Life Cycle Assessment of Asphalt Pavements

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ABSTRACT: The increasing use of recycled materials in asphalt pavements calls for environmental assessment of such key impacts as the energy consumption and CO_2 footprint. Life cycle assessment (LCA) is being accepted by the road industry for such purposes. This paper reviews relevant LCA resources including the tools and databases; and describes the development of a LCA model for construction and maintenance of asphalt pavements. Details are provided of the data sourcing and calculation methods. This is followed by a discussion of the challenges of applying LCA to the asphalt pavements, and further work needed. The model is applied to a case study, in which the energy and CO_2 savings by using innovative asphalt materials are analysed and compared to conventional hot mix asphalt (HMA), based on equivalent engineering performance for a new construct pavement. These non-standard asphalt materials include the use of Foamix (foamed bitumen mixed with recycled asphalt pavement, RAP), and the asphalt mixed at lower temperatures (half warm asphalt). It is found that both the Foamix and half warm asphalt used less energy; whilst the Foamix pavement had higher CO_2 footprint. This is followed by data analysis and sensitivity check.

KEY WORDS: Asphalt pavements, life cycle assessment, recycling, sustainable construction.

1 INTRODUCTION

The use of recycled materials in pavement construction needs prescriptive assessment of the associated environmental impacts including energy consumption, emissions and leaching, etc. A life cycle approach is gaining ground in meeting the needs of sustainable construction. Accredited by a number of industries already, life cycle assessment (LCA) is being accepted and applied by the road industry, to measure and compare the key environmental impacts of its materials and laying processes.

Life cycle assessment starts with a definition of the aim and scope of the study. The main work is in the development of a life cycle inventory (LCI), in which all the significant environmental impacts (input and output) during the life time of the product or process are quantified and compiled. This is followed by a life cycle impact assessment (LCIA) that interprets and presents the result in a predefined way that comparison or further analysis can be carried out. The concept and procedures of LCA (Figure 1) are described in the ISO14040

(British Standards Institution, 2006). LCA was initially used in civil engineering, as a tool for evaluating the solid waste management options. Relevant practice in roads and asphalt pavements, notably where recycling and maintenance are taken into account, is limited.

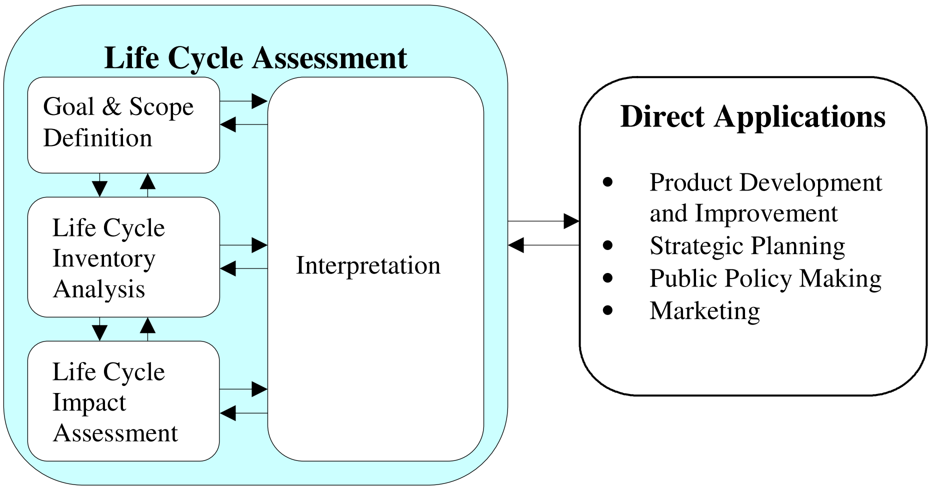

Figure 1: Framework of life cycle assessment (British Standards Institution, 2006)

A few LCA models were developed for the road sector between 1996 and 2005 in the US, Japan and Scandinavia. These models were investigated, and practical results reviewed, which paved the way for applying the LCA to the UK road construction. However, a LCA model developed for one country usually cannot be applied automatically in another due to different material options, construction techniques and the validity of data. Significantly, few models have allowed for the use of recycled materials. As a result, a new LCA model was developed, based on the UK practice.

