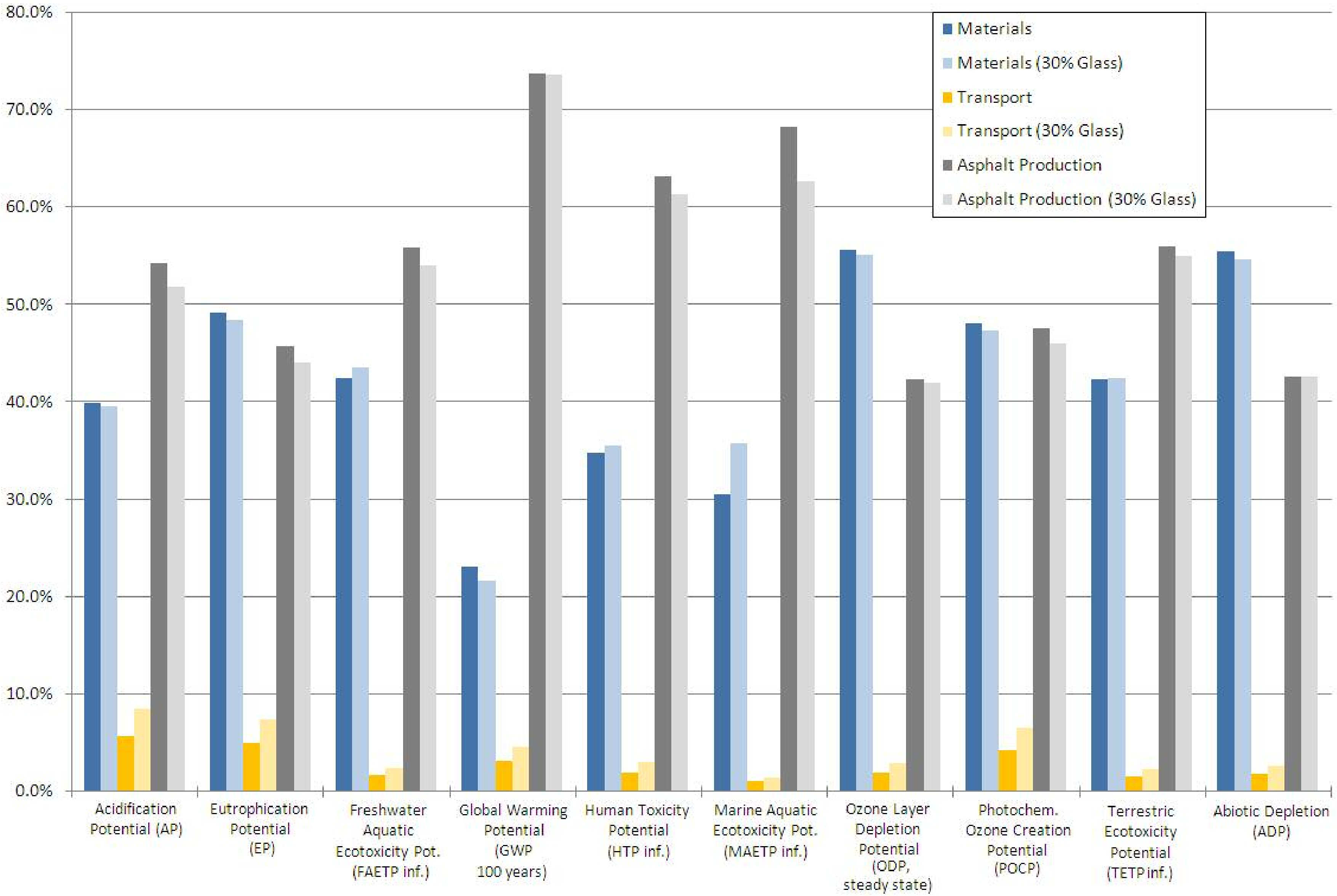

Figure 8. Relative impacts of the different life cycle stages in asphalt production

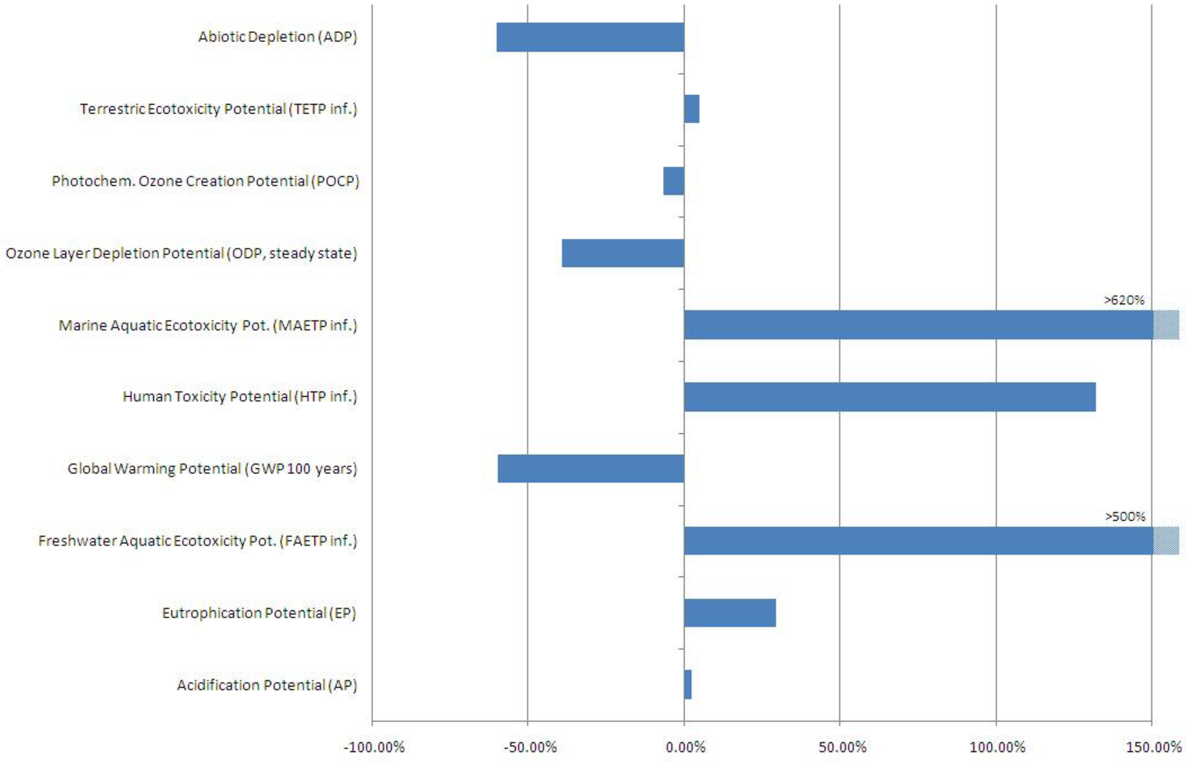

Figure 9. Glass aggregate production impacts relative to virgin aggregate production