2 DEVELOPMENT OF A LCA MODEL

The LCA model was developed in accordance with the ISO14044 (British Standards Institution, 2006). This model has been applied to, and calibrated by, real pavement projects that have built up the scope and adaptability of its computing tool (Excel® spreadsheet). An example is given in the case study later. Depending on the nature and deliverables, asphalt pavements differ from one another in terms of material and equipment use, transport, construction method, maintenance scheme and way of disposal, etc. The construction and maintenance of asphalt pavements can be generally defined having the following processes (Figure 2, waste glass as an example of secondary aggregates).

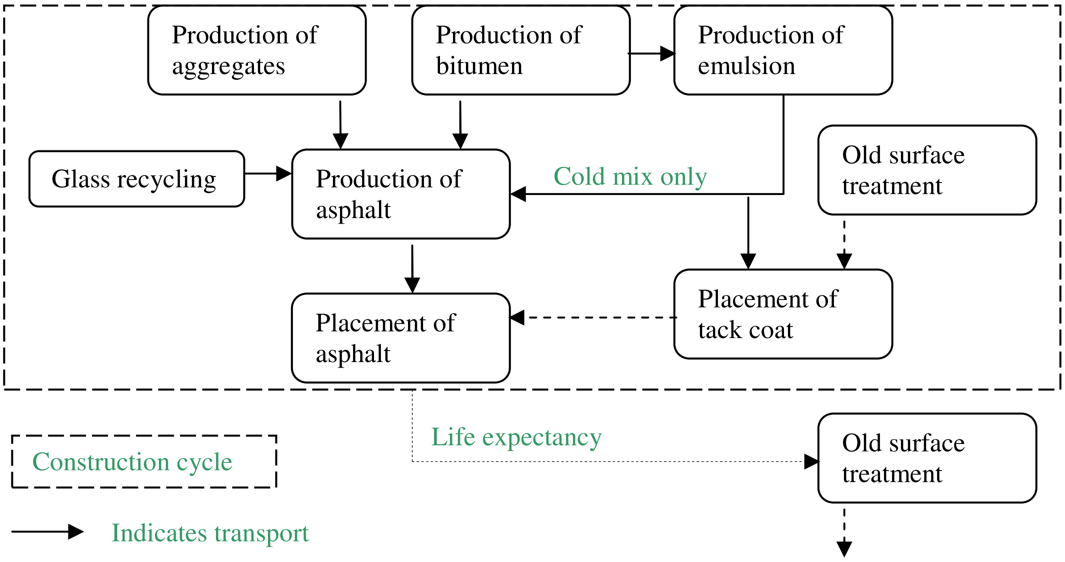

Figure 2: Construction and maintenance of asphalt pavements

2.1 LCA MODEL OVERVIEW

The model consists of five worksheets, namely process parameters, pavement parameters, unit inventory, project inventory and characterisation results. Data in the worksheet 'process parameters' and 'pavement parameters' are specific to a project. The worksheet 'unit inventory' contains the LCI of unit processes. Inventory results in the unit of the pavement project are presented in the 'project inventory' worksheet. The inventory loadings are characterised for impact assessment; the characterisation model and factors can be found in the 'characterisation results' worksheet. Data in these worksheets are linked by calculation formulae. For instance, when the unit inventory of a certain process is altered, the project inventory and characterisation results will change accordingly. The structure of the LCA model and relationships between the worksheets are illustrated in Table 1 and Figure 3.

Table 1: Worksheets in LCA model

Worksheet	Description	Sub-worksheet
Process Parameters	Data on transport distance and fuel efficiency, energy consumption of unit processes in a pavement project	'Energy in transport' 'Energy in materials production' 'Energy in pavement construction'
Pavement Parameters	Data on pavement dimension and materials recipe, determine the tonnage of materials in a pavement project	'Pavement dimensions' 'Materials recipe' 'Pavement life time'
Unit Inventory	Inventory data for unit operation of transport, materials production and pavement construction	'Energy production' 'Combustion of fossil fuels' 'Transport vehicle operation' 'Construction vehicle operation'
Project Inventory	Unit inventory data are aggregated into the unit of the pavement project	'Production process' 'Transport process' 'Construction process'
Characterisation Results	Inventory results are assigned to defined impact categories, characterised by selected models and presented by category indicators	'Global warming' 'Acidification' 'Human toxicity' 'Eco-toxicity', etc

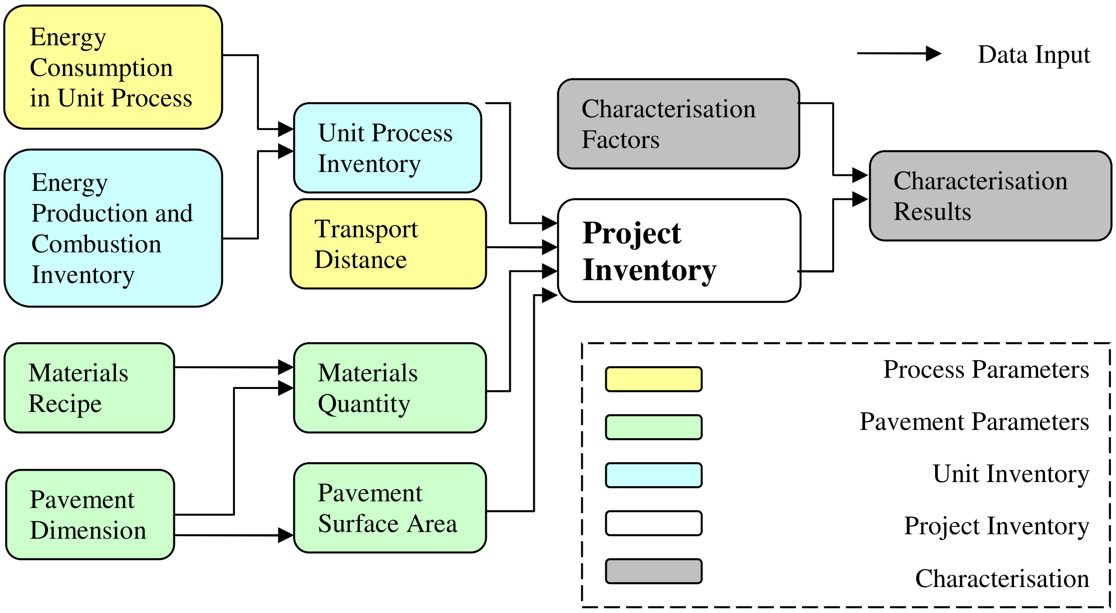

Figure 3: Relationships between worksheets in LCA model

2.2 PROCESS PARAMETERS

The ‘process parameters’ worksheet includes data on transport distance (km), fuel efficiency of transport vehicles (litre/km or litre/km*tonne) and energy consumption per unit of materials production (MJ/tonne) and pavement construction (MJ/m^2) in a pavement project. Data on energy consumption include both the amount and type. The calorific values defined by UK Department of Trade and Industry (DTI) are used in this model to convert the volume of combusted fossil fuels into the universal energy unit (MJ). Parameters can be grouped into ‘energy in materials production’, ‘energy in transport’ and ‘energy in pavement construction’.

The primary sources of process related data for this model are UK plants and contractors, supplemented by other European LCA studies reviewed (Huang, 2007). It is recognised that the data on energy consumption are also available from other sources including the US Department of Energy, National Crushed Stone Association and Canadian National Research Council, etc (Zapata and Gambatese, 2005). One of the essential elements of LCA is the transparency. That is, a user or reviewer of the model will know the origin of the data in the model and the assumptions have been made in the calculations. Data analysis, including quality and sensitivity checks, can be carried out later in the ‘interpretation’ stage.