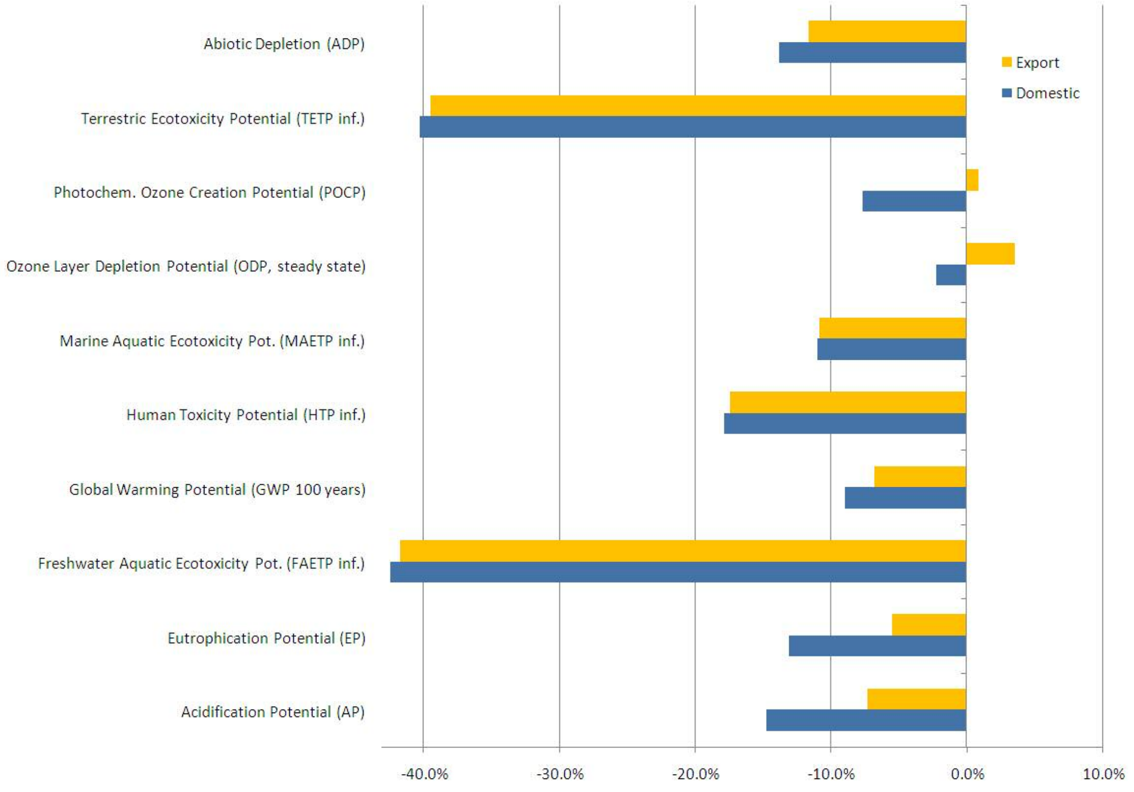

Figure 10. Relative environmental benefits, recycling in the UK or in Portugal

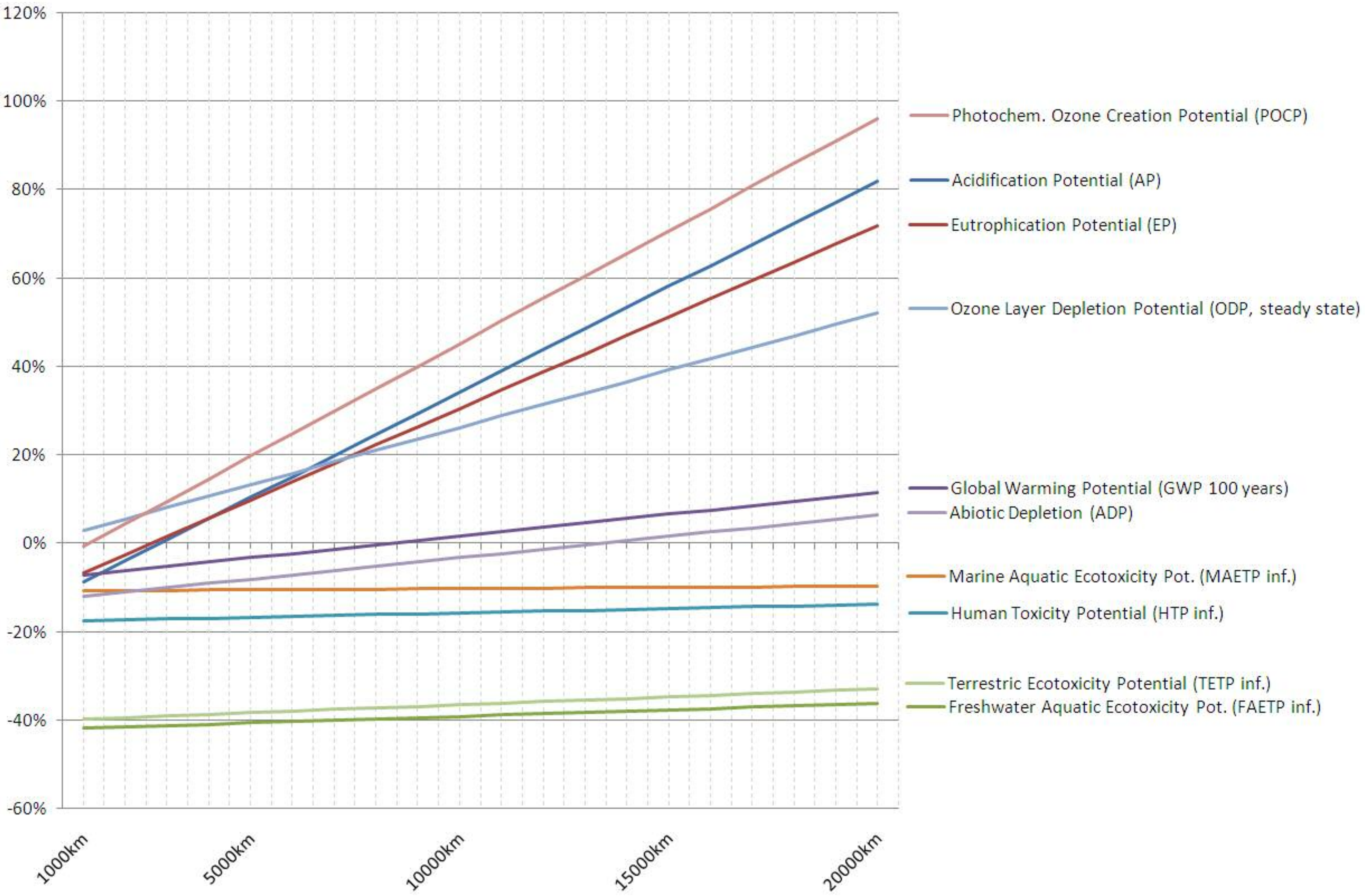

Figure 11. Tipping points for sea transport (at zero on the x-axis)