The distance and type of vehicles for transport depend on the construction process and source of materials, which will have an effect on vehicle fuel efficiency. When calculating the fuel consumption, vehicles are normally assumed to deliver at ‘full load’ and be ‘empty on return’. The fuel consumption rates differentiate between these two scenarios. Another key feature of the model that was created is its adaptability. Users are able to change assumptions, to reflect the real circumstances of a project, for example a cargo ship or rail locomotive could be used for long-distance heavy-load haulage. Similarly, in the asphalt laying process, the roller will pass over freshly paved material a certain number of times. It must roll before the temperature drops too much, so it can never get too far behind the paver, or too close where the material is still too soft. Therefore the working speeds of paver and roller in a pavement project are related to each other; the selected figures for LCA calculation must refer to the management of each project.

2.3 PAVEMENT PARAMETERS

The ‘pavement parameters’ worksheet includes data on pavement dimensions (surface area, layer thickness) and the material recipe (ratio of aggregates, filler, bitumen, etc). The tonnage of each material involved in the project can be calculated, based on these parameters. Together with the (transport distance) data in ‘process parameters’, it will determine the workloads in a pavement project for inventory calculation. Parameters can be grouped into ‘pavement dimensions’, ‘materials recipe’ and ‘pavement life time’.

The tonnage of materials that would be used in a project is normally available from the contractor / materials supplier. Bitumen emulsion is seen in tack coat, chip seal (surface dressing) or cold mix asphalt. Both the bitumen and the emulsifier content are different between these applications. Emulsion usage in tack coat and chip seal is measured in the unit of ‘kg/m^2’, whilst in cold mix asphalt, by weight ratio of the mixture. Similarly, a different service life should be applied to the asphalt layers in the pavement structure, for example, 12 years for the surface course, and 15 years for the binder course, etc. Pavement life expectancy is a key factor affecting the inventory results as it can alter the frequency with which maintenance operations occur.

2.4 UNIT INVENTORY

In the ‘unit inventory’ worksheet, an environmental input and output inventory is built up for the unit processes in a pavement project. The inventory data for the ‘primary’ processes (e.g. energy production, vehicle engine operation) are presented first, followed by progressive calculations to get the inventory results for other processes in the pavement project. Emissions from a process have two origins. One is from the process itself (e.g. diesel engine operation, gas oil combustion); the other is the production of energy consumed in that process. Figures on energy consumption of vehicles and equipments come from the ‘process parameters’ worksheet. The ‘unit inventory’ worksheet can be grouped into ‘energy production’, ‘combustion of fossil fuel’, ‘transport vehicle operation’ and ‘construction vehicle operation’.

Transport and construction vehicles are assumed in this LCA model to run at their ‘operating capacity’ as specified by contractors. As discussed above, the unit inventory of (transport for example) vehicles operation (g/km) can be calculated by multiplying the fuel consumption (FC, MJ/km) by the sum of engine operation (g/MJ) and fuel production (g/MJ).

$$\text{Unit inventory (g/km)} = \text{FC (MJ/km)} * [\text{engine operation (g/MJ)} + \text{fuel production (g/MJ)}] \quad (1)$$

2.5 PROJECT INVENTORY

In the ‘project inventory’ worksheet, unit inventory data for material production, transport and pavement construction are aggregated into the unit of the pavement project, based on the workloads calculated from ‘pavement parameters’ (for materials tonnage and pavement area) and ‘process parameters’ (for transport distance). The results can be grouped into ‘materials production’, ‘transport’ and ‘pavement construction’. At the end of the worksheet is the total of environmental input (e.g. energy, aggregates) and output (e.g. CO_2, PM) for that pavement project. The percentage that each individual process accounts for are also indicated, to help identify the most significant variables in the project.

2.6 IMPACT ASSESSMENT

This LCA model refers to the review of existing LCIA methods (Pennington, 2004), and the LCIA methods recommended by UK Building Research Establishment (BRE) and ISO14047 (Howard, 1999; British Standards Institution, 2003) for selection of impact categories and characterisation methods. Based on the findings, 11 impact categories were selected for use in this model (examples are presented in Table 1), alongside the assessment method (characterisation model and characterisation factor) in the 'characterisation results' worksheet. The characterised result for an impact category is the total of all the individually characterised loadings in that category (see equation below).

$$\text{Characterisation result} = \sum_i InventoryLoading_i \times CharacterisationFactor_i \qquad (2)$$

The details of the impact assessment are not described in the following case study, for: 1) it would be purely an environmental analysis process that needs very little input from road engineers once the inventory is complete and, 2) the case study is to compare the energy consumption and emissions using only the inventory results.

3 CASE STUDY - FOAMIX AND HALF WARM ASPHALT

The concept about half warm asphalt (HWA) is to heat the aggregates to just below 100ºC (e.g. 95ºC) before mixing with the binder, compared to 150-190ºC required for conventional hot mix asphalt. To reduce the viscosity at lower temperatures, binder in the half warm asphalt is either foamed, or mixed with chemical additives. In Foamix, recycled asphalt pavement (RAP) feedstock is mixed with hydraulic binders (e.g. pulverised fuel ash (PFA), cement/hydrated lime) and foamed bitumen. These mixtures can be used in place of dense bitumen macadam (DBM, a type of hot mix asphalt) for structural courses in the pavement.

A need has been identified by the Foamix and half warm asphalt manufacturer to measure the energy consumption and carbon footprint of these products, and to make a comparison with hot mix asphalt that fulfils the same function in the pavement structure. The manufacturer's plants in Greenwich (for Foamix) and Astley (for half warm asphalt) provided the data for materials production. The energy data for fossil fuels and hydraulic binders were obtained from UK Carbon Trust and the Concrete Centre, respectively (Carbon Trust, 2004; The Concrete Centre, 2009). The rest of the data required came from the LCA model described above. Comparable pavements were designed to benchmark these non-standard materials against hot mix asphalt, with a functional unit of 1km x 7.5m asphalt pavement defined, in this case study.

3.1 PAVEMENT DESIGN

Previous energy and CO_2 analysis of pavement materials were usually undertaken on a tonne-for-tonne basis, excluding the difference between the materials' performance (i.e. stiffness, durability). This case study took into account the asphalt stiffness, but assumed the same durability of all three material options.

Fully-flexible pavements for 30msa (million standard axle) and 2msa traffic were designed, based on the asphalt stiffness provided by the manufacturer. Stone mastic asphalt (SMA, 2,000MPa) and dense bitumen macadam (DBM50, 4,700MPa) were assumed to form the surface course and binder course (if any), respectively. The design (Table 2) referred to the UK Design Manual for Roads and Bridges (UK Highways Agency, 2006), Interim Advice Note (UK Highways Agency, 2008) and research report (Merrill, Nunn et al., 2004). These stiffness and thickness were run through Scott Wilson Ltd's pavement life calculation software, MPTRN ensuring that these pavements have comparable strain at the bottom of the base (the critical location for determining pavement life).

TABLE 2: DESIGN OF COMPARABLE PAVEMENTS

		Foamix	Half warm asphalt	Hot mix asphalt
30msa	Pavement Structure	40mm SMA 60mm DBM50 200mm heavy duty (B4) Foamix	40mm SMA 60mm HWA 190mm HWA	40mm SMA 60mm DBM50 210mm DBM50
		Foundation Class 2		
	Base stiffness (MPa)	5200	5400	4700
	Pavement life (msa)	34.1	30.0	34.7
	Strain at base bottom	72.3×10^{-6}	73.9×10^{-6}	72.8×10^{-6}
2msa	Pavement Structure	40mm SMA 40mm DBM50 120mm heavy duty (B4) Foamix	40mm SMA 160mm HWA	40mm SMA 160mm DBM50
		Foundation Class 2		
	Base stiffness (MPa)	5200	5400	4700
	Pavement life (msa)	2.4	2.6	2.0
	Strain at base bottom	138.0×10^{-6}	134.0×10^{-6}	146.0×10^{-6}

3.2 INVENTORY ANALYSIS OF COMPARABLE PAVEMENTS

All products and processes related to the pavement construction, namely the manufacture of asphalt and ingredient materials, transport, paving and rolling, were considered in this case study. The system boundary for Foamix is illustrated in Figure 4, as an example.