Figure 11 suggests that the GWP produced by exporting glass remains beneficial (below 100% of impacts of glass production without recycling) up until it has been shipped around 8500km. To put this in to perspective, the cullet could be shipped to Brazil (Southampton, UK to Natal, Brazil is 7100km) and save approximately 2% of the GWP of glass production in the UK without using waste glass. At this distance however, four of the other impact categories are between 120% and 140% of glass manufacture from virgin materials. Ozone Layer Depletion Potential (ODP) is the impact category with the lowest tolerance to transport distance, exceeding 100% at approximately 700km (not shown).

4.1.5 Diversion of furnace grade cullet to highway construction

In the scenario where glass that is processed for remelting is diverted to aggregate, the difference between the processing of waste glass for use as an aggregate and for remelting is considerable. The British Standards PAS 101 includes a grading scheme for the quality of cullet and most glass manufacturers operate a maximum tolerance of 50ppm (50g/t or 0.005% by mass) for contaminants (Head, 2008). However the level of contaminants permissible in an aggregate is much higher, the equivalent of *10,000* ppm (10kg/t or 1% by mass) as specified in the Manual of Contract Documents for Highways Works (Specification for Highways Works Series 700, Clause 710). This results in the processes having quite different energy consumptions and therefore associated environmental impacts.

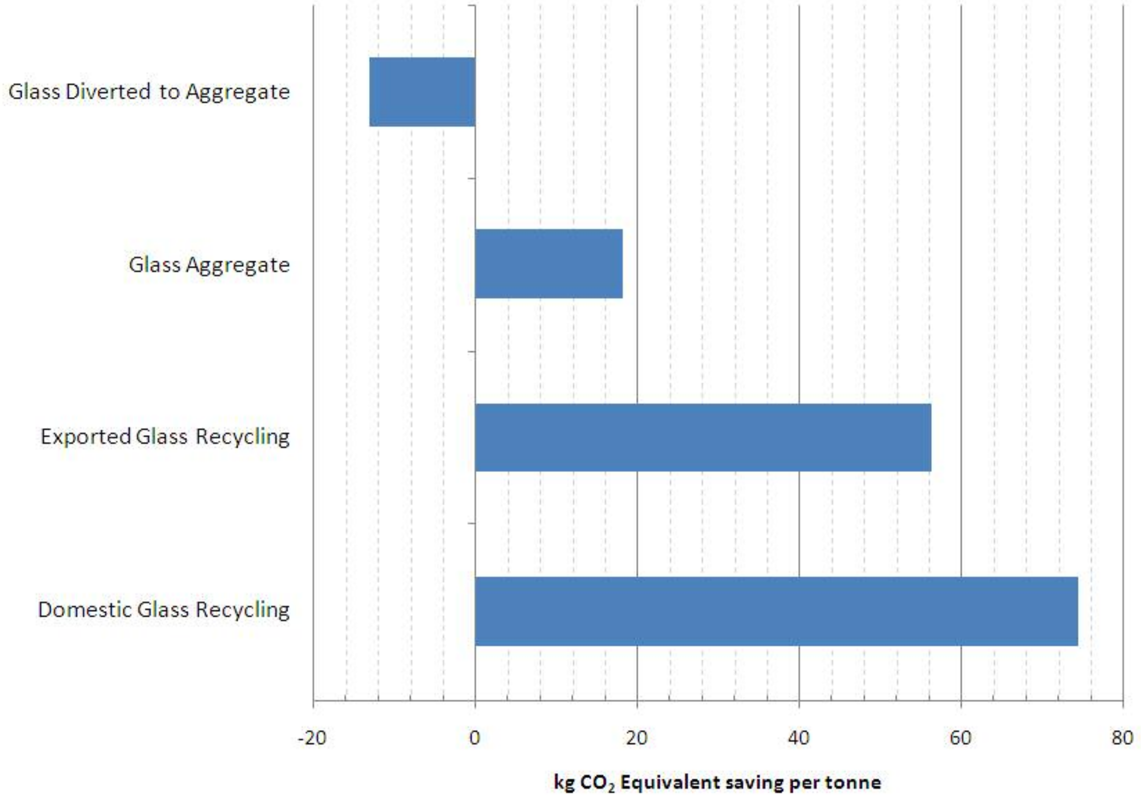

Figure 12. GWP savings of glass recycling options (inc. diverted cullet from remelt to aggregate)

Figure 12 represents the GWP savings for the different recycling options of waste glass. This highlights the benefits of closed-loop recycling of glass into containers over its use as an aggregate. More importantly it shows the effect on GWP of the diversion of cullet processed and sorted to a standard suitable for remelting which is then diverted to highway aggregate. This is a theoretical waste management option for the excess green cullet which arises in the UK. These results show that export of the cullet for remelting would have a much greater positive effect on GWP than this diversion into aggregate. Diverting glass in this way would have an environmental impact greater than the use of virgin aggregate in highway construction.

5 Conclusions and recommendations

5.1.1 Conclusions

The process of turning waste container glass into aggregate has lower impacts than the quarrying of primary aggregate in 7 out of the 10 impact categories examined. These benefits, with contribution to climate change being the sole exception, are counteracted when used in a binder course. This is due to the increased transport and the nature of that transport. However, in other systems where different transport distances and modes of transport are used, this may not always be the case. This highlights the importance of utilising carefully considered logistics on highway construction projects. Comparing the 30% glass and virgin binder courses in greater depth, the transport has a greater proportion of the impact across all categories for the glass scenario.

In the context of other research which has been conducted, this study reinforces previous work on the subject, but which has generally only considered the contribution to climate change of glass recycling, rather than the nine impact categories investigated here. This study has highlighted that national recycling targets in the form that they are stated, and the local government policies which are introduced to meet them, may not result in achieving the optimal environmental benefit overall where waste glass is concerned. The co-mingled glass collections (mixed colour and mixed with other materials) which are widely pursued by local authorities due to the simplicity they offer for householders and the financial advantages for authorities mean that colour separated cullet is decreasing in quantity. Co-mingled glass collection has the effect of precluding the glass collected, now destined for sorting in a MRF, from closed- loop recycling back into container glass. This is due to the higher levels of contamination in co-mingled glass collections. For co-mingled glass to be recycled, it must be used as an aggregate or in another alternative use with a higher contamination tolerance. This dramatically reduces the actual benefits gained compared to the potential benefits for closed-loop recycling even if the colour separated cullet is exported a considerable distance.