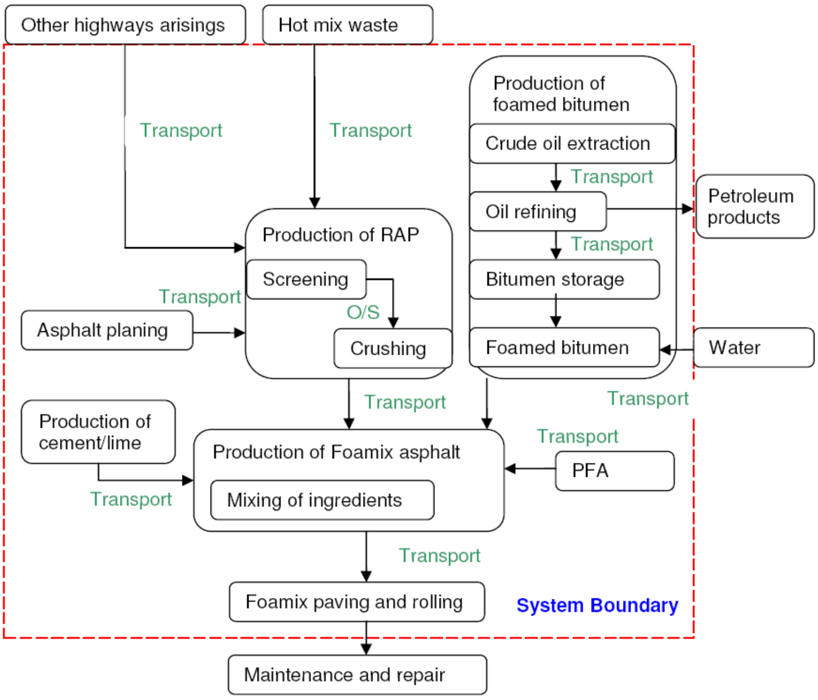

FIGURE 4: SYSTEM BOUNDARY OF FOAMIX PAVEMENT

The energy saving by producing half warm asphalt comes predominantly from the reduced need to heat the aggregates, as high as 53% during the drying and heating process. Production of Foamix is a ‘cold’ process consuming only about 13% of the energy required for hot mix asphalt production. On the other hand, the heavy duty B4 Foamix contained 4% cement by weight, whose carbon footprint is a lot higher than other ingredients of the mixture.

Transport in this case study was defined in Figure 5, in which elements 3-8 were specific to the Foamix production. The transport for half warm asphalt was assumed the same as hot mix asphalt. Elements 10-12 were not included in this case study but might be applicable to other projects. A universal scenario of 32km, 20t payload, 8mpg (miles per gallon, fully loaded) and 10mpg (empty loaded) were assumed for all transport processes. The percentage that transport accounts for the inventory total is presented in Table 3. It can be seen that transport accounted for 12-16% of the CO_2 emission, and 8-12% of the energy consumption.

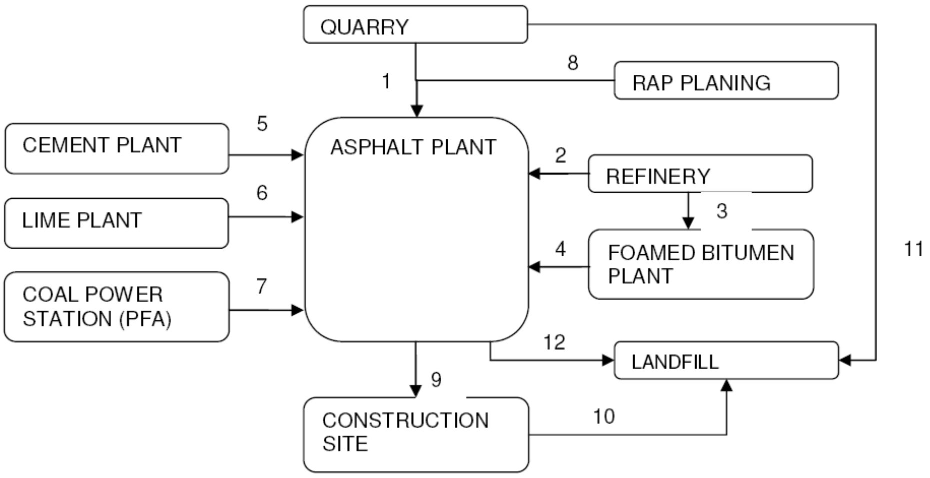

FIGURE 5: TRANSPORT IN FOAMIX PRODUCTION

3.3 RESULTS DISCUSSION

The calculated inventories for all three material options are presented in Table 3 (30msa as an example).

TABLE 3: INVENTORY RESULTS FOR 30msa PAVEMENTS

Foamix		**Energy input (MJ)**				**Emission to air (g)**						
	Energy total	Electricity	Natural gas	Petroleum oil	Coal	SO2	NOx	CO	CO2	NMVOC	PM	Heavy metals
Materials	3.38E+06	3.27E+05	1.86E+06	4.68E+05	7.22E+05	6.99E+05	9.22E+05	9.14E+04	2.43E+08	3.79E+04	2.46E+05	9.41E+02
Transport	4.67E+05	0.00E+00	0.00E+00	4.67E+05	0.00E+00	1.17E+04	1.69E+05	7.14E+04	3.32E+07	0.00E+00	9.47E+02	0.00E+00
Paving	3.60E+04	0.00E+00	0.00E+00	3.60E+04	0.00E+00	8.49E+02	2.39E+04	1.69E+04	2.52E+06	3.37E+03	1.04E+03	0.00E+00
Total	3.88E+06	3.27E+05	1.86E+06	9.71E+05	7.22E+05	7.12E+05	1.11E+06	1.80E+05	2.79E+08	4.12E+04	2.48E+05	9.41E+02

Half warm		**Energy input (MJ)**				**Emission to air (g)**						
	Energy total	Electricity	Natural gas	Petroleum oil	Coal	SO2	NOx	CO	CO2	NMVOC	PM	Heavy metals
Materials	4.89E+06	3.16E+05	3.83E+06	5.41E+05	2.04E+05	6.77E+05	7.69E+05	1.17E+05	1.89E+08	5.58E+04	1.32E+05	1.10E+03
Transport	4.46E+05	0.00E+00	0.00E+00	4.46E+05	0.00E+00	1.12E+04	1.62E+05	6.83E+04	3.17E+07	0.00E+00	9.04E+02	0.00E+00
Paving	3.60E+04	0.00E+00	0.00E+00	3.60E+04	0.00E+00	8.49E+02	2.39E+04	1.69E+04	2.52E+06	3.37E+03	1.04E+03	0.00E+00
Total	5.37E+06	3.16E+05	3.83E+06	1.02E+06	2.04E+05	6.89E+05	9.55E+05	2.02E+05	2.23E+08	5.91E+04	1.34E+05	1.10E+03

Hot mix		**Energy input (MJ)**				**Emission to air (g)**						
	Energy total	Electricity	Natural gas	Petroleum oil	Coal	SO2	NOx	CO	CO2	NMVOC	PM	Heavy metals
Materials	5.38E+06	2.96E+05	4.33E+06	5.64E+05	1.93E+05	7.01E+05	8.14E+05	1.25E+05	2.02E+08	5.85E+04	1.35E+05	1.17E+03
Transport	4.77E+05	0.00E+00	0.00E+00	4.77E+05	0.00E+00	1.20E+04	1.73E+05	7.30E+04	3.39E+07	0.00E+00	9.67E+02	0.00E+00
Paving	3.60E+04	0.00E+00	0.00E+00	3.60E+04	0.00E+00	8.49E+02	2.39E+04	1.69E+04	2.52E+06	3.37E+03	1.04E+03	0.00E+00
Total	5.90E+06	2.96E+05	4.33E+06	1.08E+06	1.93E+05	7.14E+05	1.01E+06	2.15E+05	2.38E+08	6.18E+04	1.37E+05	1.17E+03