Despite the low intensity of reprocessing associated with turning the waste glass into aggregate compared to the much higher energy demands of reprocessing cullet for closed-loop recycling, the environmental benefits of closed-loop recycling are far greater. Diverting colour separated cullet of furnace quality once destined for closed-loop recycling into aggregate should ideally never occur. This is not an environmentally sustainable option since the extra processing undergone by the colour separated cullet increases the environmental impacts across all categories and environmental impacts would overall be higher than using virgin aggregate.

When comparing a highway incorporating reprocessed glass with a traditional virgin aggregate highway, the inclusion of glass as an aggregate only changes the material production and transport phases of the lifecycle. In the overall system the model has demonstrated that the highest impacts come from the asphalt production phase, regardless of whether glass or stone is used for aggregate. It is therefore recommended that future efforts into reducing the energy intensity and environmental impacts of highway construction are concentrated in this area.

Utilising higher capacity vehicles for the transportation of glass aggregate from processing to the asphalt plant is a way in which the environmental benefits of glass aggregate based construction systems can be increased. A recommendation to those responsible for the logistics involved in materials and asphalt production would therefore be that they use the highest capacity vehicles available, providing that they can be filled.

Overall, the study did not reveal any unforeseen problems with the use of glass as an aggregate. However, the reported benefits associated with its use, such as the reported heat retention and workability from either the engineer’s or environmental perspective, were not investigated within the scope of this study.

5.1.2 Further work

The framework used for investigation in this study and the technique of LCA could potentially be used to investigate closely related material applications, as detailed below:

- Investigating the use of glass as a pozzolanic replacement for cement in concrete. Relative to aggregate production, cement production is a high environmental impact activity, which means that there is greater scope for reduction of impacts with material substitution.
- Studying the impacts of a range of other commonly used or potential MSW materials used in construction. Glass is a relatively simple material to substitute into construction, given its inert nature. As this study has reaffirmed, the drawback with using glass as a replacement for construction material is that there is the option of closed-loop recycling with much greater benefits. The use of waste materials in construction with lower potential benefits associated with closed-loop recycling, or for which no practical closed-loop recycling is available could be more beneficial.

Sufficient data availability and quality is essential for any LCA study. The following improvements to datasets are recommended if further LCA studies in closely related areas were to be carried out:

- More detailed analysis of the process impacts associated with recycling material into aggregate/ highway material. The more information gathered about individual processes, fugitive emissions from processes and other parameters, the greater confidence that can be had about the validity of the results. Particular focus should be concentrated in gathering data from asphalt plants and the influences of varying constituent materials and mixtures on energy consumption.
- Explore the potential impacts of the changing UK energy mixture. A crossroads has been reached where more sustainable energy sources must now be tapped to meet future energy demand. Using predicted and proposed future electricity mixtures would allow an estimate to be made of how the relationship between the environmental impacts of virgin and recycled aggregates will change. A similar analysis could be conducted for the changing oil reserves which will be tapped to provide bitumen and fuel for highway construction in the future.

Appendix A – Significant process contributions

	Base Course	Acidification Potential (AP)	Eutrophication Potential (EP)	Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.)	Global Warming Potential (GWP 100 years)	Human Toxicity Potential (HTP inf.)	Marine Aquatic Ecotoxicity Pot. (MAETP inf.)	Ozone Layer Depletion Potential (ODP, steady state)	Photochem. Ozone Creation Potential (POCP)	Terrestric Ecotoxicity Potential (TETP inf.)	Abiotic Depletion (ADP)
		[kg SO2-Equiv.]	[kg Phosphate-Equiv.]	[kg DCB-Equiv.]	[kg CO2-Equiv.]	[kg DCB-Equiv.]	[kg DCB-Equiv.]	[kg R11-Equiv.]	[kg Ethene-Equiv.]	[kg DCB-Equiv.]	[kg Sb-Equiv.]
	Base Course Asphalt Production	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
Processes	RER: heat, light fuel oil, at industrial furnace 1MW	48.90%	46.64%	50.88%	67.10%	59.38%	33.42%	46.25%	46.19%	54.59%	41.34%
	diesel, burned in building machine (Own) [b]	2.32%	1.71%	0.01%	0.78%	0.19%	0.00%	0.00%	2.10%	0.03%	0.00%
Materials	CH: sand, at mine	0.13%	0.10%	0.53%	0.06%	0.20%	0.14%	0.04%	0.13%	0.32%	0.04%
	DE: Limestone, crushed gravel (grain size 2/16) PE	8.43%	4.45%	0.70%	13.39%	2.05%	2.63%	3.07%	7.04%	3.39%	8.77%
	RER: bitumen, at refinery	28.40%	40.84%	36.44%	8.49%	28.32%	23.91%	47.93%	37.32%	34.18%	42.63%
Transport	GLO: Truck 20 - 26 t total cap. / 17,3 t payload / Euro 3 (Truck fleet, local) PE [b]	0.35%	0.26%	0.00%	0.18%	0.06%	0.00%	0.00%	0.23%	0.00%	0.00%
	GLO: Truck from 32 t total cap. / 24,7 t payload / Euro 3 PE [b]	2.02%	1.53%	0.00%	1.15%	0.28%	0.00%	0.00%	1.18%	0.00%	0.00%
	GLO: Truck-trailer up to 28 t total cap./ 12,4 t payload / Euro 3 (specific) PE [b]	0.10%	0.08%	0.00%	0.06%	0.01%	0.00%	0.00%	0.06%	0.00%	0.00%
Energy	RER: diesel, at regional storage	1.12%	1.52%	1.42%	0.35%	1.11%	0.92%	1.75%	1.40%	1.36%	1.55%
	UK Energy Generation	8.23%	2.86%	10.02%	8.44%	8.40%	38.98%	0.98%	4.34%	6.12%	5.67%

	Surface Course	Acidification Potential (AP)	Eutrophication Potential (EP)	Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.)	Global Warming Potential (GWP 100 years)	Human Toxicity Potential (HTP inf.)	Marine Aquatic Ecotoxicity Pot. (MAETP inf.)	Ozone Layer Depletion Potential (ODP, steady state)	Photochem. Ozone Creation Potential (POCP)	Terrestric Ecotoxicity Potential (TETP inf.)	Abiotic Depletion (ADP)
		[kg SO2-Equiv.]	[kg Phosphate-Equiv.]	[kg DCB-Equiv.]	[kg CO2-Equiv.]	[kg DCB-Equiv.]	[kg DCB-Equiv.]	[kg R11-Equiv.]	[kg Ethene-Equiv.]	[kg DCB-Equiv.]	[kg Sb-Equiv.]
	Surface Course Asphalt Production	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
Processes	diesel, burned in building machine (Own) [b]	1.87%	1.29%	0.01%	0.73%	0.15%	0.00%	0.00%	1.62%	0.02%	0.00%
	RER: heat, light fuel oil, at industrial furnace 1MW	39.38%	34.99%	39.73%	62.35%	48.60%	28.22%	33.77%	35.50%	43.21%	31.14%
Materials	RER: bitumen, at refinery	40.02%	53.63%	49.78%	13.80%	40.56%	35.33%	61.24%	50.20%	47.34%	56.21%
	CH: sand, at mine	0.08%	0.06%	0.33%	0.05%	0.13%	0.09%	0.02%	0.08%	0.20%	0.02%
	DE: Limestone, crushed gravel (grain size 2/16) PE	6.64%	3.27%	0.53%	12.17%	1.64%	2.17%	2.19%	5.29%	2.63%	6.46%
Transport	GLO: Truck 20 - 26 t total cap. / 17,3 t payload / Euro 3 (Truck fleet, local) PE [b]	0.44%	0.31%	0.00%	0.27%	0.08%	0.00%	0.00%	0.28%	0.00%	0.00%
	GLO: Truck from 32 t total cap. / 24,7 t payload / Euro 3 PE [b]	3.18%	2.24%	0.00%	2.09%	0.45%	0.00%	0.00%	1.78%	0.00%	0.00%
	GLO: Truck-trailer up to 28 t total cap./ 12,4 t payload / Euro 3 (specific) PE [b]	0.29%	0.20%	0.00%	0.19%	0.04%	0.00%	0.00%	0.16%	0.00%	0.00%
Energy	RER: diesel, at regional storage	1.47%	1.85%	1.80%	0.53%	1.47%	1.26%	2.07%	1.75%	1.75%	1.90%
	UK Energy Generation	6.63%	2.15%	7.82%	7.84%	6.87%	32.92%	0.71%	3.34%	4.84%	4.27%

	Binder Course Traditional Asphalt (0% Glass)	Acidification Potential (AP)	Eutrophication Potential (EP)	Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.)	Global Warming Potential (GWP 100 years)	Human Toxicity Potential (HTP inf.)	Marine Aquatic Ecotoxicity Pot. (MAETP inf.)	Ozone Layer Depletion Potential (ODP, steady state)	Photochem. Ozone Creation Potential (POCP)	Terrestric Ecotoxicity Potential (TETP inf.)	Abiotic Depletion (ADP)
		[kg SO2-Equiv.]	[kg Phosphate-Equiv.]	[kg DCB-Equiv.]	[kg CO2-Equiv.]	[kg DCB-Equiv.]	[kg DCB-Equiv.]	[kg R11-Equiv.]	[kg Ethene-Equiv.]	[kg DCB-Equiv.]	[kg Sb-Equiv.]
	Binder Course Asphalt Production	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
Processes	RER: heat, light fuel oil, at industrial furnace 1MW	44.38%	41.27%	46.25%	64.78%	54.92%	31.37%	40.90%	41.37%	49.91%	37.05%
	diesel, burned in building machine (Own) [b]	2.10%	1.52%	0.01%	0.76%	0.17%	0.00%	0.00%	1.88%	0.03%	0.00%
Materials	CH: sand, at mine	0.12%	0.09%	0.48%	0.06%	0.18%	0.13%	0.03%	0.12%	0.30%	0.03%
	DE: Limestone, crushed gravel (grain size 2/16) PE	7.57%	3.90%	0.63%	12.78%	1.88%	2.44%	2.68%	6.23%	3.07%	7.77%
	RER: bitumen, at refinery	32.22%	45.18%	41.40%	10.24%	32.74%	28.05%	52.99%	41.79%	39.06%	47.77%
Transport	GLO: Truck 20 - 26 t total cap. / 17,3 t payload / Euro 3 (Truck fleet, local) PE [b]	0.63%	0.46%	0.00%	0.35%	0.11%	0.00%	0.00%	0.41%	0.00%	0.00%
	GLO: Truck from 32 t total cap. / 24,7 t payload / Euro 3 PE [b]	3.62%	2.67%	0.00%	2.19%	0.52%	0.00%	0.00%	2.10%	0.00%	0.00%
	GLO: Truck-trailer up to 28 t total cap./ 12,4 t payload / Euro 3 (specific) PE [b]	0.23%	0.17%	0.00%	0.14%	0.03%	0.00%	0.00%	0.14%	0.00%	0.00%
Energy	RER: diesel, at regional storage	1.67%	2.21%	2.11%	0.56%	1.68%	1.42%	2.53%	2.06%	2.04%	2.28%
	UK Energy Generation	7.47%	2.53%	9.11%	8.15%	7.77%	36.59%	0.86%	3.89%	5.59%	5.09%