It can be seen that, for 30msa traffic, using Foamix and half warm asphalt as a pavement base course reduced the energy consumption from 5.90×10^6MJ to 3.88×10^6MJ (by 34.2%) and 5.37×10^6MJ (by 8.9%), respectively, compared to using hot mix asphalt as a base material. Using half warm asphalt also reduced the CO_2 by 15t (6.5%) compared with hot mix asphalt. However, the CO_2 output from using Foamix was 41t (17.2%) higher than the hot mix asphalt. A similar pattern was found in the 2msa design, where Foamix and half warm asphalt reduced the energy consumption by 28.5% and 15.1%, respectively, whereas the CO_2 savings were -17.2% and 6.5%, respectively, confirming that the Foamix pavement has a higher CO_2 footprint than the hot mix asphalt pavement.

Table 2 indicated that the Foamix and half warm asphalt base was thinner, due to the higher stiffness of these materials, than the hot mix asphalt base. To eliminate the effects of a thinner pavement layer on the overall energy/CO_2 footprint, a tonne-for-tonne comparison was made between the Foamix, half warm asphalt and hot mix asphalt. The results, shown below with the hot mix asphalt being used as the baseline, indicated that the CO_2 footprint associated with using Foamix was still the highest of the three material options. This confirmed that the embodied CO_2 of the cement in Foamix outweighed the savings from the mixing and transport process, driving up the overall CO_2 footprint of the Foamix.

[Energy consumption] Foamix: half warm asphalt: hot mix asphalt = 0.52: 0.81: 1.00
[CO_2 footprint] Foamix: half warm asphalt: hot mix asphalt = 1.31: 0.88: 1.00

4 CONCLUSIONS AND RECOMMENDATION

Life cycle assessment is an important tool to support making an informed decision for sustainable construction. If this technique is to reflect current practice in the UK road construction industry, LCA models should accommodate realistic maintenance and recycling scenarios, with good quality and relevant data. A practical model should also be tested and calibrated by case studies of real projects. Data in this LCA model came from a mixed source of UK plants, European standards and previous LCA studies. There is still some scope for improving the quality of data in the model. However this is unlikely to affect the overall findings of the case study.

The concept of Foamix is similar to that of additive based half warm asphalt: to reduce the viscosity of the binder at lower temperatures, and consequently the energy inputs, than required for hot mix asphalt. In addition, Foamix has the benefit of using recycled pavement materials in place of natural aggregates. The case study indicated that the construction of comparable pavements using Foamix base consumed less energy but released more CO_2, compared to hot mix asphalt. The pavement using half warm asphalt base reduced both the energy consumption and CO_2 footprint. These effects are due to: 1) A thinner base layer was required for Foamix and half warm asphalt due to the higher stiffness of the material and, 2) The embodied CO_2 in cement was substantially high that drove up the overall CO_2 of the Foamix outweighing the savings from a thinner pavement. Reducing the cement/lime content in Foamix (e.g. replace with PFA or ground granulated blastfurnace slag (GGBS), which has a lower CO_2 footprint) therefore, is an area further research would be very beneficial. Other benefits such as the RAP replacement are yet to be quantified in the LCA study.

A life cycle approach in accordance with the ISO14040 requires a functional unit be defined so that the different pavement materials can be assessed on a performance related basis. Strictly speaking, a life cycle assessment should take into account the durability of materials laid in place and use a fairly long analysis period (e.g. 40 years) with a defined intervention scheme. This will require further material testing and prediction of the material behaviour over time. More case studies would enable the scope and computing capacity of the model, as well as its accuracy, to be enhanced.

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