	Binder Course 15% Glass Aggregate	Acidification Potential (AP)	Eutrophication Potential (EP)	Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.)	Global Warming Potential (GWP 100 years)	Human Toxicity Potential (HTP inf.)	Marine Aquatic Ecotoxicity Pot. (MAETP inf.)	Ozone Layer Depletion Potential (ODP, steady state)	Photochem. Ozone Creation Potential (POCP)	Terrestric Ecotoxicity Potential (TETP inf.)	Abiotic Depletion (ADP)
		[kg SO2-Equiv.]	[kg Phosphate-Equiv.]	[kg DCB-Equiv.]	[kg CO2-Equiv.]	[kg DCB-Equiv.]	[kg DCB-Equiv.]	[kg R11-Equiv.]	[kg Ethene-Equiv.]	[kg DCB-Equiv.]	[kg Sb-Equiv.]
	Binder Course Asphalt Production	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
Processes	diesel, burned in building machine (Own) [b]	2.07%	1.49%	0.01%	0.76%	0.17%	0.00%	0.00%	1.86%	0.03%	0.00%
	RER: heat, light fuel oil, at industrial furnace 1MW	43.66%	40.63%	45.76%	65.09%	54.39%	30.66%	40.77%	40.87%	49.70%	37.18%
Materials	Glass Kerbside collection	0.18%	0.15%	0.05%	0.09%	0.06%	0.03%	0.06%	0.15%	0.05%	0.05%
	Glass to Aggregate	0.22%	0.11%	0.19%	0.19%	0.17%	0.71%	0.03%	0.15%	0.12%	0.12%
	MRF Glass	0.87%	0.56%	0.52%	0.59%	0.49%	1.66%	0.18%	0.67%	0.37%	0.35%
	RER: bitumen, at refinery	31.70%	44.48%	40.96%	10.29%	32.42%	27.41%	52.82%	41.29%	38.89%	47.93%
	CH: sand, at mine	0.12%	0.09%	0.48%	0.06%	0.18%	0.13%	0.03%	0.11%	0.29%	0.03%
	DE: Limestone, crushed gravel (grain size 2/16) PE	6.21%	3.20%	0.52%	10.71%	1.55%	1.99%	2.23%	5.13%	2.54%	6.50%
Transport	GLO: Truck 20 - 26 t total cap. / 17,3 t payload / Euro 3 (Truck fleet, local) PE [b]	0.62%	0.46%	0.00%	0.35%	0.11%	0.00%	0.00%	0.41%	0.00%	0.00%
	GLO: Truck 20 - 26 t total cap. / 17,3 t payload / Euro 3 (Truck fleet, local) PE [b]	1.85%	1.37%	0.00%	1.05%	0.32%	0.00%	0.00%	1.23%	0.00%	0.00%
	GLO: Truck from 32 t total cap. / 24,7 t payload / Euro 3 PE [b]	2.97%	2.19%	0.00%	1.84%	0.43%	0.00%	0.00%	1.73%	0.00%	0.00%
	GLO: Truck-trailer up to 28 t total cap./ 12,4 t payload / Euro 3 (specific) PE [b]	0.23%	0.17%	0.00%	0.14%	0.03%	0.00%	0.00%	0.14%	0.00%	0.00%
Energy	RER: diesel, at regional storage	1.97%	2.60%	2.50%	0.67%	1.99%	1.66%	3.02%	2.43%	2.43%	2.74%
	UK Energy Generation	7.35%	2.50%	9.01%	8.19%	7.69%	35.76%	0.86%	3.84%	5.57%	5.10%

Binder Course 30% Glass Aggregate		Acidification Potential (AP)	Eutrophication Potential (EP)	Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.)	Global Warming Potential (GWP 100 years)	Human Toxicity Potential (HTP inf.)	Marine Aquatic Ecotoxicity Pot. (MAETP inf.)	Ozone Layer Depletion Potential (ODP, steady state)	Photochem. Ozone Creation Potential (POCP)	Terrestric Ecotoxicity Potential (TETP inf.)	Abiotic Depletion (ADP)
		[kg SO2-Equiv.]	[kg Phosphate-Equiv.]	[kg DCB-Equiv.]	[kg CO2-Equiv.]	[kg DCB-Equiv.]	[kg DCB-Equiv.]	[kg R11-Equiv.]	[kg Ethene-Equiv.]	[kg DCB-Equiv.]	[kg Sb-Equiv.]
	Binder Course Asphalt Production	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
Processes	diesel, burned in building machine (Own) [b]	2.04%	1.47%	0.01%	0.76%	0.17%	0.00%	0.00%	1.84%	0.03%	0.00%
	RER: heat, light fuel oil, at industrial furnace 1MW	42.97%	40.01%	45.28%	65.41%	53.87%	29.98%	40.64%	40.38%	49.49%	37.30%
Materials	Glass Kerbside collection	0.35%	0.30%	0.09%	0.18%	0.13%	0.06%	0.11%	0.29%	0.09%	0.10%
	Glass to Aggregate	0.44%	0.22%	0.38%	0.38%	0.33%	1.38%	0.07%	0.30%	0.25%	0.23%
	MRF Glass	1.72%	1.11%	1.03%	1.18%	0.97%	3.25%	0.36%	1.31%	0.73%	0.71%
	RER: bitumen, at refinery	31.20%	43.80%	40.53%	10.34%	32.11%	26.80%	52.65%	40.79%	38.73%	48.09%
	CH: sand, at mine	0.12%	0.09%	0.47%	0.06%	0.18%	0.12%	0.03%	0.11%	0.29%	0.03%
	DE: Limestone, crushed gravel (grain size 2/16) PE	4.89%	2.52%	0.41%	8.61%	1.23%	1.56%	1.78%	4.06%	2.03%	5.21%
Transport	GLO: Truck 20 - 26 t total cap. / 17,3 t payload / Euro 3 (Truck fleet, local) PE [b]	0.61%	0.45%	0.00%	0.35%	0.10%	0.00%	0.00%	0.40%	0.00%	0.00%
	GLO: Truck 20 - 26 t total cap. / 17,3 t payload / Euro 3 (Truck fleet, local) PE [b]	3.64%	2.69%	0.00%	2.10%	0.63%	0.00%	0.00%	2.42%	0.00%	0.00%
	GLO: Truck from 32 t total cap. / 24,7 t payload / Euro 3 PE [b]	2.34%	1.73%	0.00%	1.48%	0.34%	0.00%	0.00%	1.36%	0.00%	0.00%
	GLO: Truck-trailer up to 28 t total cap./ 12,4 t payload / Euro 3 (specific) PE [b]	0.22%	0.16%	0.00%	0.14%	0.03%	0.00%	0.00%	0.13%	0.00%	0.00%
Energy	RER: diesel, at regional storage	2.25%	2.98%	2.88%	0.78%	2.29%	1.88%	3.50%	2.80%	2.82%	3.20%
	UK Energy Generation	7.23%	2.46%	8.92%	8.23%	7.62%	34.96%	0.86%	3.80%	5.55%	5.12%

Binder Course 15% Glass Alternative Transport		Acidification Potential (AP)	Eutrophication Potential (EP)	Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.)	Global Warming Potential (GWP 100 years)	Human Toxicity Potential (HTP inf.)	Marine Aquatic Ecotoxicity Pot. (MAETP inf.)	Ozone Layer Depletion Potential (ODP, steady state)	Photochem. Ozone Creation Potential (POCP)	Terrestric Ecotoxicity Potential (TETP inf.)	Abiotic Depletion (ADP)
		[kg SO2-Equiv.]	[kg Phosphate-Equiv.]	[kg DCB-Equiv.]	[kg CO2-Equiv.]	[kg DCB-Equiv.]	[kg DCB-Equiv.]	[kg R11-Equiv.]	[kg Ethene-Equiv.]	[kg DCB-Equiv.]	[kg Sb-Equiv.]
	Binder Course Asphalt Production	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
Processes	diesel, burned in building machine (Own) [b]	2.10%	1.51%	0.01%	0.77%	0.17%	0.00%	0.00%	1.88%	0.03%	0.00%
	RER: heat, light fuel oil, at industrial furnace 1MW	44.36%	41.19%	45.95%	65.61%	54.70%	30.74%	40.97%	41.40%	49.90%	37.34%
Materials	Glass Kerbside collection	0.18%	0.16%	0.05%	0.09%	0.06%	0.03%	0.06%	0.15%	0.05%	0.05%
	Glass to Aggregate	0.23%	0.11%	0.19%	0.19%	0.17%	0.71%	0.03%	0.15%	0.12%	0.12%
	MRF Glass	0.89%	0.57%	0.52%	0.59%	0.49%	1.67%	0.18%	0.67%	0.37%	0.36%
	RER: bitumen, at refinery	32.21%	45.09%	41.13%	10.37%	32.60%	27.49%	53.08%	41.82%	39.05%	48.15%
	CH: sand, at mine	0.12%	0.09%	0.48%	0.06%	0.18%	0.13%	0.03%	0.12%	0.30%	0.03%
	DE: Limestone, crushed gravel (grain size 2/16) PE	6.31%	3.24%	0.52%	10.79%	1.56%	2.00%	2.24%	5.20%	2.55%	6.53%
Transport	GLO: Truck 20 - 26 t total cap. / 17,3 t payload / Euro 3 (Truck fleet, local) PE [b]	0.63%	0.46%	0.00%	0.35%	0.11%	0.00%	0.00%	0.41%	0.00%	0.00%
	GLO: Truck from 32 t total cap. / 24,7 t payload / Euro 3 PE [b]	3.02%	2.22%	0.00%	1.85%	0.43%	0.00%	0.00%	1.75%	0.00%	0.00%
	GLO: Truck from 32 t total cap. / 24,7 t payload / Euro 3 PE [b]	0.60%	0.44%	0.00%	0.37%	0.09%	0.00%	0.00%	0.35%	0.00%	0.00%
	GLO: Truck-trailer up to 28 t total cap./ 12,4 t payload / Euro 3 (specific) PE [b]	0.23%	0.17%	0.00%	0.14%	0.03%	0.00%	0.00%	0.14%	0.00%	0.00%
Energy	RER: diesel, at regional storage	1.67%	2.21%	2.10%	0.56%	1.67%	1.39%	2.54%	2.06%	2.04%	2.30%
	UK Energy Generation	7.47%	2.53%	9.05%	8.25%	7.74%	35.85%	0.86%	3.89%	5.59%	5.12%

Binder Course 30% Glass Alternative Transport		Acidification Potential (AP)	Eutrophication Potential (EP)	Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.)	Global Warming Potential (GWP 100 years)	Human Toxicity Potential (HTP inf.)	Marine Aquatic Ecotoxicity Pot. (MAETP inf.)	Ozone Layer Depletion Potential (ODP, steady state)	Photochem. Ozone Creation Potential (POCP)	Terrestric Ecotoxicity Potential (TETP inf.)	Abiotic Depletion (ADP)
		[kg SO2-Equiv.]	[kg Phosphate-Equiv.]	[kg DCB-Equiv.]	[kg CO2-Equiv.]	[kg DCB-Equiv.]	[kg DCB-Equiv.]	[kg R11-Equiv.]	[kg Ethene-Equiv.]	[kg DCB-Equiv.]	[kg Sb-Equiv.]
	Binder Course Asphalt Production	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
Processes	diesel, burned in building machine (Own) [b]	2.10%	1.51%	0.01%	0.78%	0.17%	0.00%	0.00%	1.89%	0.03%	0.00%
	RER: heat, light fuel oil, at industrial furnace 1MW	44.35%	41.11%	45.65%	66.46%	54.47%	30.13%	41.05%	41.43%	49.89%	37.64%
Materials	Glass Kerbside collection	0.36%	0.31%	0.09%	0.18%	0.13%	0.06%	0.11%	0.30%	0.09%	0.10%
	Glass to Aggregate	0.45%	0.23%	0.38%	0.38%	0.33%	1.39%	0.07%	0.30%	0.25%	0.23%
	MRF Glass	1.77%	1.14%	1.03%	1.20%	0.98%	3.27%	0.36%	1.35%	0.73%	0.72%
	RER: bitumen, at refinery	32.20%	45.00%	40.86%	10.51%	32.47%	26.95%	53.17%	41.85%	39.04%	48.52%
	CH: sand, at mine	0.12%	0.09%	0.48%	0.06%	0.18%	0.12%	0.03%	0.12%	0.30%	0.03%
	DE: Limestone, crushed gravel (grain size 2/16) PE	5.04%	2.59%	0.41%	8.74%	1.24%	1.57%	1.80%	4.16%	2.04%	5.26%
Transport	GLO: Truck 20 - 26 t total cap. / 17,3 t payload / Euro 3 (Truck fleet, local) PE [b]	0.63%	0.46%	0.00%	0.36%	0.11%	0.00%	0.00%	0.41%	0.00%	0.00%
	GLO: Truck from 32 t total cap. / 24,7 t payload / Euro 3 PE [b]	2.41%	1.78%	0.00%	1.50%	0.34%	0.00%	0.00%	1.40%	0.00%	0.00%
	GLO: Truck from 32 t total cap. / 24,7 t payload / Euro 3 PE [b]	1.21%	0.89%	0.00%	0.75%	0.17%	0.00%	0.00%	0.70%	0.00%	0.00%
	GLO: Truck-trailer up to 28 t total cap./ 12,4 t payload / Euro 3 (specific) PE [b]	0.23%	0.17%	0.00%	0.14%	0.03%	0.00%	0.00%	0.14%	0.00%	0.00%
Energy	RER: diesel, at regional storage	1.67%	2.20%	2.09%	0.57%	1.66%	1.36%	2.54%	2.06%	2.04%	2.32%
	UK Energy Generation	7.46%	2.52%	8.99%	8.36%	7.70%	35.15%	0.87%	3.90%	5.59%	5.17%

	Glass to Aggregate	Acidification Potential (AP)	Eutrophication Potential (EP)	Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.)	Global Warming Potential (GWP 100 years)	Human Toxicity Potential (HTP inf.)	Marine Aquatic Ecotoxicity Pot. (MAETP inf.)	Ozone Layer Depletion Potential (ODP, steady state)	Photochem. Ozone Creation Potential (POCP)	Terrestric Ecotoxicity Potential (TETP inf.)	Abiotic Depletion (ADP)
		[kg SO2-Equiv.]	[kg Phosphate-Equiv.]	[kg DCB-Equiv.]	[kg CO2-Equiv.]	[kg DCB-Equiv.]	[kg DCB-Equiv.]	[kg R11-Equiv.]	[kg Ethene-Equiv.]	[kg DCB-Equiv.]	[kg Sb-Equiv.]
	Glass to Aggregate	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
Processes	diesel, burned in building machine (Own) [b]	5.26%	5.83%	0.05%	2.84%	0.78%	0.01%	0.00%	6.26%	0.16%	0.00%
Materials	Glass Kerbside collection	14.02%	18.50%	6.25%	10.45%	8.92%	1.30%	20.91%	15.23%	8.59%	9.88%
	MRF Glass	68.56%	67.94%	68.56%	67.88%	67.85%	69.29%	66.30%	69.21%	68.29%	67.98%
Energy	UK Energy Generation	11.23%	5.85%	23.16%	18.37%	20.80%	28.99%	6.15%	7.78%	20.24%	18.99%
	RER: diesel, at regional storage	0.93%	1.88%	1.98%	0.46%	1.66%	0.41%	6.64%	1.52%	2.72%	3.14%

	Glass Recycling UK	Acidification Potential (AP)	Eutrophication Potential (EP)	Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.)	Global Warming Potential (GWP 100 years)	Human Toxicity Potential (HTP inf.)	Marine Aquatic Ecotoxicity Pot. (MAETP inf.)	Ozone Layer Depletion Potential (ODP, steady state)	Photochem. Ozone Creation Potential (POCP)	Terrestric Ecotoxicity Potential (TETP inf.)	Abiotic Depletion (ADP)
		[kg SO2-Equiv.]	[kg Phosphate-Equiv.]	[kg DCB-Equiv.]	[kg CO2-Equiv.]	[kg DCB-Equiv.]	[kg DCB-Equiv.]	[kg R11-Equiv.]	[kg Ethene-Equiv.]	[kg DCB-Equiv.]	[kg Sb-Equiv.]
	Glass Recycling	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
Processes	Glass Remelting	93.02%	87.25%	96.05%	93.46%	98.13%	99.39%	84.02%	86.18%	94.14%	93.01%
Transport	CH: operation, passenger car, diesel, EURO3 [b]	0.51%	0.77%	0.22%	1.13%	0.13%	0.00%	0.00%	1.71%	1.00%	0.00%
	CH: operation, passenger car, petrol, EURO3 [b]	0.12%	0.18%	0.22%	1.22%	0.37%	0.00%	0.00%	1.94%	1.01%	0.00%
	GLO: Truck 14 - 20 t total cap. / 11,4 t payload / Euro 3 PE [b]	1.23%	1.85%	0.00%	0.92%	0.09%	0.00%	0.00%	1.48%	0.00%	0.00%
	GLO: Truck 14 - 20 t total cap. / 11,4 t payload / Euro 3 PE [b]	2.84%	4.29%	0.00%	2.14%	0.21%	0.00%	0.00%	3.43%	0.00%	0.00%
Energy	RER: diesel, at regional storage	1.57%	4.26%	2.45%	0.68%	0.73%	0.33%	12.24%	3.67%	2.73%	5.20%
	RER: petrol, unleaded, at regional storage	0.59%	1.30%	0.88%	0.27%	0.28%	0.12%	3.67%	1.47%	0.99%	1.60%
	UK Energy Generation	0.12%	0.08%	0.18%	0.17%	0.06%	0.15%	0.07%	0.12%	0.13%	0.20%

Glass Recycling Exported to Portugal		Acidification Potential (AP)	Eutrophication Potential (EP)	Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.)	Global Warming Potential (GWP 100 years)	Human Toxicity Potential (HTP inf.)	Marine Aquatic Ecotoxicity Pot. (MAETP inf.)	Ozone Layer Depletion Potential (ODP, steady state)	Photochem. Ozone Creation Potential (POCP)	Terrestric Ecotoxicity Potential (TETP inf.)	Abiotic Depletion (ADP)
		[kg SO2-Equiv.]	[kg Phosphate-Equiv.]	[kg DCB-Equiv.]	[kg CO2-Equiv.]	[kg DCB-Equiv.]	[kg DCB-Equiv.]	[kg R11-Equiv.]	[kg Ethene-Equiv.]	[kg DCB-Equiv.]	[kg Sb-Equiv.]
	Glass Recycling	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
Process	Glass Remelting	85.54%	80.23%	94.92%	91.28%	97.59%	99.23%	79.30%	78.85%	92.90%	90.72%
Transport	CH: operation, passenger car, diesel, EURO3 [b]	0.47%	0.71%	0.22%	1.11%	0.13%	0.00%	0.00%	1.56%	0.99%	0.00%
	CH: operation, passenger car, petrol, EURO3 [b]	0.11%	0.17%	0.22%	1.19%	0.37%	0.00%	0.00%	1.78%	0.99%	0.00%
	GLO: Bulk commodity carrier/1500 to 20000 dwt /coast PE [b]	6.29%	4.57%	0.00%	1.18%	0.11%	0.00%	0.00%	5.61%	0.00%	0.00%
	GLO: Truck 14 - 20 t total cap. / 11,4 t payload / Euro 3 PE [b]	1.13%	1.71%	0.00%	0.90%	0.09%	0.00%	0.00%	1.36%	0.00%	0.00%
	GLO: Truck 14 - 20 t total cap. / 11,4 t payload / Euro 3 PE [b]	2.61%	3.95%	0.00%	2.09%	0.21%	0.00%	0.00%	3.14%	0.00%	0.00%
	GLO: Truck 14 - 20 t total cap. / 11,4 t payload / Euro 3 PE [b]	1.04%	1.58%	0.00%	0.84%	0.09%	0.00%	0.00%	1.26%	0.00%	0.00%
Energy	RER: diesel, at regional storage	1.74%	4.71%	2.91%	0.79%	0.88%	0.40%	13.91%	4.04%	3.25%	6.10%
	RER: light fuel oil, at regional storage	0.41%	1.10%	0.68%	0.19%	0.20%	0.09%	3.25%	0.95%	0.76%	1.43%
	RER: petrol, unleaded, at regional storage	0.55%	1.20%	0.87%	0.27%	0.28%	0.12%	3.47%	1.35%	0.98%	1.56%
	UK Energy Generation	0.11%	0.08%	0.18%	0.16%	0.06%	0.15%	0.07%	0.11%	0.13%	0.19%

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Glossary of terms and abbreviations

AD – Abiotic Depletion

AP – Acidification Potential

EP – Eutrophication Potential

FAETP – Freshwater Aquatic Ecotoxicity Potential

GWP – Global Warming Potential

HTP – Human Toxicity Potential

MAETP – Marine Aquatic Ecotoxicity Potential

ODP – Ozone Depletion Potential

POCP – Photochemical Ozone Creation Potential

TETP – Terrestrial Ecotoxicity Potential